A Structural Decomposition of the US Yield Curve

Ferre De Graeve* Marina Emiris† Raf Wouters‡

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Abstract

We estimate a medium-scale macro-finance DSGE model of the term structure. Historical fluctuations in US bond yields are largely consistent with the rational expectations hypothesis. We interpret various episodes through the lens of the model. The inflation hike in the mid-seventies was predominantly the result of markup shocks to wages and prices, while monetary policy's commitment to fighting inflation was largely credible. Although the Fed succeeded in bringing down inflation in the early eighties, it had less success in lowering inflation expectations. The model suggests the 2004 "conundrum" is a logical consequence of the Fed's response to demand-type shocks hitting the economy. Finally, the paper investigates which structural shocks cause the yield curve to contain information about future growth.

Keywords: Term structure, DSGE, Expectations hypothesis, Conundrum

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*Ghent University (ferre.degraeve@ugent.be).

†National Bank of Belgium (marina.emiris@nbb.be).

‡National Bank of Belgium (rafael.wouters@nbb.be).

1 Introduction

Numerous contributions in finance have made it clear that imposing no-arbitrage restrictions in empirical models of the yield curve improves their empirical characteristics (see e.g. Ang et al. 2006 for a recent example). At the same time, macroeconomic research has shown that theoretical restrictions embedded in dynamic stochastic general equilibrium (DSGE) models make current macro models competitive with VAR's (see e.g. Smets and Wouters 2007). The macro-finance literature aims to combine these two types of restrictions, in view of capturing both dimensions simultaneously, and ultimately, contribute to understanding links between the real and financial economy. However, appending a term structure to the standard New-Keynesian model finds only limited support in the data. The response of the macro-finance literature has been to incorporate flexible features in the model. Examples are time-varying parameters (e.g. Fuhrer 1996, Favero 2006, Dewachter and Lyrio 2006) time-varying variances of structural shocks (e.g. Doh 2007b), flexible pricing kernels (e.g. Rudebusch and Wu 2007b), additional shocks (Bekaert et al. 2006), latent variables (e.g. Ang and Piazzesi 2003), etc. These additional features have brought model implied yields and observed yields closer together.

The present paper, by contrast, shows how a full-fledged DSGE model receives as much empirical support, without the introduction of additional flexibility. The rationale for our approach lies in the possibility that, in current macro-finance models, the description of the macroeconomy is in some way inadequate. When present, such mis-specification will feed through to yield predictions, via the formation of expectations. We therefore focus on a more rigorously specified DSGE model -in the same vein as Christiano et al. (2005) and Smets and Wouters (2007)- which, in terms of forecasting key macroeconomic aggregates, is competitive with (Bayesian) VAR's.

A more rigorous specification of the macroeconomy results in a more rigorous formation of expectations. This is a first contribution of the paper: we detail how well the rational expectations hypothesis of the term structure describes bond yield dynamics in a medium-scale DSGE model. To anticipate results, we find our restrictive DSGE model to be competitive with models that do incorporate additional flexibility. In particular, we find that 90% of yield fluctuations during the past forty years are consistent with the rational expectations hypothesis. Moreover, the model is promising in terms of out-of-sample yield predictions.

The favorable empirical properties of our DSGE model raise a number of questions. A first question traces back to existing macro-finance models of the term structure. In particular, in the literature, the fact that additional forms of flexibility invariably increase the empirical fit is often interpreted as evidence in favor of the newly introduced mechanism. This is not necessarily the only plausible interpretation, however. The empirical gain may also derive from the fact that the relatively simple description of the macroeconomy is unsatisfactory in some dimension. The additionally introduced degrees of freedom may enable the models to pick up this mis-specification, rather than being truly relevant aspects of the economy themselves. At the very least, the fact that the more elaborate description of expectations in our model -restrictive in every other respect- is able to compete with more flexible approaches should underline this possibility. While we hope this feature of extant macro-finance models is acknowledged, we leave this avenue of research open for future work[1].

We here focus on a second, more topical question of interest. Given the relative success of the model, we investigate how the model interprets the so-called "conundrum". The observation that the recent tightening of the Fed did not result in significant long rate increases has puzzled numerous economists. Many observers deem the expectations hypothesis incapable of explaining this recent episode. The alternative explanation put forth is that a fall in the term premium is

[1] A horse race between the variety of models would be insightful, though model comparison could be involving due to differences in information sets. An alternative avenue is to introduce the various forms of flexibility in the model we present, and infer how much improvement they generate, if any.

responsible for the sustained low long rates (e.g. Backus and Wright 2007). Our model advocates a different view, consistent with the expectations hypothesis. After describing the term structure response to the various structural shocks in the model, we show that the recent episode can be interpreted as the consequence of the Fed's stabilizing policy response to demand shocks hitting the economy. We provide historical decompositions that make this point explicitly, and contrast them with the behaviour of the term structure in other periods of tight monetary policy. Cochrane (2007) provides an appealing intuition for the recent US yield behaviour based on the expectations hypothesis. A second contribution of this paper lies in confronting such an argument to the data, and providing an explicit structural interpretation for it.

Moreover, the model admits an interpretation not only for the late "conundrum" episode. Including the yield curve in the analysis, in addition to macroeconomic data, provides a broader perspective on monetary policy conduct in the past decades. We detail the model's interpretation of the two inflation hikes in the seventies. Both the mid-seventies spike in inflation and the early eighties disinflation are characterized by a divergence of actual and expected inflation. These findings shed light on the credibility of the Fed's objective toward fighting inflation. Our results confirm the interpretation of Goodfriend (1993, 2002), who stresses the importance of "inflation scares" for understanding the Fed's interest rate policy. The estimated DSGE model provides structural estimates of inflation expectations which corroborate, among other things, the 1994 monetary tightening as a preemptive strike.

As a final contribution, the paper addresses the predictive ability of the yield curve. Both the short term interest rate and the term spread have an impressive record in predicting GDP growth (see Estrella 2005, Ang et al. 2006, and the references therein). Using our estimated macro-finance model, we present a structural interpretation for the informational content of the yield curve for future growth.

The paper is organized as follows. The next section describes the micro-foundations of the macro-finance model. Section 3 details the mapping of model variables to the data and the estimation procedure, and reports structural parameter estimates. In Section 4 we document the empirical fit. The model is evaluated both in and out-of-sample. We then study several implications of the model. Section 5 decomposes fluctuations in the yield curve in terms of structural macroeconomic shocks and describes how this description relates to alternative representations of the term structure. In Section 6 we investigate the historical evolution of bond yields. This necessitates a precise description of inflation expectations and, ultimately, of monetary policy. As a form of external validation, we compare model–implied inflation expectations to survey measures. Section 7 assesses the role of the term premium and documents the 2004-2006 episode with special rigour. The informational content of the yield curve for economic growth is analyzed in Section 8.

2 The model

The model we study is a close variant of Smets and Wouters (2007). The economy consists of households, final and intermediate goods firms and the monetary authority. Consumers provide differentiated labour to a monopolistically competitive labor market. They own the capital stock, decide on investment and rent capital services to firms. Consumers' utility is non-separable in consumption and labour effort. The utility households derive from consumption is relative to an external habit. In addition to these features, and different from Smets and Wouters (2007), we introduce a time-varying inflation target. The primary reason for doing so is to model inflation expectations more rigorously. Evidently, inflation expectations are key to understanding fluctuations in the term structure of interest rates. Gürkaynak et al. (2005) show how allowing for changes in the inflation target alleviates the counterfactual constant nature of long horizon forward interest implicit in standard macroeconomic models. The introduction of the inflation target alters the model of Smets and Wouters (2007) in two ways. First, the policy rule for the monetary authority aims to close the gap between actual and objective inflation. Here, it will be possible for the authority's objective to change over time. Second, the indexation of wages and prices (partially) takes into account fluctuations in the inflation target. This will alter the behaviour of wages and prices in the model. Finally, we append a term structure to the DSGE model. We maintain the assumption of rational expectations.

2.1 Decision problems and equilibrium conditions: firms and households

2.1.1 Final goods producers

The final good Y_t is a composite made of a continuum of intermediate goods $Y_t(i)$ as in Kimball (1995). The final good producers buy intermediate goods, package them into Y_t, and sell the final good to consumers, investors and the government in a perfectly competitive market. They maximize profits:

$$\max_{Y_t, Y_t(i)} P_t Y_t - \int_0^1 P_t(i) Y_t(i) di$$
$$s.t. \left[\int_0^1 G\left(\frac{Y_t(i)}{Y_t}; \varepsilon_t^p\right) di\right] = 1 \quad (\mu_{f,t})$$

where P_t and $P_t(i)$ are the price of the final and intermediate goods respectively, and G is a strictly concave and increasing function characterized by $G(1) = 1$. ε_t^p is an exogenous process that reflects shocks to the aggregator function that result in changes in the elasticity of demand and therefore in the markup. We will constrain $\varepsilon_t^p \in (0, \infty)$.

Combining the first-order conditions with respect to $Y_t(i)$ and Y_t results in:

$$Y_t(i) = Y_t G'^{-1}\left[\frac{P_t(i)}{P_t} \int_0^1 G'\left(\frac{Y_t(i)}{Y_t}\right) \frac{Y_t(i)}{Y_t} di\right]$$

As in Kimball (1995), the assumptions on G imply that the demand for input $Y_t(i)$ is decreasing in its relative price, while the elasticity of demand is a positive function of the relative price (or a negative function of the relative output).

2.1.2 Intermediate goods producers

Intermediate good producer i uses the following technology:

$$Y_t(i) = \varepsilon_t^a K_t^s(i)^\alpha \left[\gamma^t L_t(i)\right]^{1-\alpha} - \gamma^t \Phi$$

where $K_t^s(i)$ is capital services used in production, $L_t(i)$ is a composite labour input and Φ is a fixed cost. γ^t represents the labour-augmenting deterministic growth rate in the economy and ε_t^a is total factor productivity.

The firm's profit is given by:

$$P_t(i)Y_t(i) - W_t L_t(i) - R_t^k K_t^s(i)$$

where W_t is the aggregate nominal wage rate and R_t^k is the rental rate on capital.

Cost minimization yields the following first-order conditions:

$$(\partial L_t(i)) : \quad \Theta_t(i)\gamma^{(1-\alpha)t}(1-\alpha)\varepsilon_t^a K_t^s(i)^\alpha L_t(i)^{-\alpha} = W_t$$

$$(\partial K_t^s(i)) : \quad \Theta_t(i)\gamma^{(1-\alpha)t}\alpha\varepsilon_t^a K_t^s(i)^{\alpha-1} L_t(i)^{1-\alpha} = R_t^k$$

where $\Theta_t(i)$ is the Lagrange multiplier associated with the production function and equals marginal cost MC_t.

Combining these FOCs and noting that the capital-labour ratio is equal across firms implies:

$$K_t^s = \frac{\alpha}{1-\alpha}\frac{W_t}{R_t^k}L_t$$

The marginal cost MC_t is the same for all firms and equal to:

$$MC_t = \alpha^{-\alpha}(1-\alpha)^{-(1-\alpha)} W_t^{1-\alpha} R_t^{k\ \alpha} \gamma^{-(1-\alpha)t} \left(\varepsilon_t^a\right)^{-1}$$

Under Calvo pricing with partial indexation to lagged inflation, the optimal price set by the firm that is allowed to re-optimize results from the following optimization problem:

$$\max_{\tilde{P}_t(i)} E_t \sum_{s=0}^{\infty} \xi_p^s \frac{\beta^s \Xi_{t+s} P_t}{\Xi_t P_{t+s}} \left[\tilde{P}_t(i) (\Pi_{l=1}^s \pi_{t+l-1}^{\iota_p} \bar{\pi}_{t+l}^{1-\iota_p}) - MC_{t+s} \right] Y_{t+s}(i)$$

$$s.t.\ Y_{t+s}(i) = Y_{t+s} G'^{-1} \left(\frac{P_t(i) X_{t,s}}{P_{t+s}} \tau_{t+s} \right)$$

where $\tilde{P}_t(i)$ is the newly set price, ξ_p is the Calvo probability of being allowed to optimize one's price, π_t is inflation defined as $\pi_t = P_t/P_{t-1}$, $[\frac{\beta^s \Xi_{t+s} P_t}{\Xi_t P_{t+s}}]$ is the nominal discount factor for firms (which equals the discount factor for the households that are the final owners of the firms), $\tau_t = \int_0^1 G' \left(\frac{Y_t(i)}{Y_t} \right) \frac{Y_t(i)}{Y_t} di$ and

$$X_{t,s} = \left\{ \begin{array}{c} 1 \ for\ s = 0 \\ (\Pi_{l=1}^s \pi_{t+l-1}^{\iota_p} \bar{\pi}_{t+l}^{1-\iota_p}) \ for\ s = 1, ..., \infty \end{array} \right\}.$$

Firms whose prices are not re-optimized have their prices indexed to a composite of past inflation and the inflation target, with the relative weight determined by ι_p. This indexation scheme is a generalization of that in Smets and Wouters (2007), and allows for a time-varying inflation target.

The first-order condition is given by:

$$E_t \sum_{s=0}^{\infty} \xi_p^s \frac{\beta^s \Xi_{t+s} P_t}{\Xi_t P_{t+s}} Y_{t+s}(i) \left[X_{t,s} \tilde{P}_t(i) + \left(\tilde{P}_t(i) X_{t,s} - MC_{t+s} \right) \frac{1}{G'^{-1}(z_{t+s})} \frac{G'(x_{t+s})}{G''(x_{t+s})} \right] = 0$$

where $x_t = G'^{-1}(z_t)$ and $z_t = \frac{P_t(i)}{P_t} \tau_t$.

The aggregate price index in this case is given by:

$$P_t = (1 - \xi_p) P_t(i) G'^{-1} \left[\frac{P_t(i) \tau_t}{P_t} \right] + \xi_p \pi_{t-1}^{\iota_p} \bar{\pi}_t^{1-\iota_p} P_{t-1} G'^{-1} \left[\frac{\pi_{t-1}^{\iota_p} \bar{\pi}_t^{1-\iota_p} P_{t-1} \tau_t}{P_t} \right]$$

2.1.3 Households

Household j chooses consumption $C_t(j)$, hours worked $L_t(j)$, one-period bonds $B_t(j)$, investment $I_t(j)$ and capital utilization $Z_t(j)$, so as to maximize the following objective function:

$$E_t \sum_{s=0}^{\infty} \beta^s \left[\frac{1}{1-\sigma_c} (C_{t+s}(j) - \lambda C_{t+s-1})^{1-\sigma_c} \right] \exp\left(\frac{\sigma_c - 1}{1+\sigma_l} L_{t+s}(j)^{1+\sigma_l} \right)$$

subject to the budget constraint:

$$\begin{aligned} & C_{t+s}(j) + I_{t+s}(j) + \frac{B_{t+s}(j)}{\varepsilon_t^b R_{t+s} P_{t+s}} - T_{t+s} \\ \leq \quad & \frac{B_{t+s-1}(j)}{P_{t+s}} + \frac{W_{t+s}^h(j) L_{t+s}(j)}{P_{t+s}} + \frac{R_{t+s}^k Z_{t+s}(j) K_{t+s-1}(j)}{P_{t+s}} - a(Z_{t+s}(j)) K_{t+s-1}(j) + \frac{Div_{t+s}}{P_{t+s}} \end{aligned}$$

and the capital accumulation equation:

$$K_t(j) = (1-\delta) K_{t-1}(j) + \varepsilon_t^I \left[1 - S\left(\frac{I_t(j)}{I_{t-1}(j)} \right) \right] I_t(j).$$

There is external habit formation captured by the parameter λ. The one-period bond is expressed on a discount basis. ε_t^b is the financial markup: it is an exogenous premium in the return to bonds, which can reflect inefficiencies in the financial sector leading to some premium on the deposit rate versus the risk free rate set by the central bank. Goodfriend and McCallum (2007) provide a general equilibrium model which gives rise to interest rate premia that enter the model in a similar fashion. A broad class of financial frictions of this type (e.g. Bernanke et al. 1999) give rise to such a markup, as shown by Chari et al. (2007). δ is the depreciation rate, $S(\cdot)$ is the adjustment cost function, with $S(\gamma) = 0$, $S'(\gamma) = 0$, $S''(\cdot) > 0$, and ε_t^I is a stochastic shock to the price of investment relative to consumption goods. T_{t+s} are lump sum taxes or subsidies and Div_{t+s} are the dividends distributed by the intermediate goods producers and the labour unions.

Finally, households choose the utilization rate of capital. The amount of effective capital that households can rent to the firms is:

$$K_t^s(j) = Z_t(j) K_{t-1}(j)$$

The income from renting capital services is $R^k_t Z_t(j) K_{t-1}(j)$, while the cost of changing capital utilization is $P_t a(Z_t(j)) K_{t-1}(j)$.

