

# Monetary Policy, Expected Inflation, and Inflation Risk Premia\*

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## Abstract

We study variables that are normally unobservable, but very important for the conduct of monetary policy, expected inflation and inflation risk premia, within a New Keynesian business cycle model. We solve the model using third-order approximation which allows us to study time-varying risk premia. Our model is consistent with rejections of the expectations and business-cycle behavior of nominal interest rates. We show that (i) current inflation and expected inflation are significantly positively correlated, (ii) short-term real interest rates and expected inflation are significantly negatively correlated, (iii) short-term real interest rates display greater volatility than expected inflation, (iv) nominal interest rates and expected inflation are negatively correlated for short maturities, but positively correlated for long maturities, (v) inflation risk premia are very small and very constant, and (vi) inflation risk premia and expected inflation are significantly negatively correlated. Results (ii) and (iii) are consistent with empirical evidence in Pennacchi (1991). Finally, we show that our economy is consistent with Mundell-Tobin Effect, that is, increases in inflation are associated with higher nominal interest rates, but lower real interest rates.

**Keywords:** Term Structure of Interest Rates, Monetary Policy, Expected Inflation, Inflation Risk Premia, Mundell-Tobin Effect.

**JEL classification:** E43, E44, E5, G12.

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# 1. Introduction

Several variables that are very important for the conduct of the monetary policy are unobservable. These include (ex-ante) real interest rates, expected inflation, and inflation risk premia. New Keynesian models assume that monetary policy responds to expected inflation and controls the current inflation by raising short-term nominal interest rates sufficiently to reduce short-term real interest rates.<sup>1</sup> Assuming that the government issues both nominal and index-linked bonds, one has a measure for both nominal and real interest rates. However, to obtain the expected inflation as a difference between the two, one needs to have an idea about the sign and magnitude of inflation risk premium.<sup>2</sup>

There is a large empirical literature on the dynamic behavior real interest rates and expected inflation, but the literature has not produced generally accepted stylized facts. As Ang, Bekaert, and Wei (2007) note in their closely related paper,

“For example, whereas theoretical research often assumes that the real interest rate is constant, empirical estimates for the real interest rate process vary between constancy as in Fama (1975), mean-reverting behavior (Hamilton, 1985), or a unit-root process (Rose, 1988). There seems to be more consensus on the fact that real rate variation, if it exists at all, should only affect the short end of the term structure but that the variation in the long-term interest rates is primarily affected by shocks to expected inflation (see, among others, Mishkin, 1990, and Fama, 1990, but this is disputed by Pennacchi, 1991). Another phenomenon that has received wide attention is the Mundell (1963) and Tobin (1965) effect: the correlation between real rates and (expected) inflation appears to be negative.”

In this paper, we build a New Keynesian general equilibrium model to explain the term structure of interest rates. The model displays short-run monetary non-neutrality, so that the behavior of the monetary authority affects the business cycle dynamics. Because monetary policy responds systematically to movements in endogenous variables, changes in the way policy is conducted affect the co-variation of real and nominal variables, and play an important role in the dynamics of the term structure. We show that the model can match the average nominal term structure in post-war U.S. data and produces procyclical interest rates and countercyclical term spreads. The term spread has predictive power for future economic activity. Most importantly, the model is able to account for rejections of the expectations hypothesis.

Ravenna and Seppälä (2006) concentrates on the cyclical behavior of and rejections of the expectations hypothesis the nominal term structure. This paper seeks to address if our theoretical model can shed light on the dynamic behavior of real interest rates, expected inflation, and inflation risk premia. Among other things, we find that in the model (i) current inflation and expected inflation are significantly positively correlated, (ii) short-term real interest rates and expected inflation are significantly negatively correlated, (iii) short-term real interest rates display greater volatility than expected inflation, (iv) nominal interest rates and expected inflation are negatively correlated for short maturities, but positively correlated for long maturities, (v) inflation risk premia are very

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<sup>1</sup>See, e.g., Clarida, Gali, and Gertler (1999) or Woodford (2003).

<sup>2</sup>Later called inflation term premium in this paper.

small and very constant, and (vi) inflation risk premia and expected inflation are significantly negatively correlated. Results (ii) and (iii) are consistent with empirical evidence in Pennacchi (1991). Finally, we show that our economy is consistent with Mundell-Tobin Effect, that is, increases in inflation are associated with higher nominal interest rates, but lower real interest rates.

The rest of the paper is organized as follows. Section 2 explains the New Keynesian model that we use, Section 3 discusses our techniques for solving the model numerically, and Section 4 explains the parameterization of the model. Section 5 reports the results related to the nominal term structure. Section 6 reports the results related to the term structures of real interest rates, expected inflation, and inflation risk premia. Finally, Section 7 concludes.

## 2. The Model

The theoretical interest rate term structure is derived from a dynamic stochastic general equilibrium model of the business cycle. We adopt a money-in-utility-function model where nominal rigidities allow monetary policy to affect the dynamics of real variables. The modeling framework follows Calvo (1983) and the New Keynesian literature on the business cycle by assuming that prices cannot be updated to the profit-maximizing level in each period. Firms face an exogenous, constant probability of being able to reset the price in any period  $t$ . This setup can also be derived from a menu cost model, where firms face a randomly distributed fixed cost  $k_t$  of updating the price charged, and the support of  $k_t$  is  $[0; \bar{k}]$ ,  $\bar{k} \rightarrow \infty$  (see Klenow and Kryvtsov, 2004).

While a more sophisticated pricing mechanism could be introduced—such as state-dependent pricing (Dotsey, King and Wolman, 1999), partial indexation to past prices (Christiano, Eichenbaum and Evans, 2005), a mix of rule-of-thumb and forward-looking pricing (Gali and Gertler, 1999)—we limit the model to the more essential ingredients of the New Keynesian framework. This allows us to investigate the impact on term structure of four key features: (i) systematic monetary policy modeled as an interest rate rule; (ii) nominal price rigidity; (iii) habit-formation preferences; (iv) positive steady state money growth rate. Woodford (2003) offers a comprehensive treatment of the New Keynesian framework, and describes in detail the microfoundations of the model.

Each consumer owns shares in all firms, and households are rebated for any profit from the monopolistically competitive output sector. Savings can be accumulated in money balances or in a range of riskless nominal and real bonds of several maturities. The government runs a balanced budget in every period, and rebates to consumers any seigniorage revenue from issuing the monetary asset. Output is produced with undifferentiated labor, supplied by household-consumers, via a linear production function.

### *Households*

There is a continuum of infinitely-lived households, indexed by  $j \in [0, 1]$ . Consumers demand differentiated consumption goods, choosing from a continuum of goods, indexed by  $z \in [0, 1]$ . In the notation used throughout the paper,  $C_t^j(z)$  indicates consumption by household  $j$  at time  $t$  of the good produced by firm  $z$ .