In equilibrium households will make the same choices for consumption, hours worked, bonds, investment and capital utilization. The first-order conditions can be written as (dropping the j index):

$$
\begin{aligned}
(\partial C_t) \qquad \Xi_t &= \exp\left(\frac{\sigma_c-1}{1+\sigma_l} {L_t}^{1+\sigma_l}\right)(C_t - \lambda C_{t-1})^{-\sigma_c} \\
(\partial L_t) \qquad -\Xi_t \frac{W^h_t}{P_t} &= \left[\frac{1}{1-\sigma_c}(C_t - hC_{t-1})^{1-\sigma_c}\right] \exp\left(\frac{\sigma_c-1}{1+\sigma_l} L_t^{1+\sigma_l}\right)(\sigma_c-1) L_t^{\sigma_l} \\
(\partial B_t) \qquad \Xi_t &= \beta \varepsilon^b_t R_t E_t\left[\frac{\Xi_{t+1}}{\pi_{t+1}}\right] \\
(\partial I_t) \qquad \Xi_t &= \Xi^k_t \varepsilon^i_t \left(1 - S(\frac{I_t}{I_{t-1}}) - S'(\frac{I_t}{I_{t-1}})\frac{I_t}{I_{t-1}}\right) \\
&\quad + \beta E_t\left[\Xi^k_{t+1}\varepsilon^i_{t+1} S'(\frac{I_{t+1}}{I_t})(\frac{I_{t+1}}{I_t})^2\right] \\
(\partial \bar{K}_t) \qquad \Xi^k_t &= \beta E_t\left[\Xi_{t+1}\left(\frac{R^k_{t+1}}{P_{t+1}} Z_{t+1} - a(Z_{t+1})\right) + \Xi^k_{t+1}(1-\delta)\right] \\
(\partial Z_t) \qquad \frac{R^k_t}{P_t} &= a'(Z_t)
\end{aligned}
$$

where Ξ_t and Ξ^k_t are the Lagrange multipliers associated with the budget and capital accumulation constraint respectively. Tobin's $Q^k_t = \Xi^k_t / \Xi_t$ and equals one in the absence of adjustment costs.

2.1.4 Intermediate labour unions and labour packers

Households supply their homogenous labour to an intermediate labour union which differentiates the labour services, sets wages subject to a Calvo scheme and offers those labour services to intermediate labour packers. Labour used by the intermediate goods producers L_t is a composite made of those differentiated labour services $L_t(i)$. As with intermediate goods, the aggregator is the one proposed by Kimball (1995). The labour packers buy the differentiated labour services, package L_t, and offer it to the intermediate goods producers.

The labour packers maximize profits:

$$\max_{L_t, L_t(i)} W_t L_t - \int_0^1 W_t(i) L_t(i) di$$

$$s.t. \left[\int_0^1 H\left(\frac{L_t(i)}{L_t}; \varepsilon_t^w\right) di\right] = 1$$

where W_t and $W_t(i)$ are the price of the composite and intermediate labour services respectively,

and H is a strictly concave and increasing function characterized by $H(1) = 1$. ε_t^w is an exogenous process that reflects shocks to the aggregator function that result in changes in the elasticity of demand and therefore in the markup. We will constrain $\varepsilon_t^w \in (0, \infty)$. Combining FOCs results in:

$$L_t(i) = L_t H'^{-1}\left[\frac{W_t(i)}{W_t}\int_0^1 H'\left(\frac{L_t(i)}{L_t}\right)\frac{L_t(i)}{L_t} di\right]$$

The labour unions are an intermediate between the households and the labor packers. Under Calvo pricing with partial indexation to lagged inflation, the optimal wage set by the union that is allowed to re-optimize its wage results from the following optimization problem:

$$\max_{\widetilde{W}_t(i)} E_t \sum_{s=0}^{\infty} \xi_w^s \frac{\beta^s \Xi_{t+s} P_t}{\Xi_t P_{t+s}} \left[\widetilde{W}_t(i)(\Pi_{l=1}^s \gamma \pi_{t+l-1}^{\iota_w} \bar{\pi}_{t+l}^{1-\iota_w} - W_{t+s}^h\right] L_{t+s}(i)$$

$$s.t.\ L_{t+s}(i) = L_{t+s} H'^{-1}\left(\frac{W_t(i) X_{t,s}^w}{W_{t+s}} \tau_{t+s}^w\right)$$

where $\widetilde{W}_t(i)$ is the newly set wage, ξ_w is the Calvo probability of being allowed to optimize one's

wage, $\tau_t^w = \int_0^1 H'\left(\frac{L_t(i)}{L_t}\right)\frac{L_t(i)}{L_t} di$ and

$$X_{t,s}^w = \left\{\begin{array}{c} 1\ for\ s = 0 \\ (\Pi_{l=1}^s \gamma \pi_{t+l-1}^{\iota_w} \bar{\pi}_{t+l}^{1-\iota_w})\ for\ s = 1, ..., \infty \end{array}\right\}$$

The first-order condition is given by:

$$E_t \sum_{s=0}^{\infty} \xi_w^s \frac{\beta^s \Xi_{t+s} P_t}{\Xi_t P_{t+s}} L_{t+s}(i) \left[X_{t,s}^w \widetilde{W}_t(i) + \left(\widetilde{W}_t(i) X_{t,s}^w - W_{t+s}^h\right) \frac{1}{H'^{-1}(z_{t+s}^w)} \frac{H'(x_{t+s}^w)}{H''(x_{t+s}^w)}\right] = 0$$

where $x_t^w = H'^{-1}(z_t^w)$ and $z_t^w = \frac{W_t(i)}{W_t}\tau_t^w$.

The aggregate wage index is in this case given by:

$$W_t = (1-\xi_w)\widetilde{W}_t H'^{-1}\left[\frac{\widetilde{W}_t \tau_t^w}{W_t}\right] + \xi_w \gamma \pi_{t-1}^{\iota_w} \bar{\pi}_t^{1-\iota_w} W_{t-1} H'^{-1}\left[\frac{\gamma \pi_{t-1}^{\iota_w} \bar{\pi}_t^{1-\iota_w} W_{t-1} \tau_t^w}{W_t}\right]$$

The markup of the aggregate wage over the wage received by the households is distributed to the households in the form of dividends (see the budget constraint of households).

2.1.5 Government Policies

The central bank follows a nominal interest rate rule by adjusting its instrument in response to deviations of inflation and output from their respective target levels:

$$\frac{R_t}{RR^* \bar{\pi}_t} = \left(\frac{R_{t-1}}{RR^* \bar{\pi}_{t-1}}\right)^{\rho} \left[\left(\frac{\pi_t}{\bar{\pi}_t}\right)^{r_\pi} \left(\frac{Y_t}{Y_t^*}\right)^{r_y}\right]^{(1-\rho)} \left(\frac{Y_t / Y_{t-1}}{Y_t^* / Y_{t-1}^*}\right)^{r_{\Delta y}} \varepsilon_t^r$$

where RR^* is the steady state real rate and Y_t^* is natural output. The parameter ρ determines the degree of interest rate smoothing. ε_t^r is the exogenous monetary policy shock.

The government budget constraint is of the form

$$P_t G_t + B_{t-1} = T_t + \frac{B_t}{R_t}$$

where T_t are nominal lump-sum taxes (or subsidies) that also appear in household's budget constraint. Government spending is exogenous and expressed relative to the steady state output path as $\varepsilon_t^g = G_t/(Y\gamma^t)$.

2.1.6 The natural output level

The natural output level is defined as the output in the flexible price and wage economy without mark-up shock in prices and wages. Persistent markup shocks may therefore result in persistent conflicts between stabilizing inflation and output gap and therefore in persistent deviations of inflation from the inflation target.

2.1.7 Resource constraint

Integrating the budget constraint across households and combining with the government budget constraint and the expressions for the dividends of intermediate goods producers and labour unions gives the overall resource constraint:

$$C_t + I_t + G_t + a(Z_t)K_{t-1} = Y_t$$

2.2 Detrending and linearization

The model can be detrended with the deterministic trend γ and nominal variables can be replaced by their real counterparts. The non-linear system is then linearized around the stationary steady state of the detrended variables. Starred variables denote steady state values. We first describe the aggregate demand side of the model and then turn to the aggregate supply.

2.2.1 Aggregate demand side

The aggregate resource constraint is given by:

$$\widehat{y}_t \;=\; \hat{\varepsilon}_t^g \;+\; \frac{c_*}{y_*}\widehat{c}_t \;+\; \frac{i_*}{y_*}\widehat{i}_t \;+\; \frac{r_*^k k_*}{y_*}\widehat{z}_t. \tag{1}$$

Output ($\widehat{y}_t$) is absorbed by consumption ($\widehat{c}_t$), investment ($\widehat{i}_t$), capital-utilization costs that are a function of the capital utilization rate ($\widehat{z}_t$) and exogenous spending ($\hat{\varepsilon}_t^g$). We assume that exogenous spending follows a first-order autoregressive process with an IID-Normal error term and is also affected by the productivity shock as follows: $\hat{\varepsilon}_t^g \;=\rho_g\hat{\varepsilon}_{t-1}^g \;+\rho_{ga}\epsilon_t^a + \epsilon_t^g$. The latter is empirically motivated by the fact that in estimation exogenous spending also includes net exports, which may be affected by domestic productivity developments.

The dynamics of consumption follows from the consumption Euler equation and is given by:

$$\widehat{c}_t = \frac{1}{(1+(\lambda/\gamma))} E_t\left[\widehat{c}_{t+1}\right] + \frac{(\lambda/\gamma)}{(1+(\lambda/\gamma))}\widehat{c}_{t-1}$$
$$-\frac{(1-\lambda/\gamma)}{\sigma_c(1+(\lambda/\gamma))}(\hat{\varepsilon}_t^b + \widehat{R}_t - E_t[\widehat{\pi}_{t+1}]) - \frac{(\sigma_c-1)(w_*^h L/c_*)}{\sigma_c(1+(\lambda/\gamma))}(E_t\left[\widehat{L}_{t+1}\right] - \widehat{L}_t). \quad (2)$$

Current consumption ($\widehat{c}_t$) depends on a weighted average of past and expected future consumption, and on expected growth in hours worked ($E_t\left[\widehat{L}_{t+1}\right] - \widehat{L}_t$), the ex-ante real interest rate ($\widehat{R}_t - E_t[\widehat{\pi}_{t+1}]$) and a disturbance term $\hat{\varepsilon}_t^b$. This disturbance term represents a wedge between the interest rate controlled by the central bank and the return on assets held by the households. A positive shock to this wedge increases the required return on assets and reduces current consumption. At the same time, it also increases the cost of capital and reduces the value of capital and investment, as shown below. The disturbance is assumed to follow a first-order autoregressive process with an IID-Normal error term: $\hat{\varepsilon}_t^b = \rho_b \hat{\varepsilon}_{t-1}^b + \epsilon_t^b$.

The dynamics of investment ($\widehat{i}_t$) comes from the investment Euler equation and is given by:

$$\widehat{i}_t = \frac{1}{(1+\overline{\beta}\gamma)}(\widehat{i}_{t-1} + (\overline{\beta}\gamma)\widehat{i}_{t+1} + \frac{1}{\gamma^2 S''}\hat{Q}_t^k) + \hat{\varepsilon}_t^I \quad (3)$$

where S'' is the steady-state elasticity of the capital adjustment cost function and $\overline{\beta} = (\beta/\gamma^{\sigma_c})$, with β the discount factor applied by households. As in Christiano et al. (2005), a higher elasticity of the cost of adjusting capital reduces the sensitivity of investment to the real value of the existing capital stock ($\hat{Q}_t^k$). Modelling capital adjustment costs as a function of the change in investment rather than its level introduces additional dynamics in the investment equation, which is useful in capturing the hump-shaped response of investment to various shocks. Finally, $\hat{\varepsilon}_t^I$ represents a disturbance to the investment-specific technology process and is assumed to follow a first-order autoregressive process with an IID-Normal error term: $\hat{\varepsilon}_t^I = \rho_I \hat{\varepsilon}_{t-1}^I + \epsilon_t^I$.

The corresponding arbitrage equation for the value of capital is given by:

$$\hat{Q}_t^k = -\hat{\varepsilon}_t^b - (\widehat{R}_t - E_t[\widehat{\pi}_{t+1}]) \ + \ \frac{r_*^k}{r_*^k + (1-\delta)} E_t[\hat{r}_{t+1}^k] + \frac{(1-\delta)}{r_*^k + (1-\delta)} E_t[\hat{Q}_{t+1}^k] \tag{4}$$

The current value of the capital stock ($\hat{Q}_t^k$) depends positively on its expected future value and the expected real rental rate on capital ($\hat{r}_{t+1}^k$) and negatively on the ex-ante real interest rate and the financial markup disturbance.

2.2.2 Aggregate supply side

Turning to the supply side, the aggregate production function is given by:

$$\widehat{y}_t \ = \Phi(\ \alpha \hat{k}_t^s \ + \ (1-\alpha)\widehat{L}_t + \hat{\varepsilon}_t^a) \tag{5}$$

Output is produced using capital ($\widehat{k}_t$) and labour services (hours worked, $\widehat{L}_t$). Total factor productivity ($\hat{\varepsilon}_t^a$) is assumed to follow a first-order autoregressive process: $\hat{\varepsilon}_t^a \ = \rho_a \hat{\varepsilon}_{t-1}^a + \epsilon_t^a$. The parameter α captures the share of capital in production and the parameter Φ is one plus the share of fixed costs in production, reflecting the presence of fixed costs in production.

As newly installed capital becomes only effective with a one-quarter lag, current capital services ($\hat{k}_t^s$) used in production are a function of capital installed in the previous period ($\hat{k}_{t-1}$) and the degree of capital utilization ($\widehat{z}_t$):

$$\hat{k}_t^s \ = \ \widehat{z}_t \ + \ \hat{k}_{t-1}. \tag{6}$$

Cost minimization by the households that provide capital services implies that the degree of capital utilization is a positive function of the rental rate of capital:

$$\widehat{z}_t = \frac{1-\psi}{\psi} \widehat{r}_t^k. \tag{7}$$

where ψ is a positive function of the elasticity of the capital utilization adjustment cost function and normalized to be between zero and one. When $\psi = 1$, it is extremely costly to change the utilization of capital and the utilization of capital remains constant. In contrast, when $\psi = 0$, the marginal cost of changing the utilization of capital is constant and as a result in equilibrium the rental rate on capital is constant.

The accumulation of installed capital ($\hat{k}_t$) is not only a function of the flow of investment but also of the relative efficiency of these investment expenditures as captured by the investment-specific technology disturbance:

$$\hat{k}_t = (1 - \frac{i_*}{k_*})\ \hat{k}_{t-1} + \frac{i_*}{k_*}\hat{i}_t + \frac{i_*}{k_*}(1 + \overline{\beta}\gamma)\gamma^2 S''\hat{\varepsilon}_t^I. \tag{8}$$

Due to price stickiness as in Calvo (1983) and indexation to lagged and target inflation of those prices that can not be re-optimized as in Smets and Wouters (2003), prices adjust only sluggishly to their desired mark-up. Profit maximization by price-setting firms gives rise to the following New-Keynesian Phillips curve:

$$\widehat{\pi}_t = \frac{1}{(1 + \overline{\beta}\gamma\iota_p)}(\iota_p\widehat{\pi}_{t-1} + \overline{\beta}\gamma E_t\left[\widehat{\pi}_{t+1}\right] + (1-\iota_p)\widehat{\overline{\pi}}_t - \overline{\beta}\gamma(1-\iota_p)E_t[\widehat{\overline{\pi}}_{t+1}] + \frac{1}{((\phi_p - 1)\varepsilon_p + 1)}\frac{(1 - \xi_p\overline{\beta}\gamma)(1 - \xi_p)}{\xi_p}\widehat{mc}_t) + \hat{\varepsilon}_t^p \tag{9}$$

Inflation ($\widehat{\pi}_t$) depends positively on past and expected future inflation, negatively on the current price mark-up and positively on a price mark-up disturbance ($\hat{\lambda}_{p,t}$). The price mark-up disturbance is assumed to follow an ARMA(1,1) process: $\hat{\varepsilon}_t^p = \rho_p\hat{\varepsilon}_{t-1}^p - \mu_p\epsilon_{t-1}^p + \epsilon_t^p$ where ϵ_t^p is an IID-Normal price mark-up shock. The inclusion of the MA term is designed to capture the high-frequency fluctuations in inflation.

When the degree of indexation to past inflation is zero ($\iota_p = 0$) and the inflation target is constant, equation (10) reverts to a standard purely forward-looking Phillips curve. The assumption that all prices are indexed to either lagged inflation or the target inflation rate ensures that the Phillips curve is vertical in the long run. The speed of adjustment to the desired mark-up depends among others on the degree of price stickiness (ξ_p), the curvature of the Kimball goods market aggregator (ε_p) and the steady-state mark-up, which in equilibrium is itself related to the share of fixed costs in production ($\phi - 1$) through a zero-profit condition. A higher ε_p slows down the speed of adjustment because it increases the strategic complementarity with other price setters. When all prices are flexible ($\xi_p = 0$) and the price-mark-up shock is zero, the inflation equation reduces to the familiar condition that the price mark-up is constant or equivalently that there are no fluctuations in the wedge between the marginal product of labour and the real wage. The marginal cost is given by:

$$\widehat{mc}_t \;=\; (1-\alpha)\,\widehat{w}_t + \alpha\,\widehat{r}_t^k - \hat{\varepsilon}_t^a \tag{10}$$

Cost minimization by firms will also imply that the rental rate of capital is negatively related to the capital-labour ratio and positively to the real wage (both with unitary elasticity):

$$\hat{k}_t^s \;=\; \widehat{w}_t \;-\; \widehat{r}_t^k \;+\; \widehat{L}_t \tag{11}$$

Similarly, due to nominal wage stickiness and partial indexation of wages to inflation, real wages only adjust gradually to the desired wage mark-up:

$$\begin{aligned}\widehat{w}_t \;&=\; \frac{1}{(1+\overline{\beta}\gamma)}(\widehat{w}_{t-1} + \overline{\beta}\gamma E_t\left[\widehat{w}_{t+1}\right] - (1+\overline{\beta}\gamma\iota_w)\widehat{\pi}_t + \iota_w\widehat{\pi}_{t-1} + \overline{\beta}\gamma E_t\left[\widehat{\pi}_{t+1}\right] + (1-\iota_w)\widehat{\overline{\pi}}_t - \overline{\beta}\gamma(1-\iota_w)E_t[\widehat{\overline{\pi}}_{t+1}] \\ &+\frac{(1-\xi_w\overline{\beta}\gamma)(1-\xi_w)}{\xi_w((\phi_w-1)\varepsilon_w+1)}[\frac{1}{1-\lambda/\gamma}\widehat{c}_t - \frac{\lambda/\gamma}{1-\lambda/\gamma}\widehat{c}_{t-1} \;+\sigma_l\widehat{L}_t - \widehat{w}_t\;]) + \hat{\varepsilon}_t^w\end{aligned} \tag{12}$$

The real wage is a function of expected and past real wages, expected, current and past inflation, the inflation target, the wage mark-up and a wage-markup disturbance ($\hat{\varepsilon}_t^w$). If wages are perfectly flexible ($\xi_w = 0$), the real wage is a constant mark-up over the marginal rate of substitution between consumption and leisure. In general, the speed of adjustment to the desired wage mark-up depends on the degree of wage stickiness (ξ_w) and the demand elasticity for labour, which itself is a function of the steady-state labour market mark-up ($\phi_w - 1$) and the curvature of the Kimball labour market aggregator (ε_w). When wage indexation is zero (ι_w), real wages do not depend on lagged inflation and fully respond to changes in target inflation. The wage-markup disturbance ($\hat{\varepsilon}_t^w$) is assumed to follow an ARMA(1,1) process with an IID-Normal error term: $\hat{\varepsilon}_t^w = \rho_w \hat{\varepsilon}_t^w - \mu_w \epsilon_{t-1}^w + \epsilon_t^w$. As in the case of the price mark-up shock, the inclusion of an MA term allows us to pick up some of the high frequency fluctuations in wages.

Finally, the model is closed by adding the following empirical monetary policy reaction function:

$$
\begin{aligned}
\widehat{R}_t \;&=\; \rho_R \widehat{R}_{t-1} \;+ (1-\rho_R)\widehat{\overline{\pi}}_t + \rho_R(\widehat{\overline{\pi}}_t - \widehat{\overline{\pi}}_{t-1}) \\
&\quad + \,(1-\rho_R)(r_\pi(\widehat{\pi}_t - \widehat{\overline{\pi}}_t) \;+\; r_y(\widehat{y}_t - \widehat{y}_t^{flex})) \\
&\quad + r_{\Delta y}(\widehat{y}_t - \widehat{y}_{t-1} - (\widehat{y}_t^{flex} - \widehat{y}_{t-1}^{flex})) \;+ \hat{\varepsilon}_t^r
\end{aligned} \tag{13}
$$

The monetary authorities follow a generalized Taylor rule by gradually adjusting the policy-controlled interest rate ($\widehat{R}_t$) in response to inflation and the output gap, defined as the difference between actual and potential output (Taylor, 1993). Consistently with the DSGE model, potential output is defined as the level of output that would prevail under flexible prices and wages in the absence of the wage and price markup shocks. In addition, there is also a short-run feedback from the change in the output gap (Walsh, 2003). The inflation target is subject to IID-Normal shocks and assumed to have the following general form: $\Delta\widehat{\overline{\pi}}_t = \rho_{\overline{\pi}} \Delta\widehat{\overline{\pi}}_{t-1} + \epsilon_t^{\overline{\pi}}$. When $\rho_{\overline{\pi}}$ is zero the inflation target reduces to a random walk. Positive values of $\rho_{\overline{\pi}}$ imply smoother changes in the target. The parameter ρ_R captures the degree of interest rate smoothing. Finally, we assume that the monetary policy shocks ($\hat{\varepsilon}_t^r$) follows a first-order autoregressive process with an IID-Normal error term: $\hat{\varepsilon}_t^r = \rho_r \hat{\varepsilon}_{t-1}^r + \epsilon_t^r$.

2.2.3 The term structure of interest rates

Theoretically consistent yield dynamics are constructed through the rational expectations hypothesis. That is, today's yields are determined as a weighted average of expected future short term interest rates:

$$\hat{R}_t^N = \frac{1}{N} E_t \left\{ \hat{R}_t + \hat{R}_{t+1} + \hat{R}_{t+2} + ... + \hat{R}_{t+N-1} \right\} \tag{14}$$

where R_t^N denotes the yield on a bond of N quarters and the one period interest rate is $R_t^1 = R_t$. Future short term (one period) interest rates are denoted by $\hat{R}_{t+N}$. The corresponding one period forward interest rates measure their expectation at date t, $E_t \hat{R}_{t+N}$. The expectations in (14) are rational and fully determined by the dynamics of the DSGE model. In practice, there are several ways of computing bond yields in this framework. First, forward rate dynamics can be derived by iterating forward on the rational expectations solution of the system described by equations (1)-(13). Then, using (14), one can easily determine bond yields. More specifically, denoting the vector of state variables in the model by X, and the structural shocks by ε, the RE solution is of the form $X_t = AX_{t-1} + B\varepsilon_t$. Tomorrow's forward rate is today's expectation of tomorrow's short rate, $E_t \hat{R}_{t+1}$. This can be computed as $e(\hat{R}_t)AX_t$, where $e(\hat{R}_t)$ is a vector which selects the row of X_t corresponding to $\hat{R}_t$. Future period forward rates can be derived iterating further, thus enabling the calculation of the entire term structure, via (14).

A second way to obtain bond yields is by combining the log-linear rational expectations solution with a lognormal approximation of the stochastic discount factor. This approach was suggested by Jermann (1999) for asset prices and is used for bonds by, among others, Bekaert et al. (2006) and

Wu (2005). Given a pricing kernel, risk-free bonds -which have a certain nominal value at some point in the future- can be priced recursively from that future point.

The two approaches have identical implications for bond yield dynamics. The difference between the two arises because the first approach assumes risk neutrality. As a result, it ignores second order terms of the pricing kernel, which generate a constant risk premium under the second approach. Our estimations are performed using a third, equivalent, approach. In particular, we extend the state space with forward rates and yields. As a result, the rational expectations solution directly contains the reduced form for the bond yields of interest. This is a feasible setup when interest is confined to bond yield dynamics[2]. We find this approach to be the most convenient to implement and reasonably fast.

Equations (1)-(13) determine thirteen endogenous macroeconomic variables: $\widehat{y}_t$, $\widehat{c}_t$, $\widehat{i}_t$, $\widehat{q}_t$, $\hat{k}_t^s$, $\widehat{k}_t$, $\widehat{z}_t$, $\widehat{r_t^k}$, $\widehat{mc_t}$, $\widehat{\pi}_t$, $\widehat{w}_t$, $\widehat{L}_t$ and $\widehat{R}_t$. The complete model also contains the counterparts of these variables in the flexible price economy: this gives eleven additional variables as inflation and the real marginal cost drop out. In addition, the model includes forward rates $E_t\hat{R}_{t+N}$ for $N = 1, ..., 39$. These are used to compute model consistent bond yields with maturity up to ten years ($\hat{R}_t^N$ for $N = 2, ..., 40$). The stochastic behaviour of the entire system of linear rational expectations equations is driven by eight exogenous processes and their respective disturbances: total factor productivity ($\hat{\varepsilon}_t^a, \epsilon_t^a$), investment-specific technology ($\hat{\varepsilon}_t^I, \epsilon_t^I$), financial mark-up ($\hat{\varepsilon}_t^b, \epsilon_t^b$), exogenous spending ($\hat{\varepsilon}_t^g, \epsilon_t^g$), price mark-up ($\hat{\varepsilon}_t^p, \epsilon_t^p$), wage mark-up ($\hat{\varepsilon}_t^w, \epsilon_t^w$), inflation target ($\widehat{\bar{\pi}}_t, \epsilon_t^{\bar{\pi}}$) and monetary policy ($\hat{\varepsilon}_t^r, \epsilon_t^r$) shocks. Next we turn to the estimation of the model.

[2]Note that it differs from the log-linear lognormal approximation only by the constant term. The log-linear lognormal approximation additionaly takes up constant risk compensation terms. We control for this difference in the measurement equation, below.

3 Estimation

The rational expectations solution to (1)-(13), along with the yields implied by the expectations hypothesis described in (14) form the transition equation governing the DSGE model. We here describe the measurement equation which maps model variables to the data.

3.1 Measurement equation

The model is estimated using six key macroeconomic quarterly US time series, the short term interest rate and four bond yields as observable variables. The macro data consist of the log difference of real GDP, real consumption, real investment and the real wage, log hours worked, the log difference of the GDP deflator and the federal funds rate. The observable bond yields are for zero coupon bonds with maturities of 1, 3, 5 and 10 years (expressed below as $R_t^{4,obs}$, $R_t^{12,obs}$, $R_t^{20,obs}$, and $R_t^{40,obs}$, respectively). A full description of the data used is given in the appendix. The corresponding measurement equation is:

$$O_t = \begin{bmatrix} dlGDP_t \\ dlCONS_t \\ dlINV_t \\ dlWAGE_t \\ lHOURS_t \\ dlP_t \\ FEDFUNDS_t \\ R_t^{4,obs} \\ R_t^{12,obs} \\ R_t^{20,obs} \\ R_t^{40,obs} \end{bmatrix} = \begin{bmatrix} \overline{\gamma} \\ \overline{\gamma} \\ \overline{\gamma} \\ \overline{\gamma} \\ \overline{L} \\ \overline{\pi} \\ \overline{r} \\ c^4 \\ c^{12} \\ c^{20} \\ c^{40} \end{bmatrix} + \begin{bmatrix} \widehat{y}_t - \widehat{y}_{t-1} \\ \widehat{c}_t - \widehat{c}_{t-1} \\ \widehat{i}_t - \widehat{i}_{t-1} \\ \widehat{w}_t - \widehat{w}_{t-1} \\ \widehat{L}_t \\ \widehat{\pi}_t \\ \widehat{R}_t \\ \hat{R}_t^4 \\ \hat{R}_t^{12} \\ \hat{R}_t^{20} \\ \hat{R}_t^{40} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \eta_t^4 \\ \eta_t^{12} \\ \eta_t^{20} \\ \eta_t^{40} \end{bmatrix} \tag{15}$$

where l and dl stand for log and log difference respectively, $\overline{\gamma} = 100(\gamma - 1)$ is the common quarterly trend growth rate to real GDP, consumption, investment and wages, $\overline{\pi} = 100(\Pi_* - 1)$ is the quarterly steady-state inflation rate and $\overline{r} = 100(\gamma^{\sigma_c}\Pi_*/\beta - 1)$ is the steady-state nominal interest rate. Given the estimates of the trend growth rate and the steady-state inflation rate, the latter will be determined by the estimated discount rate. Finally, $\overline{L}$ is steady-state hours-worked. The model is estimated over a sample period from 1966:1 until 2007:1.

Our specification allows for deviations of the model implied yields from the actual yields in two ways. On the one hand, the measurement equations for the yields are augmented with measurement errors, η_t^N. These measurement errors serve two purposes. First, a common way of assessing fit in empirical term structure models is to evaluate the standard deviation of yield measurement errors. Below, we follow this tradition. Second, many authors interpret the difference between the expectations-hypothesis-implied yield and the observed yield as a measure of fluctuations in the term premium. The measurement errors capture that very difference.

On the other hand, we include free constants c^N to capture the mean of the yields. In other words, we study (the weak form of) the expectations hypothesis, disregarding theoretical constant risk premia. It is well known that standard DSGE models cannot account for the average shape of the yield curve[3]. As a result, most extant macro-finance research focuses on dynamics of demeaned yields, or spreads. The inclusion of the free constants in the measurement equation is tantamount to such an approach. An alternative approach assumes an affine term structure representation of the yields, combining the solution of the log-linearized DSGE model with a lognormal approximation to the pricing kernel[4].

Estimation is performed using Bayesian methods. First, we estimate the mode of the posterior distribution by maximizing the log posterior function, which combines the prior information on the parameters with the likelihood of the data. In a second step, the Metropolis-Hastings algorithm is used to get a complete picture of the posterior distribution and to evaluate the marginal likelihood of the model.

3.2 Data

Our sample period starts in 1966 and ends in 2007. The end of the period is chosen to maximize the number of observations, while the starting date is chosen from the perspective of the macro data (Smets and Wouters 2007). Moreover, long term bonds were not frequently traded prior to 1964, resulting in possibly unreliable yield data. Our choice for the inclusion of 1, 3, 5 and 10 year yields aims to incorporate fluctuations over the entire yield curve. Data sources are detailed in Appendix.

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[3] See, e.g., Den Haan (1995).

[4] We have also estimated our model imposing the theoretically implied constant risk premia. The estimated term structure is ultimately downward sloping, while deep parameters of the model are virtually unaffected.

3.3 Prior distribution

The first columns of Tables (1) and (2) contain information on the prior distributions of the model parameters. The standard errors of the structural innovations are assumed to follow Inverse-Gamma distributions with a mean of 0.10 (0.01 for the inflation target shock) and two degrees of freedom, which corresponds to a rather loose prior. The persistence of the AR(1) processes is Beta distributed with mean 0.5 and standard deviation 0.2. A similar distribution is assumed for the MA parameter in the process for the price and wage mark-up. The measurement errors in the yield equations are given very flexible priors. First, their standard deviations have a positive Uniform prior. Second, we allow for correlation between the various measurement errors. These correlations are assumed to have Uniform distributions over [-1,1].

The quarterly trend growth rate is assumed to be Normal distributed with mean 0.4 (quarterly growth rate) and standard deviation 0.1. The steady-state inflation rate and the discount rate are assumed to follow a Gamma distribution with a mean of 2.5% and 1% on an annual basis. The constants in the yield measurement equations all receive a Uniform prior distribution.

Five parameters are fixed in the estimation procedure. The depreciation rate is fixed at 0.025 (on a quarterly basis) and the exogenous spending-GDP ratio is set at 18%. Both of these parameters would be difficult to estimate unless the investment and exogenous spending ratios would be directly used in the measurement equation. Three other parameters are clearly not identified: the steady-state mark-up in the labour market (λ_w), which is set at 1.5, and the curvature parameters of the Kimball aggregators in the goods and labour market (ε_p and ε_w), which are both set at 10.

The parameters describing the monetary policy rule are based on a standard Taylor rule: the prior for the long run reaction on inflation is described by a Normal distribution with mean 1.5 and a standard error of 0.25. The priors on the output gap and its growth rate have a beta prior with a mean of 0.125 and a standard error of 0.1. The persistence of the policy rule is determined by the coefficient on the lagged interest rate which is assumed to be Normal around a mean of 0.75 with a standard error of 0.1.

The parameters of the utility function are assumed to be distributed as follows. The mean of the intertemporal elasticity of substitution is set at 1.5 with a standard error of 0.375; the habit parameter is assumed to fluctuate around 0.7 with a standard error of 0.1 and the elasticity of labour supply is assumed to be around 2 with a standard error of 0.75. These are all quite standard calibrations. The prior on the adjustment cost parameter for investment is set around 4 with a standard error of 1 and the capacity utilization elasticity is set at 0.5 with a standard error of 0.15. The share of fixed costs in the production function is assumed to have a prior mean of 0.25. Finally, there are the parameters describing the price and wage setting. The Calvo probabilities are assumed to be around 0.5 for both prices and wages, suggesting an average length of price and wage contracts of half a year. This is compatible with the findings of Bils and Klenow (2004) for prices. The prior mean of the degree of indexation to past inflation is also set at 0.5 in both goods and labour markets.

3.4 Posterior distribution

Posterior estimates are given in Tables (1) and (2). The estimated trend growth rate is 0.43. Steady-state inflation is 2 percent in annual terms. The parameters of the utility function are somewhat lower than their prior means: risk aversion is estimated at 1.15, while the habit persistence parameter is 0.42. Investment adjustment costs are fairly high, as are the costs of changing capital utilization. The monetary policy rule is characterized by a strong response to inflation (1.75) and to growth of the output gap (0.54). The funds rate is fairly persistent, with a smoothing parameter of around 0.8. The degree of persistence in the Phillips curve and the corresponding wage equation is moderate, with indexation parameters of around 0.30. The Calvo parameters on wages and prices suggest contract lengths of around two quarters.

Let us now turn to the parameter estimates pertaining to the yield measurement equations. The optimization reduces the five year measurement error to zero[5]. To understand how this works, consider the following. With measurement errors for all variables the model has more shocks than variables, so the stochastic dimension of the model can (but need not) be reduced. The likelihood of the model improves by dropping the five year yield measurement error, while assigning fluctuations in the five year yield to the structural shocks. The reason this is preferable in likelihood terms is because, contrary to the measurement errors, the structural shocks have the potential to jointly determine several yields. The inflation target is the first candidate because of 1) its persistence, which it shares with yields, and 2) its obvious theoretical link to bond yields via inflation expectations. Gürkaynak et al. (2005), for instance, show how time variation in the inflation target is compatible with movements in long term interest rates.

The fact that it is the five year yield whose measurement error is expendable is natural because it is the most intermediate in terms of maturity of all the yields (the average maturity being 4.75). With the five year yield perfectly matched by the model, the signs of the correlations between the measurement errors are easily understood. That is, when shorter term yields (1 and 3 year bonds) are overestimated, the long yield (10 year) will tend to be underestimated, and vice versa. With respect to the magnitude of the correlations, the absolute value of the correlation of the 10 year and the 3 year bond measurement error is higher than that between 1 and 10 year bonds, because the former two bonds are closer in terms of maturity. In other words, the negative correlation between the measurement errors points out that the model implied yield curve is somehow too linear. The model is not able to reproduce all the curvature in the yield curve dynamics.

[5] The standard deviation of the 5 year yield measurement error, as well as its correlations with other measurement errors are therefore not contained in Table (2).