Households' preferences over the basket of differentiated goods are defined by the CES aggre-

gator:

$$C_t^j = \left[ \int_0^1 C_t^j(z)^{\frac{\theta-1}{\theta}} dz \right]^{\frac{\theta}{\theta-1}}, \quad \theta > 1. \quad (1)$$

The representative household chooses  $\left\{ C_{t+i}^j, C_{t+i}^j(z), N_{t+i}^j, \frac{M_{t+i}^j}{P_{t+i}}, \frac{B_{t+i}^j}{P_{t+i}} \right\}_{i=0}^{\infty}$  where  $N_t$  denotes labor supply,  $M_t$  nominal money balances,  $P_t$  the aggregate price level, and  $B_t$  bond holdings, to maximize

$$E_t \sum_{i=0}^{\infty} \beta^i \left\{ \frac{(C_{t+i}^j - bC_{t+i-1}^j)^{1-\gamma}}{1-\gamma} D_{t+i} - \frac{\ell N_{t+i}^{1+\eta}}{1+\eta} + \frac{\xi}{1-\gamma_m} \left( \frac{M_{t+i}^j}{P_{t+i}} \right)^{1-\gamma_m} \right\} \quad (2)$$

subject to

$$\int_0^1 C_t^j(z) P_t(z) dz = W_t N_t^j + \Pi_t^j - (M_t^j - M_{t-1}^j) - (\vec{p}_t \vec{B}_t^j - B_{t-1}^j) - \tau_t^j, \quad (3)$$

and (1). When  $b > 0$  preferences are characterized by habit formation (Boldrin, Christiano, and Fisher, 2001 and Jermann, 1998).  $D_t$  is an aggregate stochastic preference shock. Each element of the row vector  $\vec{p}_t$  represents the price of an asset with maturity  $k$  that will pay one unit of currency in period  $t+k$ . The corresponding element of  $\vec{B}_t$  represents the quantity of such claims purchased by the household.  $B_{t-1}^j$  indicates the value of the household portfolio of claims maturing at time  $t$ .  $W_t$  is the nominal wage rate, and  $\tau$  is the lump-sum tax imposed by the government. Finally, the households own the firms and  $\Pi_t$  is the profit from the firms.

The solution to the intratemporal expenditure allocation problem between the varieties of differentiated goods gives the demand function for individual good  $z$ :

$$C_t^j(z) = \left[ \frac{P_t(z)}{P_t} \right]^{-\theta} C_t^j. \quad (4)$$

Equation (4) is the demand for good  $z$  from household  $j$ , where  $\theta$  is the price elasticity of demand. The associated price index  $P_t$  measures the minimum expenditure on differentiated goods that will buy a unit of the consumption index:

$$P_t = \left[ \int_0^1 P_t(z)^{1-\theta} dz \right]^{\frac{1}{1-\theta}}. \quad (5)$$

Since all households solve an identical optimization problem and face the same aggregate variables, in the following we omit the index  $j$ . Equations (4) and (5) yield budget constraint:

$$C_t = \frac{W_t}{P_t} N_t + \frac{\Pi_t}{P_t} - \frac{M_t - M_{t-1}}{P_t} - \frac{\vec{p}_t \vec{B}_t - B_{t-1}}{P_t} - \frac{\tau_t}{P_t},$$

The first order conditions with respect to labor and real money balances are

$$\begin{aligned} MUC_t &= E_t \left[ \frac{D_t}{(C_t - bC_{t-1})^\gamma} - \beta b \frac{D_{t+1}}{(C_{t+1} - bC_t)^\gamma} \right] \\ \frac{W_t}{P_t} &= \frac{\ell N_t^\eta}{MUC_t} \end{aligned} \quad (6)$$

$$MUC_t = \xi \left( \frac{M_t}{P_t} \right)^{-\gamma_m} + E_t \left[ \beta MUC_{t+1} \frac{P_t}{P_{t+1}} \right], \quad (7)$$

where  $MUC$  is the marginal utility of consumption.

### *Firms and Price Setting*

The firm producing good  $z$  employs a linear technology:

$$Y_t(z) = A_t N_t(z), \quad (8)$$

where  $A_t$  is an aggregate productivity shock. Minimizing the nominal cost  $W_t N_t(z)$  of producing a given amount of output  $\bar{Y}$  yields the labor demand schedule:

$$MC_t^N(z) MPL_t(z) = W_t, \quad (9)$$

where  $MC_t^N$  is the nominal marginal cost,  $MPL$  is the marginal product of labor ( $Y_t(z)/N_t(z)$ ). Equation (9) implies that the real marginal cost  $MC_t$  of producing one unit of output is

$$MC_t(z) MPL_t(z) = W_t/P_t.$$

Firms adjust their prices infrequently. In each period there is a constant probability  $(1 - \theta_p)$  that the firm will be able to adjust its price regardless of past history. This implies that the fraction of firms setting prices at  $t$  is  $(1 - \theta_p)$  and the expected waiting time for the next price adjustment is  $\frac{1}{1 - \theta_p}$ . The problem of the firm setting the price at time  $t$  consists of choosing  $P_t(z)$  to maximize the expected discounted stream of profits:

$$E_t \sum_{i=0}^{\infty} (\theta_p \beta)^i \frac{MUC_{t+i}}{MUC_t} \left[ \frac{P_t(z)}{P_{t+i}} Y_{t,t+i}(z) - \frac{MC_{t+i}^N}{P_{t+i}} Y_{t,t+i}(z) \right] \quad (10)$$

subject to

$$Y_{t,t+i}(z) = \left[ \frac{P_t(z)}{P_{t+i}} \right]^{-\theta} Y_{t+i}. \quad (11)$$

In (11),  $Y_{t,t+i}(z)$  is the firm's demand function for its output at time  $t+i$ , conditional on the price set at time  $t$ ,  $P_t(z)$ . Market clearing insures that  $Y_{t,t+i}(z) = C_{t,t+i}(z)$  and  $Y_{t+i} = C_{t+i}$ . Substituting (11) into (10), the objective function can be written as

$$E_t \sum_{i=0}^{\infty} (\theta_p \beta)^i \frac{MUC_{t+i}}{MUC_t} \left\{ \left[ \frac{P_t(z)}{P_{t+i}} \right]^{1-\theta} Y_{t+i} - \frac{MC_{t+i}^N}{P_{t+i}} \left[ \frac{P_t(z)}{P_{t+i}} \right]^{-\theta} Y_{t+i} \right\}. \quad (12)$$

Since  $P_t(z)$  does not depend on  $i$ , the optimality condition is

$$P_t(z)E_t \sum_{i=0}^{\infty} (\theta_p \beta)^i MUC_{t+i} \left[ \frac{P_t(z)}{P_{t+i}} \right]^{1-\theta} Y_{t+i} = \mu E_t \sum_{i=0}^{\infty} (\theta_p \beta)^i MUC_{t+i} MC_{t+i}^N \left[ \frac{P_t(z)}{P_{t+i}} \right]^{1-\theta} Y_{t+i}, \quad (13)$$

where

$$\mu = \frac{\theta}{\theta - 1}$$

is the flexible-price level of the markup, which is also the markup that would be observed in a zero-inflation (zero money growth rate) steady state. To use rational expectations solution algorithms when the steady state money growth rate is non-zero, we must express the first order condition as a difference equation (see Ascari, 2004, and King and Wolman, 1996). This can be accomplished expressing  $P_t(z)$  as the ratio of two variables:

$$P_t(z) = \frac{G_t}{H_t},$$

and

$$G_t = \frac{(G_t/H_t)^{1-\theta}}{MUC_t} \hat{G}_t \quad (14)$$

$$H_t = \frac{(G_t/H_t)^{1-\theta}}{MUC_t} \hat{H}_t, \quad (15)$$

where

$$\hat{G}_t = \mu MUC_t MC_t P_t^{\theta-1} Y_t + \theta_p \beta \hat{G}_{t+1} \quad (16)$$

$$\hat{H}_t = MUC_t P_t^{\theta-1} Y_t + \theta_p \beta \hat{H}_{t+1}. \quad (17)$$

### Market Clearing

Since the measure of the economy is unitary, in the symmetric equilibrium it holds that  $M_t^j = M_t$ ,  $C_t^j = C_t$ , and the consumption shadow price is symmetric across households:  $MUC_t^j = MUC_t$ . Given that all firms are able to purchase the same labor service bundle, and so are charged the same aggregate wage, they all face the same marginal cost. The linear production technology ensures that  $MC$  is equal across firms—whether or not they are updating their price—regardless of the level of production, which will indeed be different. Firms are heterogeneous in that a fraction  $(1 - \theta_p)$  of firms in the interval  $[0, 1]$  can optimally choose the price charged at time  $t$ . In equilibrium each producer that chooses a new price  $P_t(z)$  in period  $t$  will choose the same new price  $P_t(z)$  and the same level of output. Thus the dynamics of the consumption-based price index will obey

$$P_t = \left[ \theta_p P_{t-1}^{1-\theta} + (1 - \theta_p) P_t(z)^{1-\theta} \right]^{\frac{1}{1-\theta}}. \quad (18)$$

Because firms charge different prices, aggregation implies  $Y_t \neq A_t N_t$ .<sup>3</sup> To see this, notice that (4) and (8) imply

$$Y_t(z) = \left[ \frac{P_t(z)}{P_t} \right]^{-\theta} C_t = A_t N_t(z).$$

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<sup>3</sup>We are grateful to Stephanie Schmitt-Grohe for pointing this out. See also Yun (1996).

Integrating over  $z$

$$\begin{aligned} A_t \int_0^1 N_t(z) dz &= \int_0^1 \left[ \frac{P_t(z)}{P_t} \right]^{-\theta} dz C_t \\ A_t N_t &= C_t \int_0^1 \left[ \frac{P_t(z)}{P_t} \right]^{-\theta} dz \\ A_t N_t &= C_t s_t, \end{aligned}$$

where  $s_t \equiv \int_0^1 \left[ \frac{P_t(z)}{P_t} \right]^{-\theta} dz$ . Up to a first order approximation,  $s_t = 1$ . But since we use higher order approximations, price dispersion results in the introduction of an additional state variable  $s_t$ . Its law of motion can be expressed recursively as

$$s_t = (1 - \theta_p) \left( \frac{\tilde{G}_t}{\tilde{H}_t} \right)^{-\theta} + \theta_p (1 + \pi_t)^\theta s_{t-1}.$$

Ravenna and Seppälä (2006) show that the inflation rate dynamics is given by

$$\begin{aligned} [(1 + \pi_t)]^{1-\theta} &= \theta_p + (1 - \theta_p) \left[ \frac{\tilde{G}_t}{\tilde{H}_t} (1 + \pi_t) \right]^{1-\theta} \\ \tilde{G}_t &\equiv \frac{\hat{G}_t}{P_t^\theta}; \quad \tilde{H}_t \equiv \frac{\hat{H}_t}{P_t^{\theta-1}}. \end{aligned} \tag{19}$$

In a steady state with gross money growth rate equal to  $\Upsilon$  and gross inflation equal to  $\Pi = \Upsilon$ ,

$$\begin{aligned} \frac{G}{HP_t} &= \frac{\tilde{G}}{\tilde{H}} = \frac{P_t(z)}{P_t} \\ \frac{P_t(z)}{P_t} &= \mu MC \frac{(1 - \theta_p \beta \Pi^{\theta-1})}{(1 - \theta_p \beta \Pi^\theta)}. \end{aligned} \tag{20}$$

Since  $P_t(z)$  is the optimal price chosen by the fraction of firms that can re-optimize at time  $t$ ,  $P_t(z)/P_t$  is the inverse of what King and Wolman (1996) define as the *price wedge*. With zero steady state inflation, the steady state average markup is equal to  $1/MC$ , so there is no price wedge. But when steady state inflation is positive, the price wedge is less than one: the average price is always smaller than the optimal price, since some firms would like to increase the price but are constrained from doing so. Combining equation (20) with equation (19) yields the steady state marginal cost and price wedge as a function of  $\Pi$ :

$$\begin{aligned} \frac{\tilde{G}}{\tilde{H}} &= \left[ \frac{(1 - \theta_p)}{(1 - \theta_p \Pi^{\theta-1})} \right]^{\frac{1}{\theta-1}} \\ MC &= \frac{1}{\mu} \left[ \frac{\Pi^{1-\theta} - \theta_p}{1 - \theta_p} \right]^{\frac{1}{1-\theta}} \frac{1}{\Pi} \frac{(1 - \theta_p \beta \Pi^\theta)}{(1 - \theta_p \beta \Pi^{\theta-1})} \end{aligned}$$

## Asset Markets

The government rebates seigniorage revenues to the household in the form of lump-sum transfers, so that in any time  $t$  the government budget is balanced. Since we defined in equation (3)  $\tau^j$  as the amount of tax levied by the government on household  $j$ , assuming  $\tau_t^j = \tau_t^i \forall j, i \in [0, 1]$ , at every date  $t$  the transfer will be equal to

$$\begin{aligned} - \int_0^1 \tau_t^j dj &= -\tau_t \int_0^1 dj = \\ &= -\tau_t = M_t^s - M_{t-1}^s. \end{aligned}$$

Equilibrium in the money market requires that

$$M_t^s = M_t^{d^j} = M_t^d.$$

We assume the monetary policy instrument is the short term nominal interest rate  $(1 + R_{1,t})$ . The money supply is set by the monetary authority to satisfy whatever money demand is consistent with the target rate.

Bonds are in zero-net supply, since the government does not issue bonds. Therefore in equilibrium it must hold that

$$B_{t,i} = 0$$

for any component of the vector  $\vec{B}_t$ .