4 Model fit

4.1 In-sample

One common metric to evaluate the empirical ability of term structure models is the size of the standard deviation of the measurement errors for the yields. Table (2) shows that the estimated standard deviations of the yield measurement errors range -in annual terms- from 17 basis points for the three year yield, to 28 basis points for the ten year yield and a maximum of 32 basis points for the one year yield. As a point of comparison, the unconditional standard deviation of these yields over our sample period is 260, 240 and 280 basis points, respectively. Figure (1) shows the fit for all interest rates.

The good fit of yields implies that a constant coefficient, constant variance version of the expectations hypothesis leaves at most 12% of historical yield fluctuations unexplained. The degree to which the yield dynamics are matched is competitive with, if not better than, that of other macro-finance model of the term structure.

To illustrate the fit relative to other macro-finance models, we consider related (in-sample) measures found in the literature. The following papers have sample periods more or less comparable to ours, ranging from the sixties to beyond 2000. Cogley (2005, p. 440) reports median absolute pricing errors[6] of 50 to 60 basis points for 1 to 4 year notes. Dewachter and Lyrio (2006) attain a minimum standard deviation of 54 basis points over their wide range of models. Bekaert et al. (2006) obtain measurement errors with a minimum standard deviation of 45 basis points. The maximum standard deviation of 32 basis points shows our model does not suffer by comparison.

On shorter sample periods, starting around the mid-eighties, Doh (2007b) estimates measurement errors ranging from 15 to 25 basis points. Rudebusch and Wu (2007b) present estimates of 13

[6] Note that, with Gaussian errors, mean or median absolute pricing errors are substantially smaller than standard deviations.

to 35 basis points. In the next section we present estimates for a similar sub-sample, with estimated measurement errors in the same ballpark[7].

Finance models of the term structure generally perform best in fitting yield curve fluctuations. This is in part due to the flexibility of the empirical approaches, and in part a consequence of not trying to fit macroeconomic fluctuations[8]. Cheridito et al. (2007) report, for their most successful specifications, standard deviations of observation errors in the range 10-30 basis points. Their sample contains monthly yield data from 1972-2002. Using weekly swap yields for the period 1987-1996, Dai and Singleton (2000) report standard deviations of 8 to 16 basis points.

Importantly, however, estimated term structure models exhibit a wide variation in modelling approach. They range from affine term structure models with unobservable factors (Dai and Singleton 2000, Duffee 2002), over time-varying Bayesian VAR's (Cogley 2005) to macro-finance models of the term structure with exogenous (Rudebusch and Wu 2007b) and endogenous (Bekaert et al. 2006) pricing kernels, possibly with time-varying volatility (e.g. Doh 2007b) or time-varying parameters (Dewachter and Lyrio 2006). Our model differs from all the above models because its perspective on the macroeconomy is more elaborate.

In many ways, our model is the most restrictive of all the above. With respect to model flexibility in matching yield dynamics, our model is most closely related to that of Bekaert et al. (2006). We also use the endogenous pricing kernel, under constant prices of risk and with homoscedastic shocks. However, our model is more restrictive in terms of stochastic structure. Whereas Bekaert et al. (2006) use five macro shocks to accommodate three macro variables and

[7] It is perhaps relevant to note that both aforementioned studies do not incorporate yields with a maturity longer than five years. Dropping the ten year yield as an observable in our model would further reduce measurement errors for bonds with maturities up to 5 year.

[8] Contrary to many macro-finance models, however, the finance approach does tend to jointly estimate the average term spreads.

two yield spreads, our model has only one more structural shock than macro variables. While we do introduce additional stochastics (more structural shocks), these are constrained by the inclusion of additional macroeconomic observable variables. The model in Bekaert et al. (2006) has more degrees of freedom in that respect. Essentially, by reducing the number of shocks relative to the number of observables, we require yield curve dynamics to be driven by macroeconomic shocks.

The other models referred to assume more flexible functional forms for matching yield dynamics. Models with only yields have essentially no link to the macroeconomy and therefore encounter less constraints in matching yield dynamics. These models often assume additional flexibility by allowing for time variation in parameters, prices of risk and/or variances (Duffee, 2002; Cogley 2005). Importantly, this class of models does not admit a macroeconomic interpretation of the term structure.

Joint macro-term structure models also incorporate various types of flexibility. Ang and Piazzesi (2003) allow for unobservable factors. Rudebusch and Wu (2007b) incorporate a flexible pricing kernel. Doh (2007b) incorporates non-linearities and time-varying shock variances. Dewachter and Lyrio (2006) encompass, by introducing learning, time-varying parameters. In addition, some of their models allow for flexible prices of risk specifications. All these models introduce new perspectives on interactions between the macroeconomy and the term structure. In these models, the additional flexibility invariably improves the in-sample fit of bond yields. The message we hope to convey here is that, even in the most restrictive of models, the empirical fit is substantial.

One implication of our finding is that a more extensive model for the macroeconomy can alleviate the need for additional forms of model flexibility. This raises questions about the empirical relevance of these additional forms of flexibility. In particular, the macro-finance literature has shown that the introduction of learning, time-varying shock volatility or time variation in parameters substantially improves the fit of yields. Does this imply these are empirically relevant phenomenae? Or does the improved fit follow from some kind of mis-specification of the macroeconomy? Our model suggests that, without any role for additional flexibility, the same empirical success can be obtained. A full model comparison exercise, e.g. a horse race among models with various forms of flexibility, is beyond the scope of the present paper. In view of comparability, we also verify how successful the model is in terms of forecasting. Forecasting performance can, to some extent, indicate the relative success of the present model. We first document the in-sample fit for two sub-samples.

4.1.1 Sub-sample results

Tables (3) and (4) present the estimated parameters for two sub-samples, viz. 1966-1979 and 1984-2007. Similar periods are frequently considered in both macro and term structure estimations. From a macro perspective, the two periods capture the "great inflation" and the "great moderation", respectively (e.g. Smets and Wouters 2007). From the term structure perspective, both periods have been distinguished among in view of more homogenous monetary policy strategies (e.g. Rudebusch and Wu 2007a). The intermediate period being characterized by a somewhat higher volatility of the yields is another reason.

Overall, our findings are in line with those of Smets and Wouters (2007). In particular, we find that the volatility of most structural shocks decreased substantially in the second sub-sample. The steady state inflation rate is virtually the same in both episodes. There are a few notable features related to the estimated policy rule. In particular, the coefficient measuring the interest rate reaction to inflation is somewhat higher in the post-80 era. The response to output and to a lesser extent to its growth rate is smaller in the second sub-sample.

There is also some evidence for more significant real and nominal rigidities in the later period, again confirming the results of Smets and Wouters (2007). An example of the former is the increase in investment adjustment costs. More significant nominal rigidities are mostly visible in the goods market: the second sample is characterized by a higher degree of price stickiness, while price indexation falls substantially.

Finally, the measurement error for the one year yield is large in the first sample, but reduces significantly after the eighties. In the second period the largest standard deviation of measurement errors is that of the ten year yield and amounts to 25 basis points.

4.2 Out-of-sample

We now compare the forecasting performance of the model to a VAR(1). The out-of-sample evaluation period starts in 1990:Q1. The VAR is estimated on all observable variables, and re-estimated each subsequent quarter. The DSGE model is re-estimated every four quarters. Table (5) shows root mean squared errors (RMSE) for the macroeconomic data, Table (6) for the interest rates. For the yields, we compare the model predictions to an additional benchmark, viz. the random walk. For the latter, we also compute the prediction errors over the entire sample period and compare them to the filtered prediction errors of the model. All statistics are computed for horizons up to three years. We consider long forecast evaluation periods in an attempt to avoid inference on forecasting properties driven by the evaluation period chosen.

With respect to the macro variables, the forecast evidence is mixed. The model forecasts for hours, wages and consumption are mostly outperformed by the VAR. The DSGE model is more successful in predicting inflation, total output and investment. Similar to Smets and Wouters (2007), DSGE forecasts tend to improve relative to those of VAR's, especially at longer horizons.

Now consider the RMSE for the yields. The left hand panel of Table (6) contains the absolute RMSE per model, the right hand panel shows the relative performance of the DSGE model with respect to the benchmarks. In absolute terms, the RMSE's are substantial. For the one quarter horizon, they range from 0.46 for the five year yield to 0.65 for the one year yield since 1990. Over the entire sample, this RMSE increases from 0.61 for the longest yields to 1.32 for the funds rate. The latter is so high mostly due to the increased short rate volatility around 1980. Doh (2007a) and Dewachter and Lyrio (2006) provide comparable statistics for the one quarter horizon over a similar sample period. The latter report (their Table 9) minimum standard deviations of 1.18, 0.96, 0.82, 0.75 and 0.70 for interest rates with maturities of 1, 4, 12, 20 and 40 quarters respectively. The prediction errors in Table (6) are lower for all bond yields, yet higher for the short rate. All in all, taking into account differences in sample periods and variables, the present DSGE model's forecasting ability seems competitive. Doh (2007a) produces one period ahead forecasts with mean absolute prediction errors of 40 to 54 basis points. The analogue statistic for the present DSGE model's prediction of yields varies from 12 basis points for the 10 year yield to a maximum of 25 basis points for the funds rate. Again, our DSGE model performs well.

Turning to finance models, in absolute terms, the model generates RMSE's in the same order of magnitude as those in Duffee (2002). Different from the latter, however, our predictions do not generally outperform those of a random walk. Exact comparisons are, unfortunately, substantially burdened by differences in sample period.

When compared to the VAR and random walk benchmarks for both evaluation periods, an interesting pattern emerges (Table (6) right hand panel). Irrespective of the forecast horizons considered, the DSGE model never outperforms benchmark forecasts for the ten year yield. In addition, for the shortest forecast horizons, the model does not improve forecasts for yields of any maturity. However, starting from short maturity yields and increasing forecast horizons, the DSGE model does generate superior forecasts. For longer maturity yields a similar improvement is observed, though it starts at longer horizons. Visually, the elements below the diagonal tend to favor the DSGE's forecasts. The longer horizon forecasts of the shorter maturity interest rates improve the most. With longer forecast horizons, longer maturity yields also tend to improve.

In a very flexible empirical model, with non-structural risk price specifications and many latent factors, Dewachter et al. (2006) present a similar result (see their Figure 10, p. 459). They also find it difficult to beat a random walk for short horizons. However, for longer horizons the random walk can be outperformed. Our restrictive specification produces a comparable improvement in the forecast performance for yields. Moreover, our model also produces sensible macroeconomic forecasts[9].

We also provide an interpretation for the improved forecasts of the shorter maturity yields at longer horizons. In particular, the driving force of the improved short rates is the inclusion of long maturity yields as observable states. The expectations hypothesis embedded in the model consistently decomposes these yields into forward rates. Thus, the information contained in long yields naturally improves expectations of future short term interest rates. One reason why the model is rather unable to improve the ten year yield forecasts is because it receives no information about forward rates at horizons that extend that far out[10].

5 A structural decomposition of the yield curve

This section decomposes yield curve fluctuations in terms of structural shocks driving the economy. Table (7) contains the variance decompositions of the yields implied by the model. The impulse responses of bond yields of different maturities are shown in Figure (2). Figures (3) through (5) contain historical decompositions for, respectively, the Fed funds rate, the bond yields and the term

[9] The poor macro-economic forecasts in Dewachter et al. (2006) are presumably the result of a) the high weight of the yields in the likelihood (6 yields vs. 2 macro observables), and b) the lack of macro-economic structure in the model. Our DSGE model avoids both by a) having a balanced set of macro-aggregates and yields, and b) estimating a fully specified DSGE model.

[10] We foresee incorporating long horizon inflation forecasts (from surveys and/or TIPS). We conjecture this will improve the longer maturity forecasts, possibly even at shorter horizons.

spread.

The variance decompositions show that, in the long run, the inflation target shock is the determining factor for all the interest rates. The inflation target shock strongly affects long yields by shifting long horizon inflation expectations. Changes in inflation expectations induce changes in forward rates and long term bond yields. The crucial role of fluctuations in the inflation target can also be inferred from the historical decompositions. For all yields, the low frequency component of its dynamics is mostly determined by the contribution of the inflation target shock. Not surprisingly, the longer the maturity of the yield, the more aligned the yield and the contribution of the inflation target. The long maturity bond yields are almost solely determined by long horizon inflation expectations, which is exactly what the inflation target represents.

Relative to finance models of the term structure, the inflation target assumes the role otherwise played by the level factor. It does so in a couple of ways. The level factor corresponds to the first principal component of yields. It distinguishes itself from other components in that it is the most persistent and affects yields of different maturities in a similar way. First, consider Figure (2), which contains immediate impulse responses of all yields to the variety of shocks. On impact, an inflation target shock raises the level of all yields by comparable amounts. This pattern of yield responses is essentially what instigated the literature to refer to one of the term structure factors as the "level" factor[11]. A second -related- reason why the inflation target relates to the level factor is because it is also the dominant factor in explaining yield fluctuations. The yield variance and historical decompositions show that the inflation target shock is by far the most important among the structural shocks. This close connection between long horizon expected inflation and the level factor is not new and has been noted by, among others, Kozicki and Tinsley (2001).

[11] In the finance approach with the yield curve decomposed into factors, factor loadings are measures for immediate impulse responses.

Both the variance and the historical decompositions show that for longer term bond yields the role of shocks other than the inflation target is limited. For shorter forecast horizons and shorter maturity yields, the other shocks play a more significant role. Short term fluctuations in the Fed funds rate, for instance, are mostly driven by the financial markup shock. A negative shock lowers the effective interest rate that applies to saving and investment decisions. Households respond by increasing both consumption and investment. The monetary authority will try to offset the inflationary effect of such a demand-type shock by increasing the interest rate.

The second shock, determining about 20% of the funds rate's forecast error variance, is the monetary policy shock. The historical decomposition shows that the importance of temporary monetary policy shocks for the short rate derives mostly from the late seventies and early eighties episode.

Following impulses to many of the structural shocks, the short term interest rate response dies out after a couple of quarters. As a result, their effects are not persistent enough to be able to influence forward rates at dates further in the future. Therefore, the variance and historical decompositions suggest only a fairly small role of these shocks for long maturity yields. It is also this type of interest rate response that enables the model to capture dynamics consistent with the so-called slope factor.

Finally, over time, the short term interest rate response to wage markup and investment-specific technology shocks is hump-shaped. Hence, the immediate impulse responses of the various yields to these shocks also exhibit a hump over maturities: the yields with maturities of one and three years respond more than both the ten year yield and the short rate. As such, these shocks are able to generate yield curve dynamics that are typically picked up by a curvature factor in latent factor models of the term structure.

6 Inflation expectations

Figure (7) compares actual inflation to expectations of inflation from the model. The chart also includes survey expectations, which are not included in the model's information set. All the expectations have a one year horizon. Over the entire sample period, two episodes stand out: the mid-seventies hike in inflation and the disinflation period in the early eighties. Both periods are characterized by persistent deviations between actual and survey expectations of inflation[12].

The Survey of Professional Forecasters (SPF) and Livingston survey did not anticipate the 1973-1975 rise in inflation. Instead, the survey expectations only rose gradually and with a lag compared to actual inflation. The model-consistent one year horizon inflation expectation reproduces this pattern observed in the surveys. A historical decomposition of inflation can shed light on why this happens. Figure (6) presents the contribution of a selected number of shocks[13] to inflation. The model essentially attributes the 1973 inflation hike to two shocks: wage and price markup shocks. This is consistent with the oil price surges of the time. Importantly, the hike in inflation was not perceived to be attributable to the Fed having a lower commitment toward fighting inflation. Our estimate of expected inflation reflects this, rising only mildly as the survey expectations did. If inflation expectations would have increased more dramatically, this should have been reflected in long term bond yields, which did not happen. If anything, movements in yields and target inflation lagged the inflation spike.

Now consider the early 1980's episode. The substantial raises in the Federal Funds rate in the first and last quarter of 1980 succeeded in curbing inflation. This is evident from the historical decomposition of inflation in Figure (6), which attributes the fall in inflation predominantly to

[12] The Michigan survey is somewhat different in that does not cover the early seventies and, in contrast to the other two surveys, followed inflation more closely during the early eighties disinflation.

[13] To maintain visibility we suppress a couple of shocks with less significant contributions.

short term monetary policy shocks. However, while inflation fell dramatically the target inflation rate continued to rise. Similarly, the rise in the SPF and Livingston survey expectations persisted a couple of quarters past the peak in inflation. Apparently, the disinflation did not buy the Fed much credibility. This is also reflected in long term bond yields which remained high until the end of 1981. According to the model, mid-1982 the Fed's perceived inflation target had reached its maximum at 10%. Figure (8) reveals that it wasn't until the end of 1982 the public revised its long run inflation expectation downwards. At the time, with inflation below 6% the Fed finally seemed to have gained some credibility. As Goodfriend (1993) points out, however, the public's belief in the Fed's commitment was short-lived. Long term yields again rose significantly in 1983:2 induced by an inflation scare, as is evident from the spike in the model implied 10 year ahead inflation expectation. The gradual fall in the estimated inflation target witnessed throughout 1982 came to a halt. Again, the Fed lost credibility, with the perceived inflation target rising once more up to mid-1984. What follows is a substantial decline in the funds rate from above 11% to below 7%, accompanied by inflation dropping below 4%. Long term bond yields and the perceived inflation target followed. In the remainder of the eighties and in the early nineties the target inflation is estimated to be approximately 5%, and was further reduced in the nineties to about 4%. From 2000 onwards the estimated inflation target fluctuates around 2%.