## Monetary Policy

The economy's dynamics are driven by business cycle shocks temporarily away from the non-stochastic steady state. In such instances, the domestic monetary authority follows a forward-looking, instrument feedback rule:

$$\frac{(1 + \bar{R}_{t,t+1})}{(1 + R^{ss})} = E_t \left( \frac{1 + \pi_{t+1}}{1 + \pi_{SS}} \right)^{\omega_\pi} \left( \frac{Y_t}{Y_{SS}} \right)^{\omega_y}. \quad (21)$$

where  $\omega_\pi, \omega_y \geq 0$  are the feedback coefficients for CPI inflation and output. The monetary authority adjusts the interest rate in response to deviations of target variables from the steady state. In the steady state, a constant money growth rate rule is followed. Choosing parameters  $\omega_\pi, \omega_y$  allows us to specify alternative monetary policies. When the central bank responds to current rather than expected inflation equation (21) yields the rule suggested by Taylor (1993) as a description of U.S. monetary policy.

We assume the central bank assigns positive weight to an interest rate smoothing objective, so that the domestic short-term interest rate at time  $t$  is set according to

$$(1 + R_{1,t}) = [(1 + \bar{R}_{t,t+1})]^{(1-\chi)} [(1 + R_{t-1,1})]^\chi \varepsilon_t^{mp}, \quad (22)$$

where  $\chi \in [0, 1)$  is the degree of smoothing and  $\varepsilon_t^{mp}$  is an unanticipated exogenous shock to monetary policy.

### 3. Algorithm

We solve the model using a third-order approximation around the non-stochastic steady state. The numerical solution is obtained using Dynare++.<sup>4</sup> It is well known that taking a first-order approximation of bond prices will yield no risk premia and that a second-order approximation will yield only constant premia. The reason is simple: second-order approximation involves only squared prediction error terms with constant expectations.

In the first step, we solve our model by third-order approximation for six state variables and seven control variables in 13 equations using Dynare++ version 1.3.1. In the second step, we generate 200,000 observations of state and control variables. In the final step, we regress the future marginal rates of substitution—see equations (25) and (26) below—on third-order complete polynomials of state variables using fitted regression to approximate conditional expectations. Our approach is very similar to the Monte Carlo approach employed by Evans and Marshall (1998). The algorithm amounts to taking a third-order approximation of bond prices. With third-order approximation, the current state variables multiply squared prediction error terms, and hence risk premia are time-varying.

### 4. Model Parameterization

Our specification of preference, technology and policy parameters follows the New Keynesian monetary business cycle literature.<sup>5</sup> Household preferences are modeled within the internal habit-formation framework of Boldrin, Christiano, and Fisher (2001). The habit formation coefficient is parameterized to  $b = 0.8$ , a value that Constantinides (1990) finds can explain the equity premium puzzle. The value of  $\gamma$  is set at 2.5, to provide adequate curvature in the utility function so as to facilitate model generation of risk-premia volatility. The preference parameterization plays a key role in the model's term-structure properties. Its impact on the results is discussed in detail in the next section. The labor supply elasticity ( $1/\eta$ ) is set equal to 2. The parameter  $\ell$  is chosen to set steady state labor hours at about 30% of available time, a value consistent with postwar data in the U.S. and in many OECD countries. The quarterly discount factor  $\beta$  is parameterized so that the steady state real interest rate is equal to 1%.

The parameterization of demand elasticity  $\theta$  implies a flexible-price equilibrium producers' markup of  $\mu = \theta/(\theta - 1) = 1.1$ . While Bernanke and Gertler (2000) use a higher value (1.2), our assumption of positive steady state inflation implies that the steady state markup is larger than in the flexible-price equilibrium. The parameterization chosen for the Calvo (1983) pricing adjustment mechanism implies an average price duration of one year. This value is in line with estimates for the U.S. over the last forty years obtained from aggregate data (Gali and Gertler, 1999, Rabanal and Rubio-Ramirez, 2005).

A large number of variants of the monetary policy instrument rule (22) have been estimated

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<sup>4</sup>Dynare++ is available for free at <http://www.cepremap.cnrs.fr/dynare>.

<sup>5</sup>Numerous authors discuss the empirical performance of the New Keynesian framework. For references to estimated and calibrated staggered price-adjustment models, see Christiano, Eichenbaum and Evans (2005), Ireland (2001), Ravenna (2006), Rabanal and Rubio-Ramirez (2005), Woodford (2003).

with U.S. data, in both single-equation and simultaneous-equation contexts. The inflation feedback coefficient  $\omega_\pi$  is set at 1.5. This value is substantially lower than the one estimated by Clarida, Gali and Gertler (2000) for the Volker-Greenspan tenure, but close to the estimate in Rabanal and Rubio-Ramirez (2005) for the longer 1960–2001 period and averages across different monetary regimes in post-war U.S. data. The choice of a value for  $\omega_y$  is more controversial; it depends on the operational definition of output gap used by the central bank at any given point in time. In our benchmark parameterization we choose a value of  $\omega_y = 0$ . Estimates of instrument rules across a large number of OECD countries consistently find very inertial behavior for the policy interest rate. In our model the smoothing parameter  $\chi$  is assumed equal to 0.9, a value consistent with available estimates. In the following sections we discuss the impact of alternative assumptions for behavior of the monetary authority on the term structure results. Quarterly steady state inflation is set equal to the average U.S. value over the period 1994 – 2004, about 0.75%. This implies an annualized steady state nominal interest rate of 7%.

The preference and technology exogenous shocks follow an AR(1) process:

$$\log Z_t = (1 - \rho_Z) \log \bar{Z} + \rho_Z \log Z_{t-1} + \varepsilon_t^Z, \quad \varepsilon_t^Z \sim \text{iid } N(0, \sigma_Z^2);$$

where  $\bar{Z}$  is the steady state value of the variable. The policy shock  $\varepsilon_t^{mp}$  is a Gaussian i.i.d. stochastic process. The autocorrelation parameters for technology and preference shocks are equal to  $\rho_a = 0.9$  and  $\rho_d = 0.95$ . The standard deviation of innovations  $\varepsilon_t^Z$  for technology, preference and policy shock is set at  $\sigma_a = 0.0035$ ,  $\sigma_d = 0.08$ ,  $\sigma_{mp} = 0.003$ . The low value for policy shock volatility implies that the major part of the short term nominal interest rate dynamics is driven by the systematic monetary policy reaction to the state of the economy. The preference shock volatility is large but very close to that estimated by Rabanal and Rubio-Ramirez (2005) with U.S. data. Compared to the business cycle literature, the technology shock volatility is low. The chosen parameterization is necessary to allow the model to generate a positive correlation between nominal interest rate and GDP, since technology shocks produce negative comovements between these variables.

An important concern in the parameterization of shocks has been to match the correlations between output and nominal and real rates with U.S. data, to be able to evaluate whether the term structure generated by the model can predict output variation, as in many empirical studies of the U.S. Table 1 compares the model’s second moments and correlations with output to the U.S. post-war data sample.<sup>6</sup> This sample is heterogeneous with respect to U.S. monetary policy goals and U.S. Federal Reserve operating procedures, and includes the 1970s inflationary episode. On the other hand, the sample can be considered representative of the variety of shocks that drove the U.S. business cycle.

The match with empirical correlations is quite good. To obtain this result the model volatilities for output, real interest rate and inflation turn out to be larger than in the data. The empirical fit of the model can be improved with a number of modifications, including sticky wages, hybrid backward and forward-looking price setting specifications, an autocorrelated exogenous process driving the

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<sup>6</sup>Standard deviation measured in per cent. The output series is logged and Hodrick-Prescott filtered. U.S. data:  $Y_t$  is real GDP,  $\pi_t$  is CPI inflation,  $R_t$  is 3-month T-bill rate,  $r_t$  is ex-post short term real interest rate. All rates are on annual basis. Quarterly data sample is 1952:1–2006:1. We chose to use the period following the Treasury-Federal Reserve Accord of 1951 in order to avoid having to contend with the constraint on interest rate movements imposed by the Federal Reserve’s “par pegging” of Government securities prices. Real GDP is from the Bureau of Economic Analysis and the rest of the data are from the St. Louis Federal Reserve Bank FRED II database.

Table 1: Selected variable volatilities and correlations. Sample: 1952–2006.

| Variable | <i>Standard Deviation</i> |           | <i>Correlation with Output</i> |           |
|----------|---------------------------|-----------|--------------------------------|-----------|
|          | Model                     | U.S. Data | Model                          | U.S. Data |
| $Y_t$    | 2.01                      | 1.59      | 1                              | 1         |
| $\pi_t$  | 3.49                      | 3.00      | 0.20                           | 0.19      |
| $R_t$    | 1.84                      | 2.82      | 0.17                           | 0.17      |
| $r_t$    | 3.84                      | 2.32      | −0.08                          | −0.13     |

dynamics of the inflation target, and cost-push shocks. Our effort focused on investigating whether a minimal set of modifications to the Neoclassical growth model can explain the behavior of risk premia over the business cycle. In the following sections we compare the parameterized model predictions to the U.S. post-war nominal term structure. Most of the stylized facts we investigate are consistent across monetary policy regime changes during this period, and so we rely on a single parameterization for the policy rule. The sensitivity analysis shows that most results are surprisingly robust to alternative parameterization assumptions.

## 5. Term Structure of Nominal Interest Rates

### *Real and Nominal Term Structures*

Let  $q_{t+1}$  denote the real stochastic discount factor

$$q_{t+1} \equiv \beta \frac{MUC_{t+1}}{MUC_t}, \quad (23)$$

and let  $Q_{t+1}$  denote the nominal stochastic discount factor

$$Q_{t+1} \equiv \beta \frac{MUC_{t+1}}{MUC_t} \frac{P_t}{P_{t+1}}. \quad (24)$$

The price of an  $n$ -period zero-coupon real bond is given by

$$\begin{aligned} p_{n,t}^b &= E_t \left[ \prod_{j=1}^n q_{t+j} \right] \\ &= E_t [q_{t+1} p_{n-1,t+1}^b], \end{aligned} \quad (25)$$

and similarly the price of an  $n$ -period zero-coupon nominal bond is given by

$$\begin{aligned} p_{n,t}^B &= E_t \left[ \prod_{j=1}^n Q_{t+j} \right] \\ &= E_t [Q_{t+1} p_{n-1,t+1}^B]. \end{aligned} \quad (26)$$

The bond prices are invariant with respect to time; hence equations (25) and (26) give a recursive formula for pricing zero-coupon real and nominal bonds of any maturity.

Forward prices for real bonds are defined by

$$p_{n,t}^f = \frac{p_{n+1,t}^b}{p_{n,t}^b}.$$

Prices are related to rates (or yields) by<sup>7</sup>

$$f_{n,t} = -\log(p_{n,t}^f) \quad \text{and} \quad r_{n,t} = -(1/n) \log(p_{n,t}^b). \quad (27)$$

Table 2 presents means, standard deviations, and correlations with output for selected maturities in the term structure in the model, and for U.S. nominal data as estimated by Global Financial Data from the first quarter of 1952 to the first quarter of 2006. Output is filtered using the Hodrick-Prescott (1980) filter with a smoothing parameter of 1600 in both the model and the data.

The average term structure is upward-sloping in both the model and the data. Means match quite well: the model produces nominal yields varying from 5.01% to 6.60% for three months to 20 years maturity, while the corresponding U.S. yields varied from 5.03% to 6.60%.

Table 2 shows that the model generates procyclical nominal interest rates and countercyclical term spreads. This matches the positive correlation between yields and the cyclical component of output observed in U.S. data at maturities up to one year. The nominal term spreads are countercyclical in both U.S. data and the model at all maturities.

These results show that the New Keynesian model can explain the term spread puzzle that emerges in the Neoclassical stochastic growth model. Donaldson, Johnsen, and Mehra (1990) show that in a stochastic growth model with full depreciation the term structure of (ex-ante) real interest rates is at odds with empirical evidence: it rises at the peak of the business cycle and falls at the trough. In addition, at the peak of the cycle the term structure lies uniformly below the term structure at the trough. The economic intuition for the behavior of interest rates is straightforward, working through the link between marginal utility of consumption, expected consumption growth and interest rates. At the cycle peak aggregate and individual consumption are expected to be, on average, lower in the future, and so the agents will want to save more. In equilibrium interest rates will therefore be lower. At the cycle trough aggregate and individual consumption are expected to be higher in the future, and so agents' incentive to save is reduced, which raises interest rates. Similar intuition explains the model's procyclical term spread.

Donaldson, Johnsen, and Mehra (1990) results are not general (Labadie, 1994). Introducing exogenous shocks, in addition to the stochastic process for total factor productivity, can generate procyclical interest rates (Walsh, 2003 gives an example in a money-in-utility framework). Yet even the models examined by King and Watson (1996), despite generating procyclical interest rates, cannot account for the empirical fact that high real or nominal interest rates predict a low level of economic activity two to four quarters in the future.

The New Keynesian model is not able to reproduce two important features of post-war U.S. data: constant volatility and decreasing correlation with output of nominal yields as the maturity increases. The model produces a downward-sloping term structure of volatilities and strong positive

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<sup>7</sup>Nominal prices and rates are obtained in a similar manner.