Both episodes that witnessed a divergence between actual and survey inflation shed light on the identification of target inflation. Incorporating yields into the set of observables implies a broader perspective on inflation expectations than embodied in macroeconomic aggregates, with quite different implications for estimates of target inflation. Ireland (2007), for instance, estimates target inflation from purely macroeconomic data. Since the information contained in the term structure is then absent, target and expected inflation follow inflation much more closely. As a result, both the seventies' inflation and the eighties' disinflation are attributed to changes in the inflation target. Doh (2007a) presents similar findings to the above results: when the set of observables used in estimation excludes yields, the inflation target resembles Ireland's estimate, when yields are incorporated target inflation is much more similar to ours. Ireland (2007) suggests his estimate is subject to a substantial amount of uncertainty. When we estimate the DSGE model of Section 2 solely with macroeconomic observables, the variability of the inflation target is drawn to zero. In other words, in at least one example of a more elaborate DSGE model estimated on macro-data, a time-varying inflation target is not even identified. Hence, in the present model, inflation target identification derives from the inclusion of term structure data.

7 The term premium, the expectations hypothesis and the conundrum

The measurement errors of the yields capture the discrepancy between fluctuations in actual and expectations hypothesis implied yields. Our measurement equation for the yields reads:

$$\hat{R}_t^{N,obs} = c^N + \hat{R}_t^N + \eta^N$$

In words, actual yields consist of three parts. The constant term, c^N, captures constant premia[14]. $\hat{R}_t^N$ denotes the yield implied by the expectations hypothesis, defined in equation (14). The third component, η^N, corresponds to the measurement errors. This term captures possible time variation in the term premium.

Table (6) indicates that the estimated standard deviations of the measurement errors are small[15].

[14] This term captures constant premia implied by the expectations hypothesis as well as term premia. As mentioned before (Section 3.1), our estimation does not aim to distinguish the relative contribution of the two.

[15] The standard deviations of yields over the sample period amount to 280 (1 year), 260 (3 year) and 240 (10 year) basis points.

This suggests a fairly small role for the time-varying term premium to explain yield fluctuations. Instead, the expectations hypothesis component captures almost 90% of historical yield fluctuations.

It is useful to try to understand how this result compares to other models. Importantly, recall that our model embeds a constant coefficient, constant variance version of the expectations hypothesis. Recent term structure models in macro have introduced various forms of additional flexibility in an attempt to reconcile yield dynamics with the expectations hypothesis. The apparent success of the expectations hypothesis in the present model comes from the fact that expectations are modelled more extensively relative to the three equation New-Keynesian DSGE model. First, expectations are formed using a larger information set, including consumption, investment, hours and wages in addition to the more traditional dataset consisting of output (or some other activity measure) and inflation. Second, the way these variables enter the model is through the restrictions of the DSGE model. Smets and Wouters (2003, 2007) show how these restrictions are useful in modelling the dynamics of macro variables. Apparently, fluctuations in long term bonds are also better captured by modelling the macro-side of the economy more extensively.

One may interpret the present model, too, as having additional degrees of flexibility to capture yield dynamics. In principle, since the model contains more shocks relative to extant models, yield fluctuations could be absorbed by more "factors" relative to standard finance and macro-finance models. However, more shocks do not necessarily buy additional degrees of freedom. The fact that there are only eight structural shocks for eleven observable variables implies that the identification of shocks is constrained to be consistent with all the observables.

In sum, the expectations hypothesis goes a long way in explaining yield fluctuations, leaving perhaps a more limited role for fluctuations in the term premium. With that in mind, it is natural to ask how the model interprets the recent yield fluctuations, dubbed the conundrum.

7.1 The conundrum

The observation that the substantial increases in the fed funds rate since 2004 were not followed by substantial raises in long term bond yields, has puzzled many observers. During this period of tight monetary policy, the spread between the five year bond yield and the funds rate narrowed from more than 2.5% in 2004 to below -0.5% in 2006. Many have attributed the sustained low bond yields to a fall in the term premium, which counterbalanced upward pressures due to the rise in the fed funds rate.

We use our model to shed light on this issue. Figures (5) and (9) presents a historical decomposition for the spread for the entire sample as well as the last years of the sample. The chart shows that the most important factor contributing to the fall of the spread since 2004 is the financial markup shock. As explained before, this shock is a demand shock to which the Fed responds by "leaning against the wind". A historical decomposition of the fed funds rate confirms that the rise is not due to exogenous monetary policy shocks, but primarily driven by the financial markup shock. A second factor contributing to the rise is the inflation target shock, which is also the reason why longer yields (slowly) move up. However, since the inflation target acts much like a level factor, its role in explaining the reduction in the spread is limited. From the impulse responses and variance decompositions in Figure (2) and Table (7) we also know the financial markup shock has no substantial effects on longer term bond yields. Hence, by tilting the funds rate while leaving long rates fairly stable, the increased financial markup is at the root of the fall in the spread from 2004 onwards.

Our findings from the historical decompositions thus suggest a different interpretation of the conundrum, which is mostly attributed to a fall in the term premium. Instead, the present model suggests the rise in the funds rate is an endogenous reaction to demand shocks. It is precisely because of this endogenous response of the Fed that long term bond yields did not rise in the recent episode. In other words, had the Fed not increased the funds rate as much as it did, inflation expectations would have risen by more than was actually observed.

One reason for the recent years to be labeled puzzling is because it differs from earlier episodes where increases in the funds rate implied substantial long rate hikes, such as 1994-1995 (e.g. Rudebusch et al. 2006). At that time, the spread experienced relatively minor fluctuations, at least not as dramatic as the recent fall. As our interpretation of the conundrum is somewhat different, we also study how the model interprets that period. Figure (10) shows that, contrary to the recent episode, inflation expectations took off, as implied by the contribution of the inflation target shock. Acting as a level factor, this shock is responsible for the rise in both the fed funds rate and the bond yield. The small reduction in the spread that was observed during this episode is attributed predominantly to exogenous monetary policy shocks. The contribution of the other shocks is small for both the short and long end of the yield curve, with no clear patterns emerging. The model's interpretation of the joint rise in long and short interest rates is consistent with the "stories" of Goodfriend (2002) and Hetzel (2006). They interpret the Fed's tightening as a "preemptive strike". The rise in the short rate was motivated as a response to expectations of higher future inflation.

In sum, the model offers a simple interpretation of the late fluctuations in interest rates. What has been labeled the conundrum really is the manifestation of the Fed's aggressive reaction to the strong output performance, i.c. its response to positive demand shocks. As such, the model makes explicit the view of Cochrane (2007). The latter suggests that fairly stable long term rates is what we should have expected following the 2004 monetary tightening. The intuition, confirmed in the present model[16], follows from the non-response of long term inflation expectations to monetary

[16] Cochrane (2007) gives the example of an exogenous monetary tightening, which should not lead to an increase in long term rates. While our model identifies a different shock at the root of the fed funds rate movement, the intuition remains the same. The endogenous response of monetary policy to an exogenous positive demand shock works in a similar way: the hike in the short rate has limited effects on long term inflation expectations.

policy actions. The somewhat different response in earlier episodes, such as the early nineties, follows from doubts about the Fed's commitment toward fighting inflation in that period. Inflation scares then contributed to the joint rise in short and long term interest rates. This is exemplified by the significant fluctuations in the estimated inflation target.

8 Why does the yield curve forecast growth?

Numerous studies have documented the forecasting power of the yield spread for GDP growth[17]. We here show how the model interprets this relation. Table (8) contains some insightful numbers in that respect. The first column contains the correlation between GDP growth and the five year term spread, for different horizons. The second column also shows correlations between the spread and future growth, yet now as implied by the estimated DSGE model. Several authors (e.g. Feroli 2004, Ang et al. 2006) have argued that the short rate, too, contains significant predictive content. In view of their finding, the second panel of Table (8) reports analogue correlations between the fed funds rate and future growth.

Our analysis focuses on correlations as a rough measure to capture the relation between interest rates, spreads and future growth. This follows from the fact that there exist several possible ways to measure the informative content of interest rates. Ang et al. (2006) provide a wide array of methods and analyze biases in them. Depending on the estimation method, conditioning variables and sample periods, substantial differences in (absolute and relative) magnitudes and significance arise. The present exercise is therefore more qualitative in nature. We aim to understand which shocks are relatively important in determining the fact that the short rate and interest rate spreads forecast growth. Smets and Tsatsaronis (1997) conduct a similar exercise in a SVAR framework.

The first two columns of Table (8) compare correlations implied by the model and the data.

[17] Estrella (2005) provides an overview of the enormous literature.

While the signs of the correlations clearly match and the magnitudes are quantitatively in the ballpark of those in the data, some differences in relative magnitudes are present. For instance, while the data correlations exhibit a hump-shaped pattern over horizons similar to that typically found in OLS regressions, the model-implied correlations do not. For reasons provided in Ang et al. (2006), we are not too worried about this mismatch. In particular, the hump shaped pattern is also absent in Ang et al. (2006) once they take into account no-arbitrage relations between interest rates of various maturities (as does the present model). Instead, their estimates tend to decrease with longer horizons, similar to what our model-implied correlations convey.

More importantly, let us turn to the structural factors that drive these correlations. First, the contribution of the financial markup is the most significant determinant of both the spread and the short rate's predictive power. Its contribution decreases with longer horizons, from 0.26 (out of 0.70 in total) at the one quarter horizon to 0.17 (out of 0.46) at the two year horizon, but remains relatively important throughout. A shock to the financial markup works much like a standard demand shock. Following a negative shock, households' opportunity returns are smaller which, following increased demand, will induce inflationary pressure. The central bank increases the short rate, inducing a flattening of the yield curve. On the real side, consumption and investment increase on impact, which feed through to GDP. After the date of the shock, GDP gradually returns to its pre-shock level. While the instantaneous output response is positive, its gradual return to baseline implies its growth rate is negative in future periods. The combination of negative expected growth and the fall in the spread (increase in the short rate) is what the positive (negative) correlations reflect.

Second, the wage markup shock also plays a significant role in explaining the predictive content of interest rates. While its quantitative contribution is smaller than that of the financial markup, it persists somewhat longer. The explanation for the forecasting power of wage markup shocks is akin to that underlying the (smaller) informative content of price markup shocks. Monetary policy counters the inflationary pressures by increasing the short rate (lowering the spread) and thereby lowers future growth.

Third, the investment shocks also induce substantial comovement between the yield curve and future GDP growth. The conditional correlations contribute at least 10% to the unconditional correlations for both the short rate and the term spread at different horizons. This demand-type shock increases both inflation and GDP in a persistent, hump shaped manner. Monetary policy responds by gradually increasing the funds rate. The slow, gradual return of GDP to its baseline level implies lower growth rates at longer horizons. This results in higher contributions for longer horizons[18].

The contribution of monetary policy shocks to the forecasting power of the yield curve is fairly small. This is not completely surprising, as exogenous policy shocks have played only a minor role in US history (e.g. Smets and Wouters 2007). Rather, it seems that monetary policy shocks generated significant effects around 1980, but not too much in other episodes. This does not mean, however, that monetary policy's role in the forecasting power of the yield curve is small, too. To the contrary, the endogenous response of monetary policy to shocks hitting the economy is perhaps the most important ingredient for understanding this relation.

The way the model interprets the forecasting power of the yield curve also sheds light on the comparative contribution of the short rate vis-a-vis the term spread. For the shocks deemed important in driving the positive covariance, the forecasting power follows from fluctuations in the short rate more than changes in the long rate. Hence, the short rate by itself captures much of the information relevant for predicting future growth. This is in line with the results of Ang et

[18] The hump in the contribution of investment and wage markup shocks is typically not maximal at the one quarter horizon, contrary to the other shocks. This follows from their "curved" impact on the yield curve, which is also evident in Figure (2).

al. (2006). The latter attribute most of the informational content to the short rate, while the term spread seems to play a secondary role. The above impulse responses provide a structural interpretation for why this is the case.

Our results are consistent with several observations in the literature. First, the role of the endogenous policy response is crucial in understanding the ability of the term spread for GDP growth. This corroborates the findings of Smets and Tsatsaronis (1997), who attribute the higher predictive content of the term spread in Germany relative to the US to the Bundesbank's stronger anti-inflationary stance. Systematic monetary policy is also crucial in the analysis of Feroli (2004), whose model shows that the informational content of the yield curve is tied closely to the specification of monetary policy. Second, demand shocks strongly contribute to the forecasting power of the yield curve, again conform Smets and Tsatsaronis (1997). Third, we find only a limited role for exogenous monetary policy shocks, while supply shocks (wage markup in particular) explain a larger portion. The limited role of exogenous monetary policy shocks contrast with Buraschi and Jiltsov (2005), but accords with Ravenna and Seppälä (2007). Finally, supply shocks play a somewhat larger role than the VAR evidence of Smets and Tsatsaronis (1997) suggests[19].

9 Conclusion

A medium-scale DSGE model combined with the rational expectations hypothesis is to a large extent able to fit historical fluctuations in the US yield curve. The DSGE model analyzed is that of Smets and Wouters (2007), extended to allow for a time-varying inflation target. On the one hand, the behaviour of yields admits a meaningful, theoretically consistent representation in terms

[19] This may be driven by the fact that the present model allows for a wider array of shocks, which may cancel each other in the smaller system of Smets and Tsatsaronis (1997). The correlations in Table (8) suggest that, at least for some horizons, productivity and markup shocks work in opposite directions.

of structural macroeconomic shocks. On the other hand, the model shows promise in terms of out-of-sample forecasts. Contrary to existing macro-finance models, the model does not introduce features that increase empirical flexibility. Nevertheless, the dynamics of the yield curve are equally well, if not better, captured by the model.

This has a number of implications. A first implication relates to the rational expectations hypothesis. Extant macro-finance models of the term structure may have understated the success of the expectations hypothesis. The gains from introducing time-variation in structural parameters or in the volatility of shocks may derive from over-simplifying the forces governing the macroeconomy. What the model here shows is how a constant coefficient, constant variance and fully structural DSGE model can fit approximately 90% of historical fluctuations in US bond yields. A fruitful avenue of research could therefore investigate whether the remaining 10% can be explained by, for instance, learning or time-varying volatility of structural shocks, thus arriving at a complete macroeconomic characterization of historical US yields.

A second implication of the estimated DSGE model is that the yield fluctuations in 2004-2006 (the "conundrum") can be interpreted meaningfully within a "traditional" line of thought. More precisely, the fact that long term bond yields did not follow the Fed funds rate increase, follows from the Fed's response to expansionary demand shocks hitting the economy. The tightening kept inflation expectations in check, thus eliminating the primary reason for long rate increases. This differs from earlier tightenings where long term bond yields increase more. The model attributes these episodes to "inflation scares", as in Goodfriend (1993).

Data appendix

Equations (1) to (15) are estimated using six macroeconomic time series and five interest rates: real GDP, consumption, investment, hours worked, real wages, prices, a short-term interest rate and yields with maturities of 1, 3, 5 and 10 years. The Bayesian estimation methodology is extensively discussed in Smets and Wouters (2003). GDP, consumption and investment are taken from the US Department of Commerce - Bureau of Economic Analysis databank. Real Gross Domestic Product is expressed in Billions of Chained 1996 Dollars. Nominal Personal Consumption Expenditures and Fixed Private Domestic Investment are deflated with the GDP-deflator. Inflation is the first difference of the log of the Implicit Price Deflator of GDP. Hours and wages come from the BLS (hours and hourly compensation for the NFB sector for all persons). Hourly compensation is divided by the GDP price deflator in order to get the real wage variable. Hours are adjusted to take into account the limited coverage of the NFB sector compared to GDP (the index of average hours for the NFB sector is multiplied with Civilian Employment (16 years and over). The aggregate real variables are expressed per capita by dividing with the population over 16. All series are seasonally adjusted. The short term interest rate is the Federal Funds Rate. The bond yields we use are from the Gürkaynak, Swanson and Wright (2006) database. The 10 year bond yield for the 1960's is that from the BIS. Consumption, investment, GDP, wages and hours are expressed in 100 times log. The interest rates and inflation rate are expressed on a quarterly basis corresponding with their appearance in the model (in the figures the series are translated on an annual basis).