Table 2: Main term structure statistics. Data: 1952–2006. (N/A missing due to shortage of data.)

|                               | Mean    | Standard Deviation | Correlation with Output |
|-------------------------------|---------|--------------------|-------------------------|
| $R_{1,t}$ (model)             | 5.01198 | 1.84042            | 0.16560                 |
| $R_{4,t}$ (model)             | 6.22698 | 1.40906            | 0.25269                 |
| $R_{40,t}$ (model)            | 6.59399 | 0.56985            | 0.40510                 |
| $R_{80,t}$ (model)            | 6.59911 | 0.33910            | 0.40896                 |
| $R_{120,t}$ (model)           | 6.59905 | 0.22477            | 0.40717                 |
| $R_{1,t}$ (data)              | 5.03359 | 2.81717            | 0.17491                 |
| $R_{4,t}$ (data)              | 5.60977 | 3.05969            | 0.14690                 |
| $R_{40,t}$ (data)             | 6.42456 | 2.76373            | −0.01473                |
| $R_{80,t}$ (data)             | 6.60014 | 2.71775            | −0.04062                |
| $R_{120,t}$ (data)            | N/A     | N/A                | N/A                     |
| $R_{40,t} - R_{1,t}$ (model)  | 1.58202 | 1.50547            | −0.04911                |
| $R_{80,t} - R_{1,t}$ (model)  | 1.58713 | 1.63395            | −0.10166                |
| $R_{120,t} - R_{1,t}$ (model) | 1.58707 | 1.70057            | −0.12540                |
| $R_{40,t} - R_{4,t}$ (model)  | 0.36702 | 0.98454            | −0.12717                |
| $R_{80,t} - R_{4,t}$ (model)  | 0.37213 | 1.14983            | −0.18905                |
| $R_{120,t} - R_{4,t}$ (model) | 0.37207 | 1.23425            | −0.21433                |
| $R_{40,t} - R_{1,t}$ (data)   | 1.39097 | 1.13509            | −0.46998                |
| $R_{80,t} - R_{1,t}$ (data)   | 1.56654 | 1.32127            | −0.45650                |
| $R_{120,t} - R_{1,t}$ (data)  | N/A     | N/A                | N/A                     |
| $R_{40,t} - R_{4,t}$ (data)   | 0.81479 | 1.01890            | −0.48109                |
| $R_{80,t} - R_{4,t}$ (data)   | 0.99037 | 1.24971            | −0.44800                |
| $R_{120,t} - R_{4,t}$ (data)  | N/A     | N/A                | N/A                     |

Table 3: Selected term structure statistics in selected time periods.

|                                        | 1952–2006 | 1960–2006 | 1980–2006 | 1988–2006 |
|----------------------------------------|-----------|-----------|-----------|-----------|
| $E[R_{4,t}]$                           | 5.60977   | 6.15297   | 6.47552   | 4.87137   |
| $E[R_{40,t}]$                          | 6.42456   | 6.99016   | 7.65848   | 6.15603   |
| $E[R_{40,t} - R_{4,t}]$                | 0.81479   | 0.83719   | 1.18295   | 1.28466   |
| $\text{std}(R_{4,t})$                  | 3.05969   | 2.96079   | 3.44313   | 2.08718   |
| $\text{std}(R_{40,t})$                 | 2.76373   | 2.59025   | 2.92400   | 1.56503   |
| $\text{std}(R_{40,t} - R_{4,t})$       | 1.01890   | 1.07935   | 1.12390   | 1.06067   |
| $\text{corr}(R_{4,t}, Y_t)$            | 0.14690   | 0.18143   | 0.07312   | 0.57920   |
| $\text{corr}(R_{40,t}, Y_t)$           | -0.01473  | 0.00426   | -0.06326  | 0.29255   |
| $\text{corr}(R_{40,t} - R_{4,t}, Y_t)$ | -0.48109  | -0.48747  | -0.38859  | -0.70809  |

correlation between yields and (the cyclical component of) output at all maturities. The decreasing volatility of nominal rates is a counterfactual implication already identified by Den Haan (1995) for flexible-price models of the business cycle.

Interestingly, the model predictions of term structure of volatilities and correlation between yields and output get closer to the data as the sample is restricted to the more recent period. Table 3 presents selected term structure statistics for the samples 1952:1–2006:1, 1960:1–2006:1, 1980:1–2006:1, and 1988:1–2006:1.

In both the 1980–2006 and 1988–2006 samples, the term structure of volatilities is clearly downward-sloping.<sup>8</sup> In the 1988–2006 sample, the correlation between yield and output is strongly positive. The upward-sloping mean term structure and countercyclical term spreads are robust features across subsamples. On the other hand, the level of interest rates depends on how much relatively high interest rates in the early 1980’s weigh on the data. The average one-year rate was 160 basis points higher in 1980–2006 compared to 1988–2006.

The high volatility of long rates observed in the full sample is associated in the data with periods of volatile inflation. What the New Keynesian model is missing is a mechanism to generate persistent changes in the inflation rate target, implying persistent changes in the expected future policy rate. As it is, the model necessarily generates strongly mean-reverting interest rates. This also means that the impact of policy shocks on long rates is much smaller than on short rates, and that the correlation between policy rate and long yields decreases with time. Adding to the model a very persistent shock to the policy inflation target, as in Rudebusch and Wu (2004) or Hördahl, Tristani, and Vestin (2005), would contribute to an increase in the volatility of long rates. Similarly, a varying long-term inflation target would lower the correlation between long maturity yields and output. Additionally, the output-nominal yields correlation would be lowered in a more realistic model including time-to-build constraints, convex costs of capital adjustment, and lags in the impact of monetary policy on real variables.

Ravenna and Seppälä (2006) perform extensive sensitivity analysis for the model.

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<sup>8</sup>Seppälä (2000) documents that UK nominal and real term structure of volatilities is downward-sloping.

Table 4: Term spread forecasts of future consumption growth  $n$  years ahead.

| Regression            | $\beta_0$ | $se(\beta_0)$ | $\beta_1$ | $se(\beta_1)$ | $R^2$  |
|-----------------------|-----------|---------------|-----------|---------------|--------|
| Benchmark ( $n = 1$ ) | -0.1997   | 0.0070        | 0.5468    | 0.0070        | 0.0307 |
| Benchmark ( $n = 2$ ) | -0.1866   | 0.0059        | 0.5112    | 0.0059        | 0.0379 |
| Benchmark ( $n = 3$ ) | -0.1827   | 0.0050        | 0.5007    | 0.0050        | 0.0493 |
| Benchmark ( $n = 4$ ) | -0.1766   | 0.0043        | 0.4841    | 0.0044        | 0.0605 |
| Data ( $n = 1$ )      | 2.6826    | 0.1694        | 0.5063    | 0.1131        | 0.1193 |
| Data ( $n = 2$ )      | 2.8213    | 0.1471        | 0.3499    | 0.0974        | 0.0824 |
| Data ( $n = 3$ )      | 2.9405    | 0.1248        | 0.1622    | 0.0852        | 0.0233 |
| Data ( $n = 4$ )      | 3.0832    | 0.0979        | 0.0084    | 0.0675        | 0.0001 |

### *Term Structure Predictions of Future Economic Activity*

Every major recession in the U.S. since the early 1950s has been predicted by an inverted (downward-sloping) term structure of interest rates.<sup>9</sup> As discussed above, the stochastic growth model with flexible prices produces the opposite prediction. The New Keynesian model can explain the term spread forecasting power found in empirical studies.