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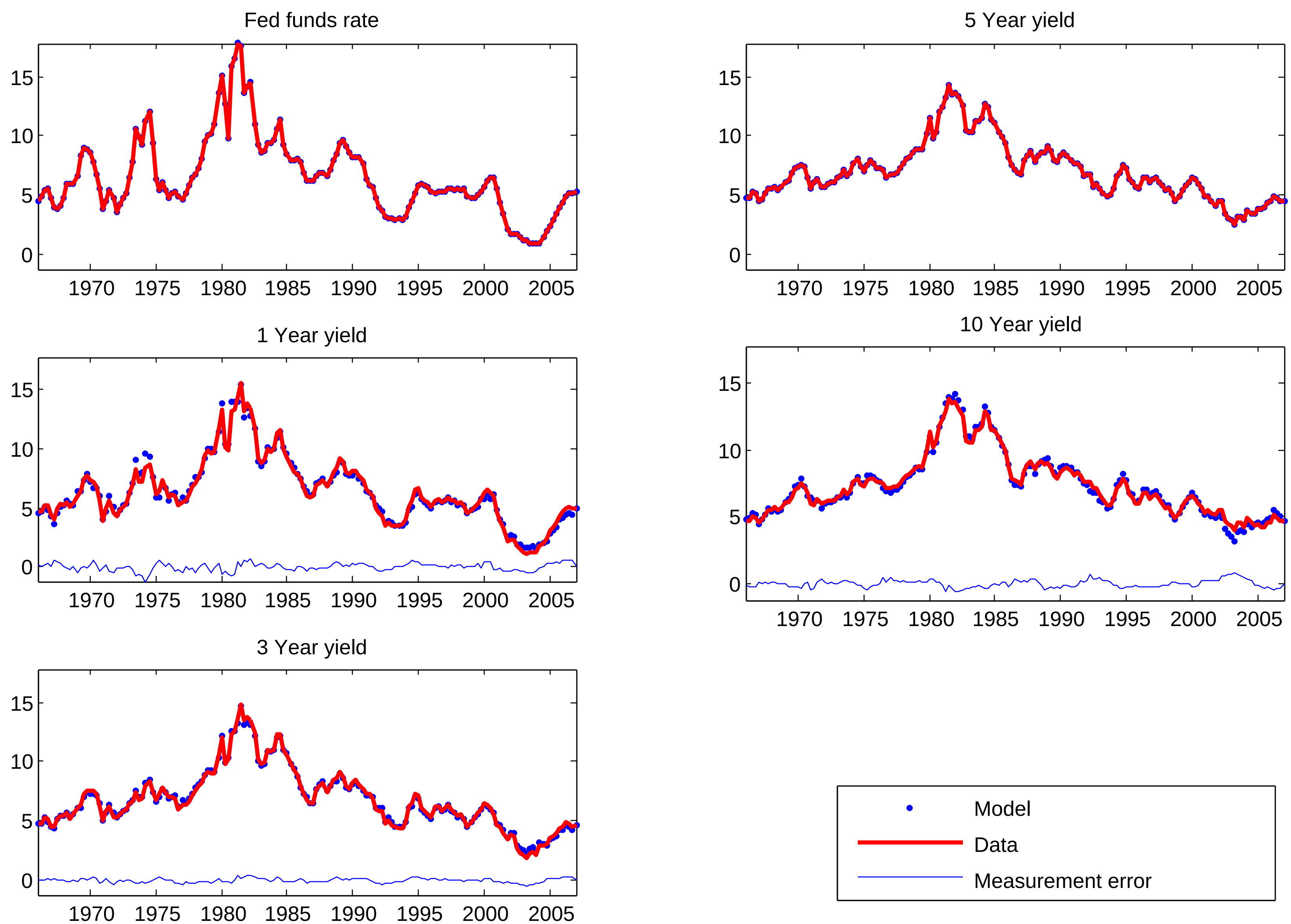

Fed funds rate
5 Year yield
1 Year yield
10 Year yield
3 Year yield
Model
Data
Measurement error

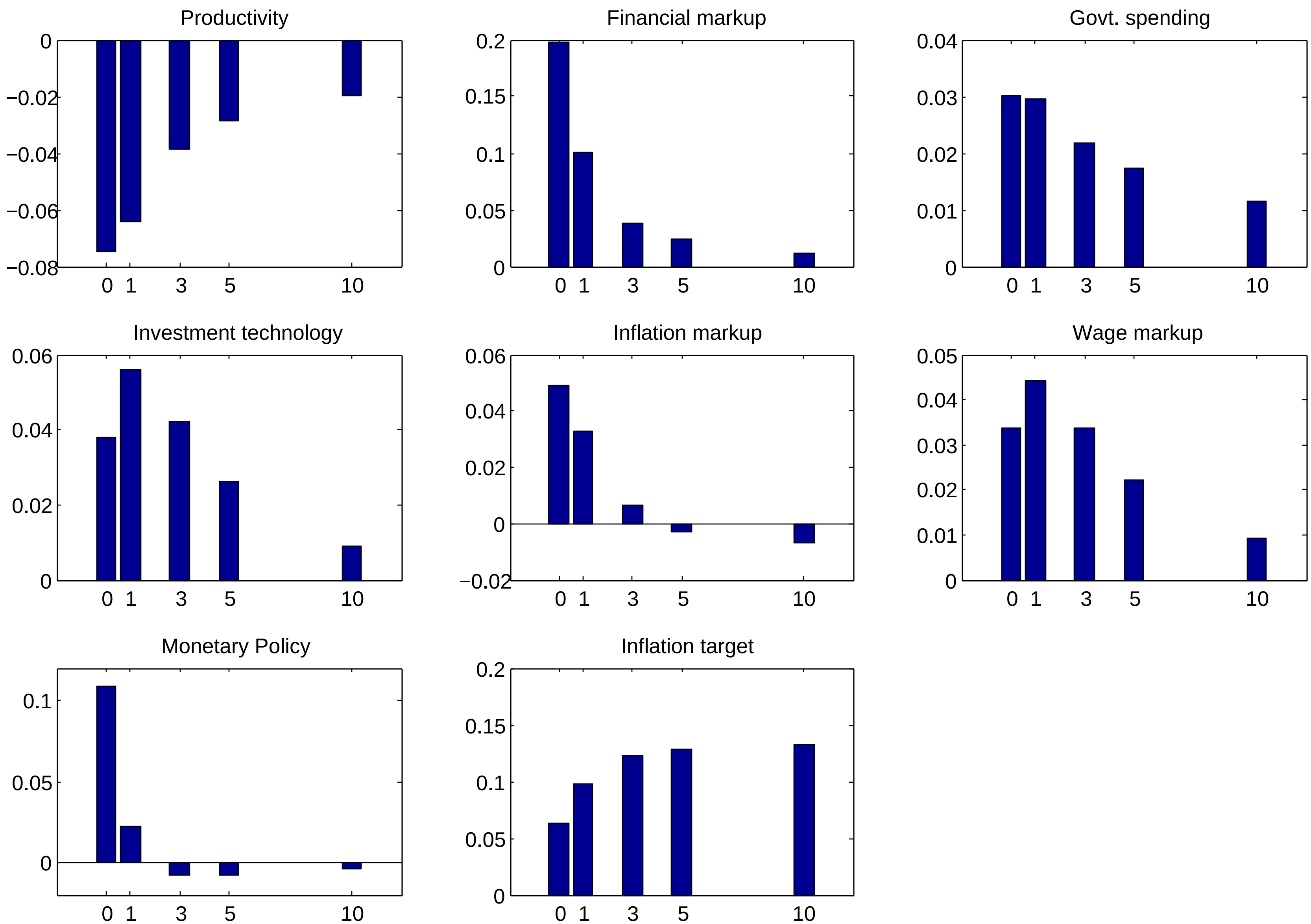

Productivity
Financial markup
Govt. spending
Investment technology
Inflation markup
Wage markup
Monetary Policy
Inflation target