We compare the New Keynesian model's predictions with one well-known paper on the relationship between term spread and future consumption growth. Estrella and Hardouvelis (1991) use the term spread to predict future changes in log consumption growth one to four years ahead. The estimation equation uses quarterly observations of U.S. real consumption of non-durables and services over the 1960:1-2006:1 sample regressed on the yield spread between 10-year government bond and 3-month Treasury bill.<sup>10</sup> Table 4 presents the regression results of equation

$$(100/n) * (\log(c_{t+n}) - \log(c_t)) = \beta_0 + \beta_1(r_{10,t} - r_{1,t}) \quad \text{for } n = 1, 2, 3, 4 \text{ years}$$

for the data and the benchmark model with 200,000 observations. The standard errors are White (1980) heteroskedasticity consistent standard errors. An upward-sloping term structure clearly predicts expansions in both our model and the data, and a downward-sloping term structure clearly predicts recessions, in both the model and the data. Moreover,  $\beta_1$  decreases with the forecast horizon in both the model and the data.

<sup>9</sup>A large literature has examined the predictive power of the term structure of interest rates for future interest rates, consumption growth, and other measures of future economic activity. Fama and Bliss (1987) use forward spread to predict future changes in one-year interest rates one to four years ahead. Estrella and Hardouvelis (1991) show that the term spread has predictive power for future changes in log-consumption growth up to four years ahead in US data from 1955 to 1988. Dotsey (1998) points out that many studies have found the term spread to contain significant information for predicting economic activity also in the most recent U.S. data. Estrella (2005) provides an exhaustive list of references.

<sup>10</sup>Consumption data are from the St. Louis Federal Reserve Bank FRED II database. Yield data are from Global Financial Data.

To define the risk premium, write (26) for a two-period bond using the conditional expectation operator and its properties:

$$\begin{aligned} p_{t,2}^B &= E_t[Q_{t+1}p_{1,t+1}^B] \\ &= E_t[Q_{t+1}]E_t[p_{1,t+1}^B] + \text{cov}_t[Q_{t+1}, p_{1,t+1}^B] \\ &= p_{1,t}^B E_t[p_{1,t+1}^B] + \text{cov}_t[Q_{t+1}, p_{1,t+1}^B], \end{aligned}$$

which implies that

$$p_{1,t}^F = \frac{p_{t,2}^B}{p_{1,t}^B} = E_t[p_{1,t+1}^B] + \text{cov}_t\left[Q_{t+1}, \frac{p_{1,t+1}^B}{p_{1,t}^B}\right]. \quad (28)$$

Since the conditional covariance term is zero for risk-neutral investors, we call it the *risk premium* for the one-period nominal forward contract,  $nrp_{1,t}$ , given by

$$nrp_{1,t} \equiv -\text{cov}_t\left[Q_{t+1}, \frac{p_{1,t+1}^B}{p_{1,t}^B}\right] = E_t[p_{1,t+1}^B] - p_{1,t}^F,$$

and similarly  $nrp_{n,t}$  is the risk premium for the  $n$ -period forward contract:

$$nrp_{n,t} \equiv -\text{cov}_t\left[\prod_{j=1}^n Q_{t+j}, \frac{p_{t+n,1}^B}{p_{1,t}^B}\right] = E_t[p_{t+n,1}^B] - p_{n,t}^F.$$

If the risk premium is zero, we obtain the oldest and simplest theory about the information content of the term structure—the so-called (pure) expectations hypothesis. According to the pure expectations hypothesis, forward rates are unbiased predictors of future spot rates. It is also common to modify the theory so that a constant risk-premium is allowed. This prediction has come to be known in the literature as the expectations hypothesis. By and large the empirical literature rejects both versions of the expectations hypothesis.

We use as a benchmark the Backus, Gregory, and Zin (1989) test equation.<sup>11</sup> These authors tested the expectations hypothesis in the complete markets endowment economy. Equation (28) and the assumption of a constant risk premium implies that

$$E_t[p_{1,t+1}^B] - p_{1,t}^F = \beta_0,$$

Therefore the regression

$$p_{1,t+1}^B - p_{1,t}^F = \beta_0 + \beta_1(p_{1,t}^F - p_{1,t}^B) \quad (29)$$

should yield  $\beta_1 = 0$ . Backus, Gregory, and Zin (1989) generated 1000 samples of 200-period paths for the endogenous variables and used a Wald test with White (1980) standard errors to

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<sup>11</sup>Both versions of the expectations hypothesis are only approximately correct. To see this, assume that agents are risk-neutral:  $\gamma = 0$ . Equation (28) then reduces to  $p_{1,t}^F = E_t[p_{1,t+1}^B]$  and from (27) we obtain  $\exp^{-f_{1,t}} = E_t[\exp^{-r_{1,t+1}}]$ . Jensen's inequality implies that  $f_{1,t} < E_t[r_{1,t+1}]$ . The difference between left and right hand sides of this equation is known as *convexity bias* and it varies with  $E_t[r_{1,t+1}]$  and  $\text{var}_t[r_{1,t+1}]$ . To avoid this issue, Backus, Gregory, and Zin (1989) test the expectations hypothesis using bond prices rather than bond yields.

Table 5: Number of rejects for each regression in benchmark model for nominal term structure.

| $y_{t+1}$                               | $p_{1,t+1}^B - p_{1,t}^F$ | $p_{1,t+1}^B - p_{1,t}^F - nrp_{1,t}$ |
|-----------------------------------------|---------------------------|---------------------------------------|
| $x_t$                                   | $p_{1,t}^F - p_{1,t}^B$   | $p_{1,t}^F - p_{1,t}^B$               |
| <i>Wald</i> ( $\beta_0 = \beta_1 = 0$ ) | 1000                      | 67                                    |
| <i>Wald</i> ( $\beta_1 = 0$ )           | 989                       | 63                                    |
| <i>Wald</i> ( $\beta_1 = -1$ )          | 1000                      | 1000                                  |

Table 6: Number of rejects for each regression in nominal term structure when  $b = 0$ .

| $y_{t+1}$                               | $p_{1,t+1}^B - p_{1,t}^F$ | $p_{1,t+1}^B - p_{1,t}^F - nrp_{1,t}$ |
|-----------------------------------------|---------------------------|---------------------------------------|
| $x_t$                                   | $p_{1,t}^F - p_{1,t}^B$   | $p_{1,t}^F - p_{1,t}^B$               |
| <i>Wald</i> ( $\beta_0 = \beta_1 = 0$ ) | 172                       | 68                                    |
| <i>Wald</i> ( $\beta_1 = 0$ )           | 181                       | 66                                    |
| <i>Wald</i> ( $\beta_1 = -1$ )          | 996                       | 999                                   |

check whether  $\beta_1 = 0$  at the 5% significance level. They could reject the hypothesis only roughly 50 times out of 1000 regressions, which is what one would expect from chance alone. On the other hand, for all values of  $\beta_1$  except  $-1$ , the forward premium is still useful in forecasting changes in spot prices. The hypothesis  $\beta_1 = -1$  was rejected every time.