Figure 3: Historical decomposition of the Fed funds rate

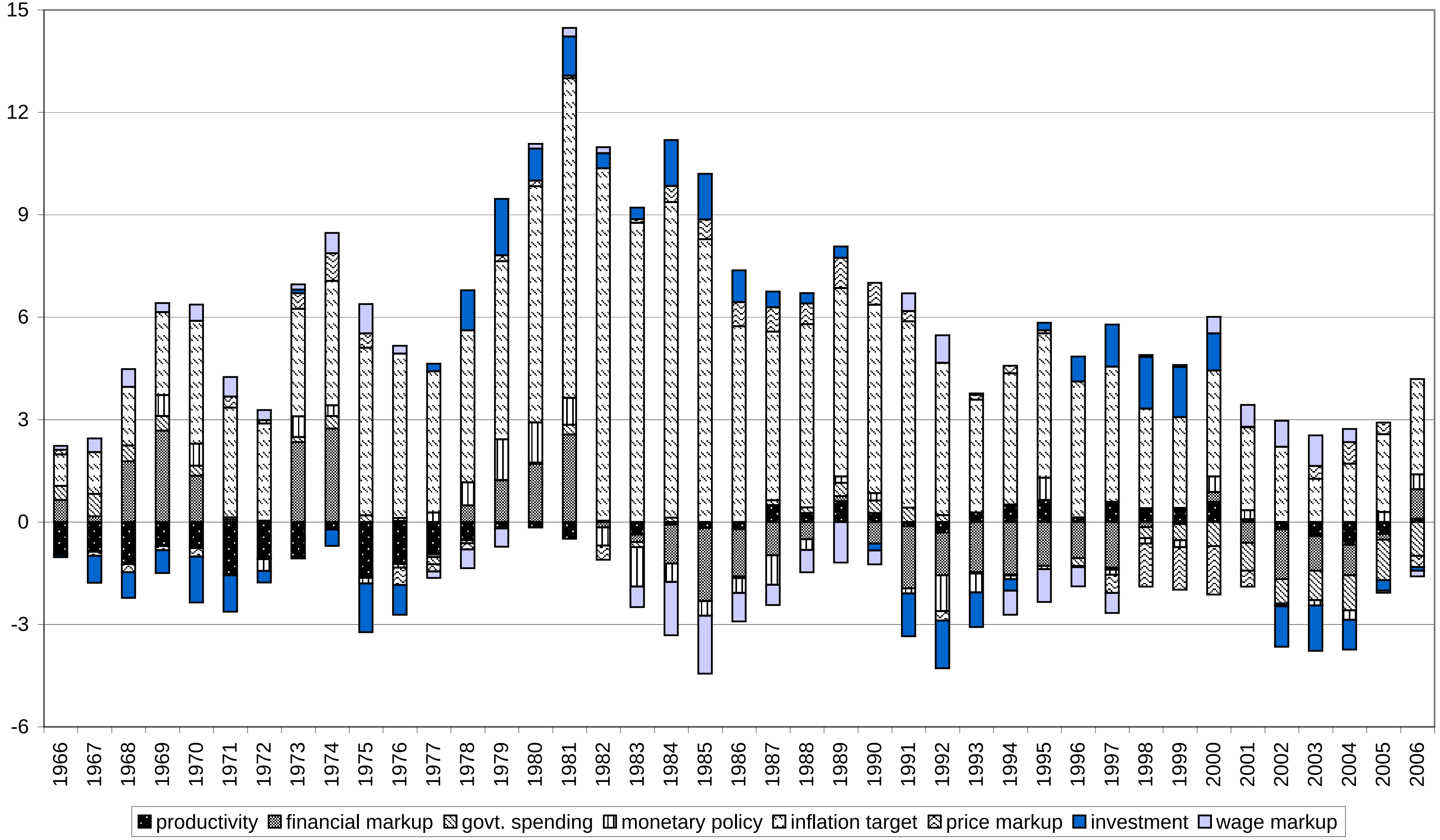


Figure 4: Historical decomposition of the 5 Year yield

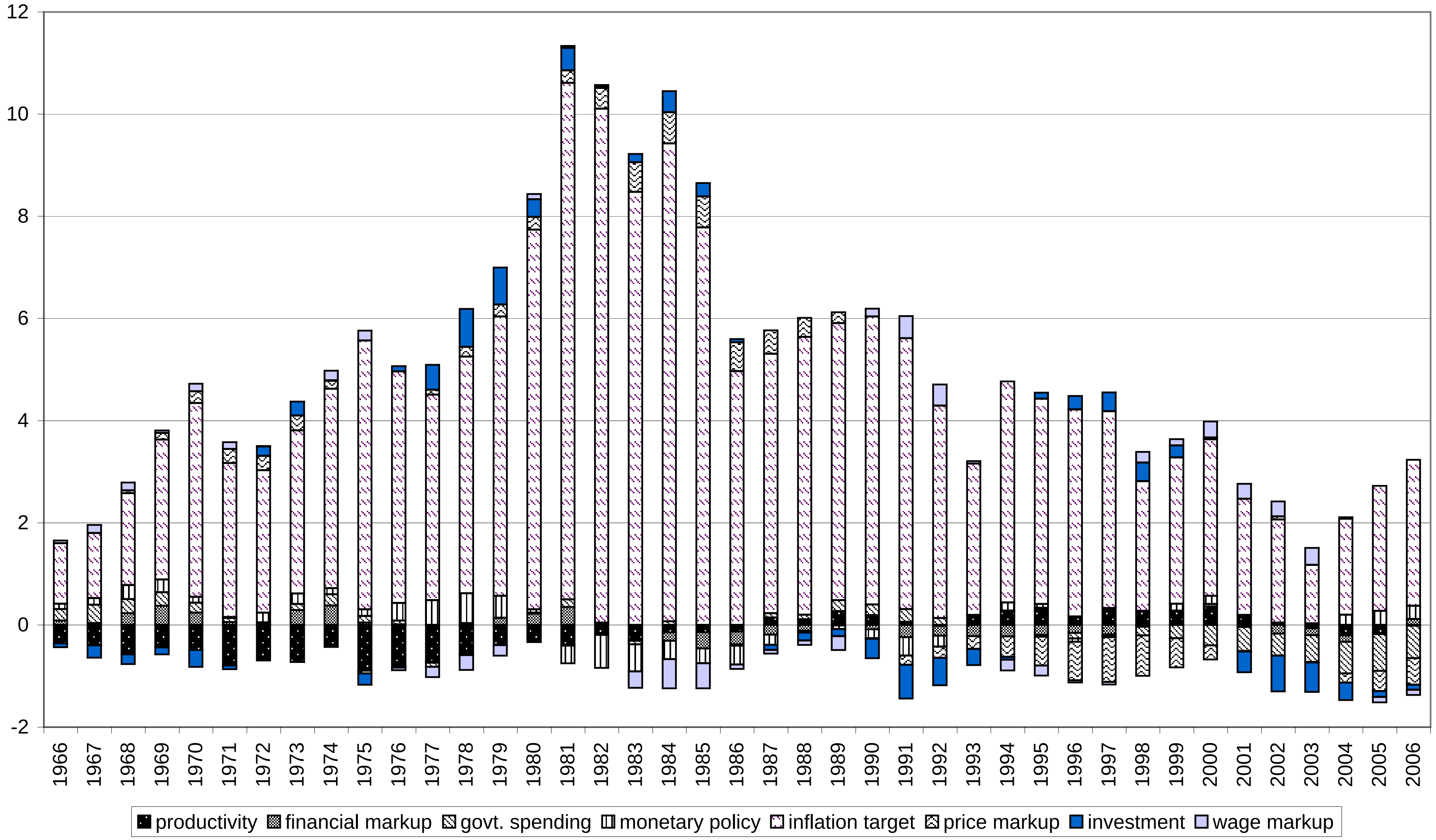


Figure 5: Historical decomposition of the term spread

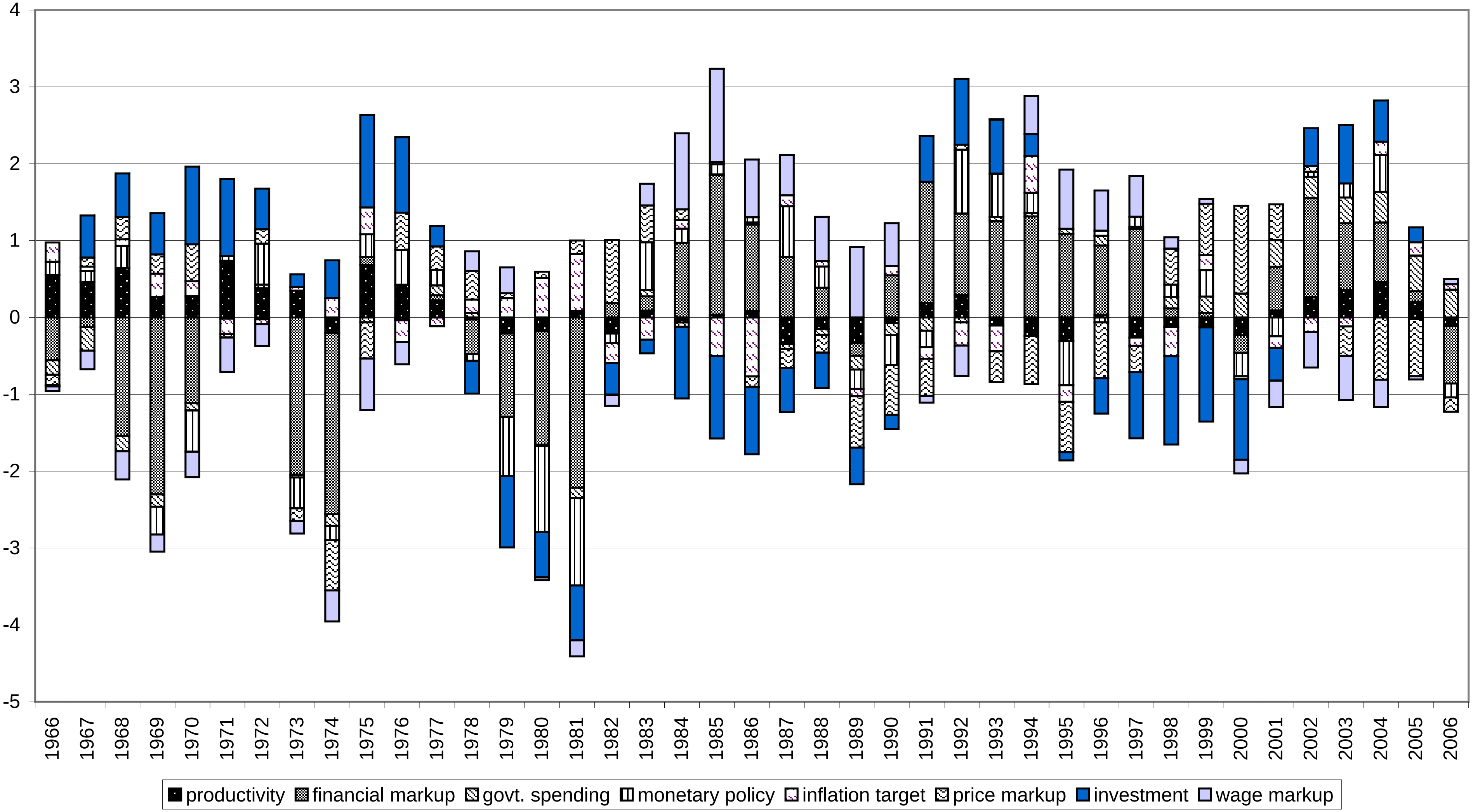


Figure 6: Historical contributions to inflation

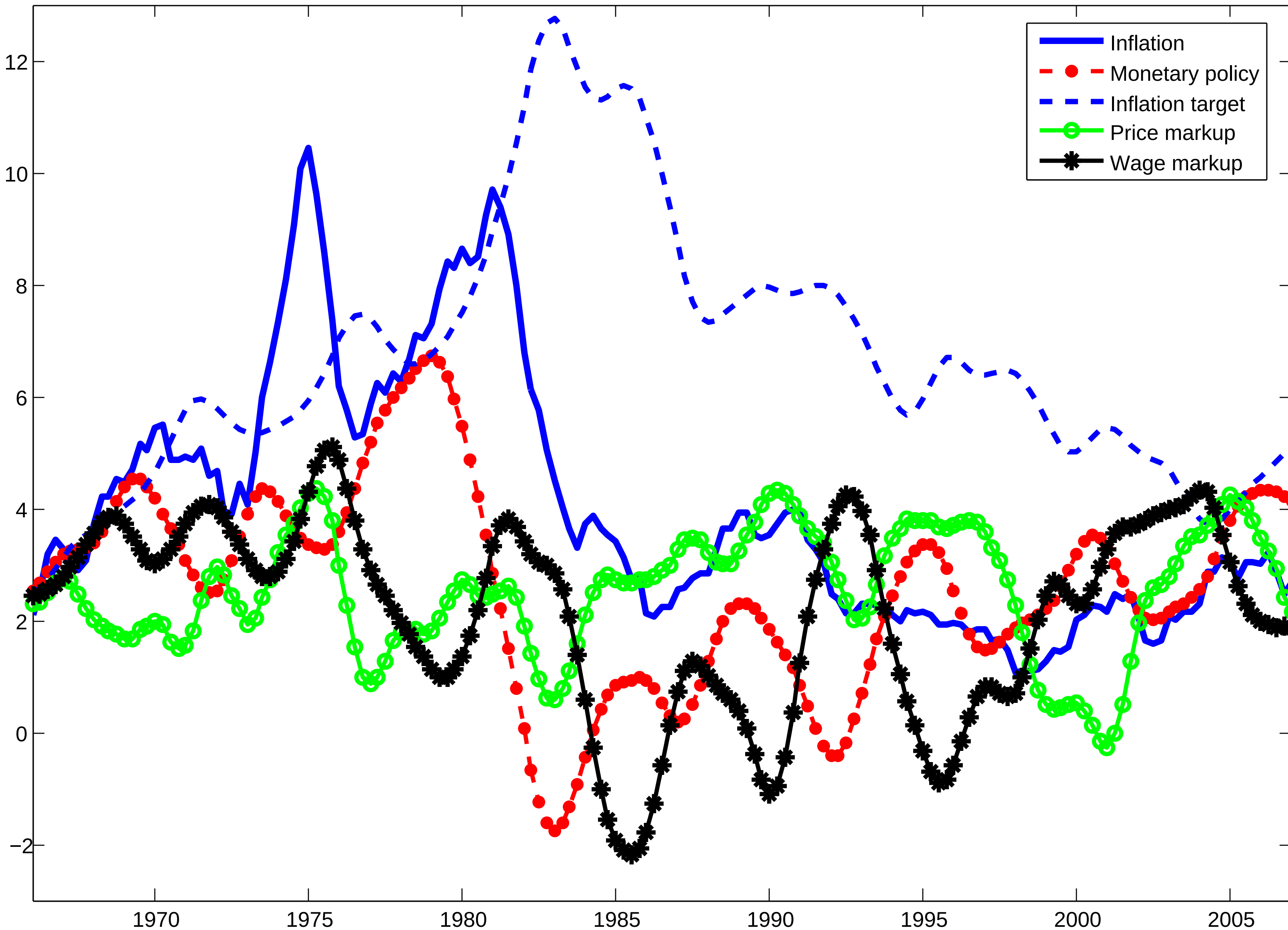


Figure 7: Expected inflation: Model and surveys

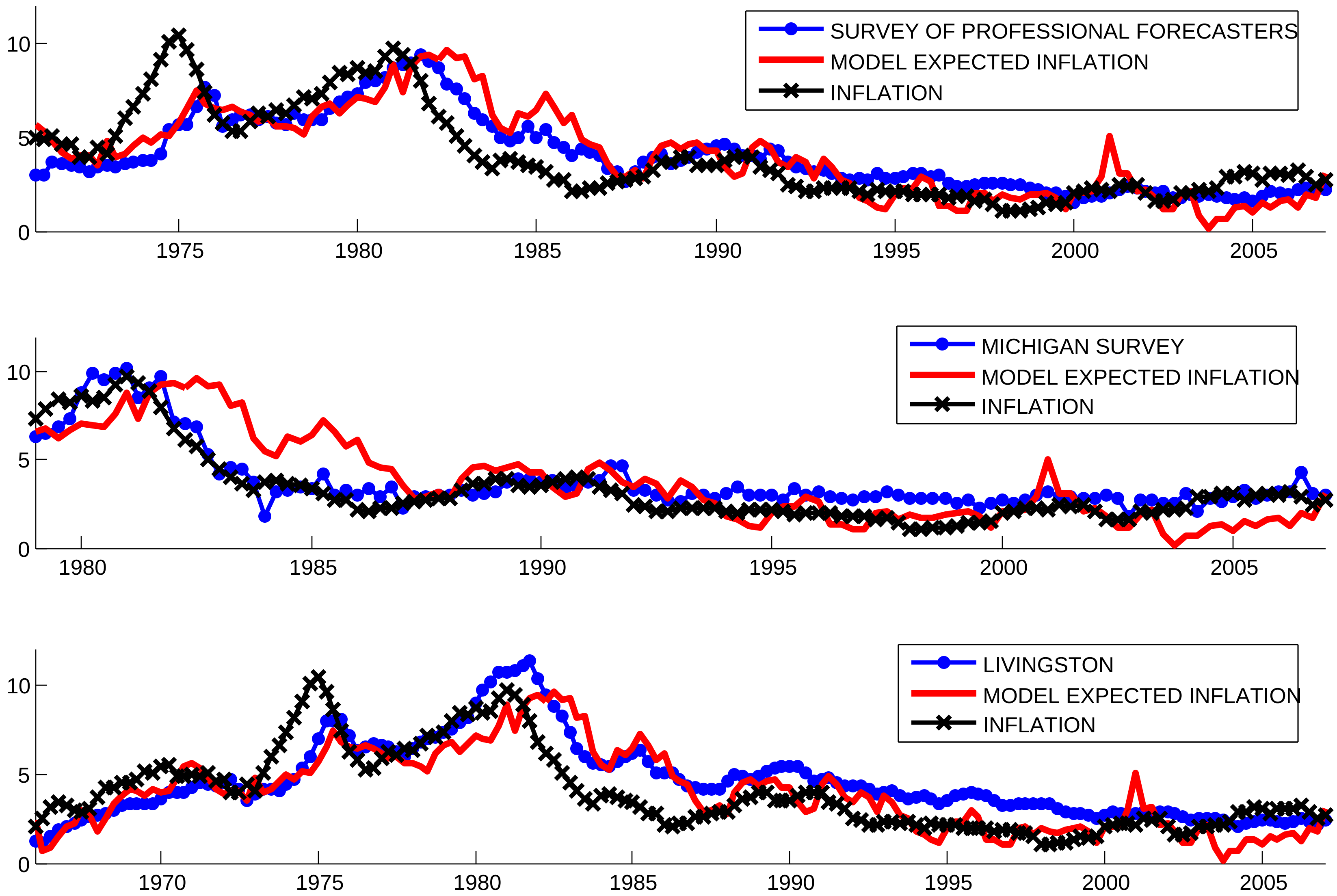
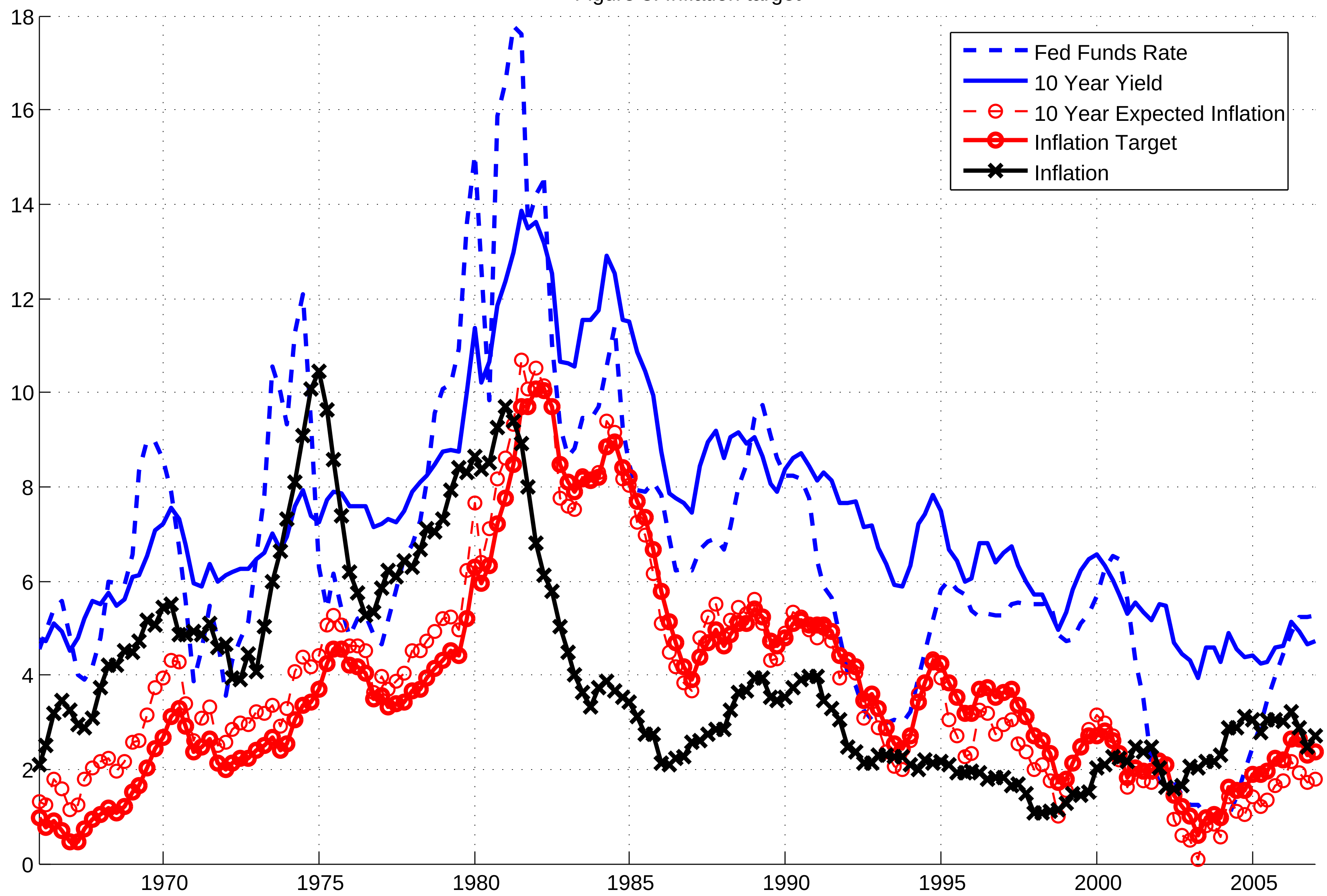
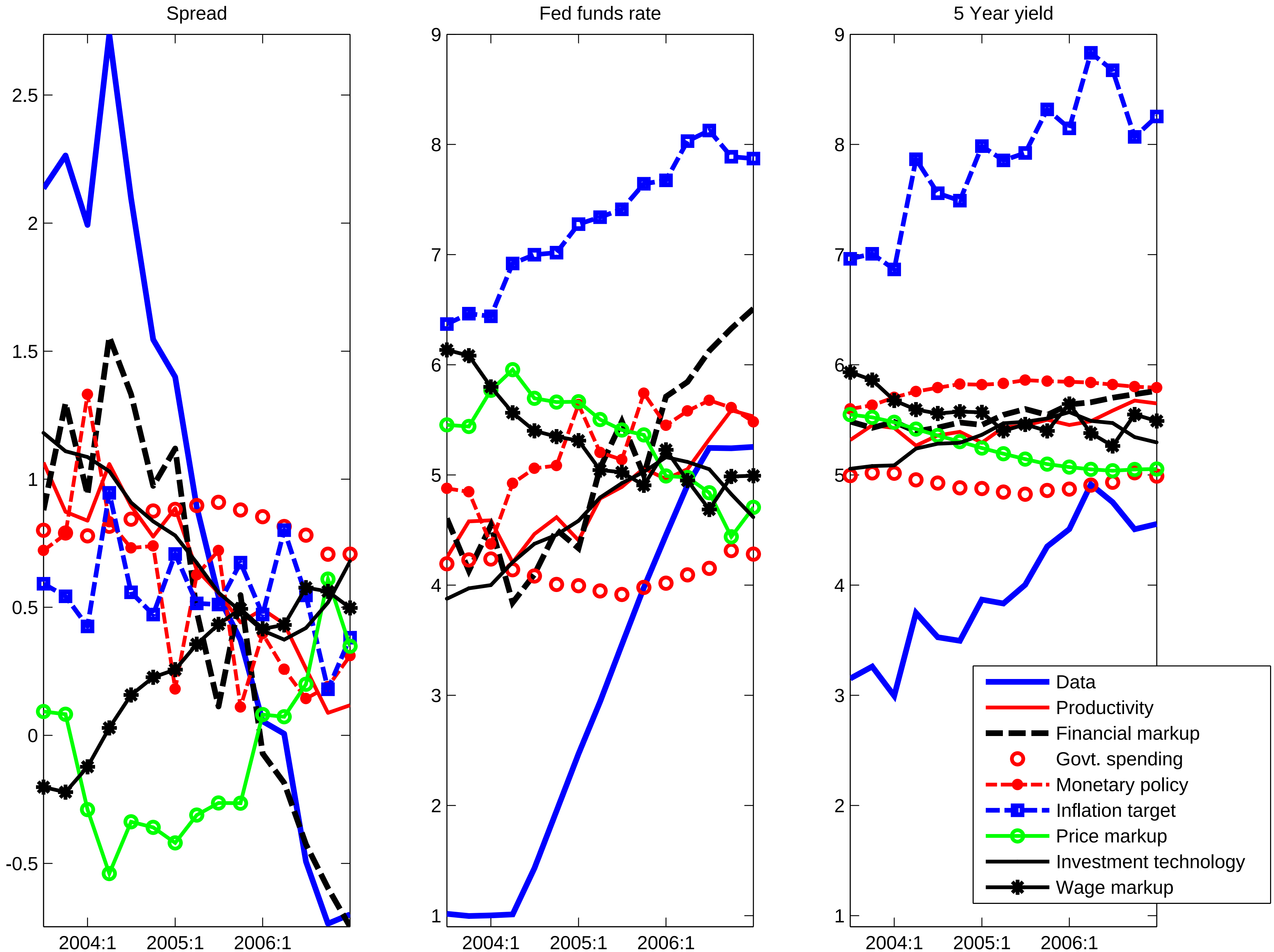
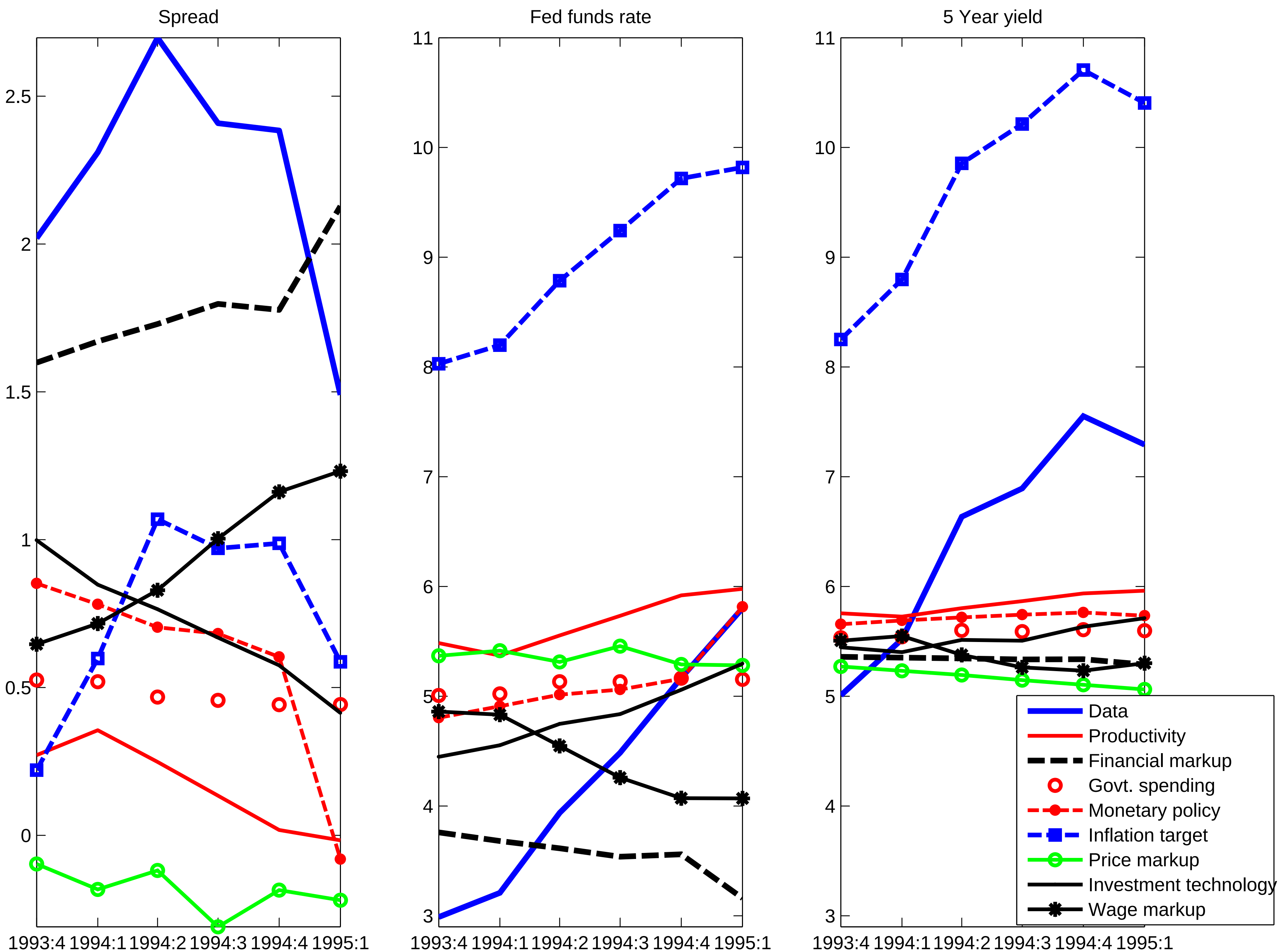


Figure 8: Inflation target




Spread
Fed funds rate
5 Year yield
2.5
2
1.5
1
0.5
0
-0.5
9
8
7
6
5
4
3
2
1
2004:1
2005:1
2006:1
Data
Productivity
Financial markup
Govt. spending
Monetary policy
Inflation target
Price markup
Investment technology
Wage markup



Spread
Fed funds rate
5 Year yield
2.5
2
1.5
1
0.5
0
11
10
9
8
7
6
5
4
3
1993:4
1994:1
1994:2
1994:3
1994:4
1995:1
Data
Productivity
Financial markup
Govt. spending
Monetary policy
Inflation target
Price markup
Investment technology
Wage markup

Table 1: Prior and posterior distribution of structural parameters

	Prior distribution			Posterior distribution			
	Distr.	Mean	St. Dev.	Mode	Mean	5%	95%
φ	Normal	4	1	8.04	7.95	6.60	9.20
σ_c	Normal	1.5	0.37	1.15	1.14	1.01	1.27
λ	Beta	0.7	0.1	0.42	0.42	0.37	0.48
ξ_w	Beta	0.5	0.1	0.40	0.40	0.30	0.50
σ_l	Normal	2	0.75	0.67	0.69	0.37	1.02
ξ_p	Beta	0.5	0.1	0.58	0.59	0.53	0.64
ι_w	Uniform	0.5	0.3	0.28	0.31	0.00	0.55
ι_w	Uniform	0.5	0.3	0.36	0.33	0.20	0.45
ψ	Beta	0.5	0.15	0.62	0.62	0.50	0.75
Φ	Normal	1.25	0.12	1.50	1.52	1.41	1.63
r_π	Normal	1.5	0.25	1.75	1.81	1.55	2.05
ρ	Beta	0.75	0.1	0.78	0.79	0.74	0.83
r_y	Beta	0.12	0.1	0.00	0.01	0.00	0.01
$r_{\Delta y}$	Beta	0.12	0.1	0.54	0.54	0.45	0.61
$\bar{\pi}$	Gamma	0.62	0.1	0.60	0.63	0.52	0.77
$100(\beta^{-1}-1)$	Gamma	0.25	0.1	0.19	0.20	0.10	0.30
$\bar{L}$	Normal	0	2	-1.49	-1.57	-4.08	0.79
$\bar{\gamma}$	Normal	0.4	0.1	0.42	0.42	0.40	0.44
α	Normal	0.3	0.05	0.19	0.19	0.17	0.21

Note: The posterior distribution is obtained using the Metropolis-Hastings algorithm

Table 2: Prior and posterior distribution of shock processes

	Prior distribution			Posterior distribution			
	Distr.	Mean	St.Dev.	Mode	Mean	5%	95%
σ_a	Invgamma	0.1	2	0.46	0.46	0.41	0.51
σ_b	Invgamma	0.1	2	0.29	0.29	0.25	0.34
σ_g	Invgamma	0.1	2	0.51	0.51	0.47	0.56
σ_I	Invgamma	0.1	2	0.56	0.56	0.47	0.64
σ_r	Invgamma	0.1	2	0.31	0.31	0.27	0.36
σ_p	Invgamma	0.1	2	0.20	0.20	0.17	0.23
σ_w	Invgamma	0.1	2	0.34	0.35	0.29	0.41
σ_π	Invgamma	0.01	2	0.05	0.06	0.04	0.07
σ_{1Y}	Uniform	2	2	0.32	0.32	0.29	0.36
σ_{3Y}	Uniform	2	2	0.17	0.18	0.16	0.19
σ_{10Y}	Uniform	2	2	0.28	0.28	0.26	0.31
ρ_a	Beta	0.5	0.2	0.95	0.95	0.93	0.97
ρ_b	Beta	0.5	0.2	0.25	0.26	0.18	0.34
ρ_g	Beta	0.5	0.2	0.95	0.95	0.94	0.96
ρ_I	Beta	0.5	0.2	0.51	0.52	0.44	0.60
ρ_r	Beta	0.5	0.2	0.04	0.07	0.00	0.14
ρ_π	Beta	0.5	0.2	0.63	0.58	0.47	0.71
ρ_p	Beta	0.5	0.2	0.96	0.95	0.94	0.97
ρ_w	Beta	0.5	0.2	1.00	1.00	1.00	1.00
μ_p	Beta	0.5	0.2	0.88	0.87	0.83	0.91
μ_w	Beta	0.5	0.2	0.74	0.74	0.61	0.89
ρ_{ga}	Beta	0.5	0.2	0.55	0.55	0.41	0.68
$\rho_{1Y,3Y}$	Uniform	0	0.75	0.86	0.84	0.79	0.89
$\rho_{1Y,10Y}$	Uniform	0	0.75	-0.69	-0.65	-0.73	-0.56
$\rho_{3Y,10Y}$	Uniform	0	0.75	-0.90	-0.90	-0.92	-0.87

Note: Yield measurement errors are in annualized percentages.

Table 3: Prior and posterior distribution of structural parameters: Subsample estimates

	1966-1979 Mean	St.Dev.	1984-2007 Mean	St.Dev.
φ	3.30	1.24	6.29	0.84
σ_c	1.24	0.13	1.46	0.08
λ	0.49	0.08	0.48	0.04
ξ_w	0.75	0.12	0.76	0.03
σ_l	0.35	0.79	1.10	0.25
ξ_p	0.54	0.09	0.59	0.04
ι_w	0.08	0.15	0.06	0.03
ι_w	0.23	0.20	0.11	0.03
ψ	0.48	0.16	0.58	0.08
Φ	1.43	0.11	1.52	0.08
r_π	1.46	0.24	1.53	0.16
ρ	0.78	0.07	0.87	0.02
r_y	0.14	0.05	0.07	0.02
$r_{\Delta y}$	0.31	0.07	0.27	0.03
$\bar{\pi}$	0.61	0.10	0.60	0.05
$100(\beta^{-1} - 1)$	0.15	0.06	0.11	0.03
$\bar{L}$	-1.74	0.85	0.86	0.63
$\bar{\gamma}$	0.27	0.04	0.49	0.01
α	0.24	0.02	0.22	0.01

Table 4: Prior and posterior distribution of shock processes: Subsample estimates

	1966-1979		1984-2007	
	Mean	St.Dev.	Mean	St.Dev.
σ_a	0.59	0.07	0.35	0.03
σ_b	0.27	0.05	0.17	0.02
σ_g	0.59	0.06	0.40	0.03
σ_I	0.65	0.11	0.42	0.04
σ_r	0.20	0.03	0.14	0.01
σ_p	0.27	0.04	0.14	0.02
σ_w	0.19	0.02	0.39	0.03
σ_π	0.04	0.01	0.04	0.01
σ_{1Y}	0.44	0.06	0.20	0.02
σ_{3Y}	0.13	0.02	0.14	0.01
σ_{10Y}	0.16	0.02	0.25	0.02
ρ_a	0.95	0.02	0.89	0.02
ρ_b	0.38	0.14	0.29	0.06
ρ_g	0.90	0.02	0.94	0.01
ρ_I	0.41	0.09	0.54	0.05
ρ_r	0.13	0.12	0.13	0.05
ρ_π	0.61	0.09	0.65	0.05
ρ_p	0.89	0.05	0.94	0.01
ρ_w	0.77	0.12	0.96	0.00
μ_p	0.83	0.05	0.75	0.06
μ_w	0.72	0.14	0.96	0.00
ρ_{ga}	0.56	0.13	0.48	0.09
$\rho_{1Y,3Y}$	0.82	0.06	0.90	0.03
$\rho_{1Y,10Y}$	-0.48	0.13	-0.78	0.05
$\rho_{3Y,10Y}$	-0.78	0.06	-0.94	0.01

Table 5: Out-of-sample prediction performance: Macro-economic aggregates

Forecast evaluation period: 1990:Q1 - 2007:Q1						
MODEL	GDP	CONS	INV	HOURS	INF	WAGE
1Q	0.61	0.61	1.46	0.55	0.29	0.74
2Q	0.96	0.98	2.71	0.95	0.33	1.08
4Q	1.54	1.59	5.17	1.60	0.35	1.62
8Q	2.06	2.35	8.16	2.28	0.46	2.58
12Q	2.18	2.87	8.85	2.58	0.52	3.36
VAR(1)						
1Q	0.60	0.58	1.63	0.48	0.26	0.75
2Q	0.99	0.91	2.98	0.81	0.33	1.05
4Q	1.76	1.55	5.51	1.41	0.40	1.54
8Q	2.52	2.35	8.69	2.07	0.53	2.54
12Q	3.00	3.01	11.17	2.41	0.59	3.63
MODEL / VAR						
1Q	1.03	1.05	0.90	1.14	1.12	0.99
2Q	0.97	1.08	0.91	1.17	1.02	1.02
4Q	0.87	1.03	0.94	1.13	0.86	1.05
8Q	0.82	1.00	0.94	1.10	0.88	1.02
12Q	0.73	0.95	0.79	1.07	0.89	0.92

Table 6: Out-of-sample prediction performance: Yields

Forecast evaluation period: 1990:Q1 - 2007:Q1											
MODEL	FFR	1Y	3Y	5Y	10Y						
1Q	0.55	0.65	0.55	0.46	0.49						
2Q	0.97	0.97	0.84	0.73	0.67						
4Q	1.62	1.53	1.31	1.13	0.94						
8Q	2.53	2.21	1.79	1.50	1.11						
12Q	2.76	2.36	2.00	1.76	1.40						
							MODEL / VAR				
VAR(1)	FFR	1Y	3Y	5Y	10Y		FFR	1Y	3Y	5Y	10Y
1Q	0.50	0.50	0.50	0.45	0.37	1Q	1.10	1.31	1.10	1.00	1.33
2Q	0.93	0.90	0.81	0.71	0.58	2Q	1.04	1.08	1.04	1.02	1.16
4Q	1.79	1.58	1.29	1.09	0.83	4Q	0.91	0.97	1.01	1.04	1.13
8Q	2.76	2.29	1.82	1.51	1.08	8Q	0.92	0.96	0.98	0.99	1.03
12Q	3.08	2.58	2.15	1.85	1.38	12Q	0.90	0.92	0.93	0.95	1.01
							MODEL / RANDOM WALK				
RANDOM WALK	FFR	1Y	3Y	5Y	10Y		FFR	1Y	3Y	5Y	10Y
1Q	0.46	0.46	0.47	0.44	0.36	1Q	1.20	1.42	1.17	1.04	1.37
2Q	0.86	0.81	0.75	0.68	0.56	2Q	1.12	1.19	1.12	1.07	1.19
4Q	1.57	1.45	1.21	1.04	0.83	4Q	1.03	1.06	1.08	1.09	1.13
8Q	2.51	2.30	1.74	1.36	0.91	8Q	1.01	0.96	1.02	1.10	1.22
12Q	2.89	2.64	2.02	1.59	1.13	12Q	0.96	0.89	0.99	1.10	1.24
Forecast evaluation period: 1966:Q1 - 2007:Q1											
MODEL	FFR	1Y	3Y	5Y	10Y						
1Q	1.32	0.89	0.69	0.61	0.61						
2Q	1.78	1.27	1.04	0.95	0.89						
4Q	2.31	1.80	1.54	1.41	1.29						
8Q	3.07	2.50	2.15	1.96	1.76						
12Q	3.41	2.82	2.48	2.30	2.08						
							MODEL / RANDOM WALK				
RANDOM WALK	FFR	1Y	3Y	5Y	10Y		FFR	1Y	3Y	5Y	10Y
1Q	1.05	0.78	0.63	0.55	0.46	1Q	1.26	1.14	1.09	1.11	1.30
2Q	1.64	1.21	0.98	0.86	0.74	2Q	1.08	1.05	1.06	1.10	1.21
4Q	2.33	1.71	1.42	1.27	1.12	4Q	0.99	1.05	1.08	1.11	1.16
8Q	3.48	2.53	2.03	1.78	1.53	8Q	0.88	0.99	1.06	1.10	1.15
12Q	3.96	2.95	2.36	2.08	1.81	12Q	0.86	0.96	1.05	1.11	1.15

Note: Annualized percentages. Rows: forecast horizons in quarters. Columns: FFR: Fed funds rate; 1Y (3Y, 5Y, 10Y): Yield of 1 (3, 5, 10) year maturity bond.

Table 7: Variance decomposition of yields

Fed funds rate	1	2	4	10	20	40
Productivity	8.3	10.3	10.7	7.5	4.9	3.0
Financial markup	58.3	51.5	36.5	19.3	11.5	6.5
Govt spending	1.2	1.7	2.1	1.8	1.3	0.9
Investment	1.9	4.3	7.8	7.6	4.7	2.8
Monetary	19.0	12.7	8.8	5.9	3.8	2.1
Inflation target	5.9	12.4	25.9	50.7	68.6	81.4
Price markup	3.6	3.9	3.2	1.8	1.5	1.1
Wage markup	1.8	3.2	5.2	5.5	3.6	2.1
1 Year yield						
Productivity	13.0	12.5	10.2	6.1	3.8	2.3
Financial markup	32.8	23.3	13.6	6.2	3.4	1.8
Govt spending	2.6	2.6	2.4	1.8	1.2	0.8
Investment	9.3	11.1	11.6	7.9	4.4	2.6
Monetary	2.0	1.3	1.8	2.1	1.3	0.7
Inflation target	30.5	39.2	51.0	69.2	81.2	89.2
Price markup	3.5	2.8	1.7	0.9	1.1	0.8
Wage markup	6.4	7.3	7.8	5.8	3.5	1.9
5 Year yield						
Productivity	4.2	3.8	3.0	1.9	1.3	0.9
Financial markup	3.0	2.1	1.2	0.5	0.3	0.1
Govt spending	1.4	1.3	1.2	0.8	0.6	0.4
Investment	3.3	3.0	2.4	1.2	0.7	0.5
Monetary	0.3	0.6	0.8	0.7	0.4	0.2
Inflation target	84.3	86.0	88.5	92.7	95.2	97.0
Price markup	0.0	0.1	0.2	0.6	0.7	0.5
Wage markup	3.4	3.2	2.7	1.6	0.9	0.5
10 Year yield						
Productivity	2.1	1.9	1.6	1.2	0.9	0.6
Financial markup	0.8	0.5	0.3	0.1	0.1	0.0
Govt spending	0.7	0.7	0.6	0.4	0.3	0.2
Investment	0.4	0.4	0.3	0.1	0.2	0.2
Monetary	0.1	0.2	0.2	0.2	0.1	0.0
Inflation target	94.7	95.2	95.9	97.1	97.9	98.6
Price markup	0.2	0.2	0.3	0.4	0.4	0.2
Wage markup	1.0	1.0	0.8	0.5	0.3	0.2
Term spread						
Productivity	3.8	5.6	7.4	7.7	7.6	7.6
Financial markup	55.2	55.3	50.1	43.0	41.6	41.4
Govt spending	0.3	0.5	0.8	1.1	1.2	1.2
Investment	0.2	1.6	5.7	12.0	13.0	13.0
Monetary	27.0	21.6	18.2	16.9	17.0	16.9
Inflation target	8.7	8.5	7.9	6.8	6.6	6.6
Price markup	4.7	6.3	7.5	7.2	7.1	7.4
Wage markup	0.1	0.7	2.4	5.3	6.0	5.9

Note: Column titles refer to different horizons, in quarters.

Table 8: Correlations between the term spread, short rate and future GDP growth

Term Spread Horizon	Data	Model	ϵ^a	ϵ^b	ϵ^g	ϵ^I	ϵ^r	$\epsilon^{\bar{\pi}}$	ϵ^p	ϵ^w
1	0.46	0.70	0.05	0.26	0.03	0.08	0.08	0.00	0.06	0.12
4	0.67	0.58	0.01	0.23	0.03	0.14	0.00	0.00	0.05	0.13
8	0.62	0.46	-0.03	0.17	0.04	0.16	-0.03	-0.01	0.03	0.13

Short Rate Horizon	Data	Model	ϵ^a	ϵ^b	ϵ^g	ϵ^I	ϵ^r	$\epsilon^{\bar{\pi}}$	ϵ^p	ϵ^w
1	-0.31	-0.42	-0.03	-0.14	-0.03	-0.03	-0.05	-0.02	-0.03	-0.09
4	-0.42	-0.38	0.01	-0.12	-0.04	-0.07	-0.02	-0.02	-0.02	-0.10
8	-0.32	-0.33	0.04	-0.09	-0.04	-0.09	-0.01	-0.02	-0.02	-0.09

Note: ϵ^a: productivity; ϵ^b: financial markup; ϵ^g: government spending; ϵ^I:investment; ϵ^r: monetary policy; $\epsilon^{\bar{\pi}}$: inflation target; ϵ^p: inflation markup; ϵ^w: wage markup shock.