Table 5 presents the number of rejections of different Wald tests in the regressions

$$y_{t+1} = \beta_0 + \beta_1 x_t$$

in our benchmark model for nominal term structure. Table 6 presents the same tests when the habit-formation parameter  $b = 0$ . Table 7 displays the same tests for real term structure, and table 8 displays the test for real term structure when  $b = 0$ . Only the benchmark model is consistent with empirical evidence on the expectations hypothesis. When the risk premium is subtracted from  $p_{1,t+1}^B - p_{1,t}^F$  the hypothesis that  $\beta_1$  is equal to zero can be rejected in less than 10% of the samples. Comparing the tables, is clear that habit-formation is a necessary condition for rejection of the expectations hypothesis. However, since the hypothesis is rejected for the real term structure only about 40% of the time, it is the case that monetary policy—which directly affects nominal rates—plays also an important role.

Table 9 presents estimates of (29) over U.S. nominal term structure data and 200,000 model-generated data. The data include quarterly observations of 3 and 6-month U.S. Treasury bills from 1960:1 to 2006:1. In Table 9, *Wald* rows refer to the marginal significance level of the corresponding Wald test. The regression coefficient  $\beta_1$  implied by the New Keynesian model is remarkably close to the value obtained with U.S. data.

Table 7: Number of rejects for each regression in benchmark model for real term structure.

| $y_{t+1}$                     | $p_{1,t+1}^b - p_{1,t}^f$ | $p_{1,t+1}^b - p_{1,t}^f - rr p_{1,t}$ |
|-------------------------------|---------------------------|----------------------------------------|
| $x_t$                         | $p_{1,t}^f - p_{1,t}^b$   | $p_{1,t}^f - p_{1,t}^b$                |
| $Wald(\beta_0 = \beta_1 = 0)$ | 1000                      | 66                                     |
| $Wald(\beta_1 = 0)$           | 424                       | 74                                     |
| $Wald(\beta_1 = -1)$          | 1000                      | 1000                                   |

Table 8: Number of rejects for each regression in real term structure when  $b = 0$ .

| $y_{t+1}$                     | $p_{1,t+1}^b - p_{1,t}^f$ | $p_{1,t+1}^b - p_{1,t}^f - rr p_{1,t}$ |
|-------------------------------|---------------------------|----------------------------------------|
| $x_t$                         | $p_{1,t}^f - p_{1,t}^b$   | $p_{1,t}^f - p_{1,t}^b$                |
| $Wald(\beta_0 = \beta_1 = 0)$ | 75                        | 54                                     |
| $Wald(\beta_1 = 0)$           | 69                        | 64                                     |
| $Wald(\beta_1 = -1)$          | 1000                      | 1000                                   |

Table 9: Tests of expectations hypothesis in a single regression.

| Variable/Test                 | Benchmark Real | Benchmark Nominal | Data       |
|-------------------------------|----------------|-------------------|------------|
| $\beta_0$                     | 0.0030         | 0.0023            | 0.0126     |
| $se(\beta_0)$                 | 0.0000         | 0.0000            | 0.0040     |
| $\beta_1$                     | -0.2588        | -0.4248           | -0.4486    |
| $se(\beta_1)$                 | 0.0044         | 0.0031            | 0.1098     |
| $R^2$                         | 0.0204         | 0.1700            | 0.0961     |
| $Wald(\beta_0 = \beta_1 = 0)$ | 0              | 0                 | 0          |
| $Wald(\beta_1 = 0)$           | 0              | 0                 | 4.365e-005 |
| $Wald(\beta_1 = -1)$          | 0              | 0                 | 5.1e-007   |

## 6. The Term Structures of Expected Inflation, Real Interest Rates, and Inflation Risk Premia

Recall the definitions of one-period zero-coupon nominal bond (26) and nominal stochastic discount factor (24)

$$p_t^B = E_t[Q_{t+1}] = E_t \left[ \beta \frac{MUC_{t+1} P_t}{MUC_t P_{t+1}} \right]. \quad (30)$$

To define the inflation risk premium, write (30) using the definition of conditional covariance and the definition of real bond price (25):

$$\begin{aligned} p_t^B &= E_t \left[ \beta \frac{MUC_{t+1} P_t}{MUC_t P_{t+1}} \right] \\ &= E_t \left[ \beta \frac{MUC_{t+1}}{MUC_t} \right] E_t \left[ \frac{P_t}{P_{t+1}} \right] + \text{cov}_t \left[ \beta \frac{MUC_{t+1}}{MUC_t}, \frac{P_t}{P_{t+1}} \right] \\ &= p_t^b E_t \left[ \frac{P_t}{P_{t+1}} \right] + \text{cov}_t \left[ q_{t+1}, \frac{P_t}{P_{t+1}} \right]. \end{aligned}$$

Since the conditional covariance term is zero for risk-neutral investors and when the inflation process is deterministic, we call it the *inflation risk premium*,  $irp_{1,t}$ , given by

$$irp_{1,t} \equiv \text{cov}_t \left[ q_{t+1}, \frac{P_t}{P_{t+1}} \right] = p_t^B - p_t^b E_t \left[ \frac{P_t}{P_{t+1}} \right],$$

and similarly  $irp_{n,t}$  is the  $n$ -period inflation risk premium:

$$irp_{n,t} \equiv \text{cov}_t \left[ \prod_{j=1}^n q_{t+j}, \frac{P_t}{P_{t+n}} \right] = p_{n,t}^B - p_{n,t}^b E_t \left[ \frac{P_t}{P_{t+n}} \right].$$

Assuming that the inflation risk premium is zero, we get the Fisher hypothesis:

$$p_{n,t}^B = p_{n,t}^b E_t \left[ \frac{P_t}{P_{t+n}} \right]$$

or by taking logs and multiplying by  $-(1/n)$ :

$$R_{n,t} \approx r_{n,t} + \frac{1}{n} E_t \left[ \log \left( \frac{P_{t+n}}{P_t} \right) \right].$$

That is, the nominal interest rate equals the sum of the (ex-ante) real interest rate and the average expected inflation.

We define

$$epi_{n,t} \equiv \frac{1}{n} E_t \left[ \log \left( \frac{P_{t+n}}{P_t} \right) \right],$$

and inflation term premium to be the difference between nominal interest rates and the sum of real interest rates and average expected inflation:

$$itp_{n,t} \equiv R_{n,t} - r_{n,t} - epi_{n,t}.$$

Table 10 presents the main statistics for the term structure of real interest rates, average expected inflation, inflation risk premia and inflation term premia in the benchmark case. Since average expected inflation is nearly constant as a function of maturity and inflation term premia very small, average term structure of real interest rates follows exactly the same pattern as the average term structure of nominal interest rates in Table 2. Both inflation risk and term premia are very small and very constant.

While average risk premia are always positive, average term premia are always negative. Figures 1–6 display impulse response functions to one standard deviation preference, productivity, and monetary policy shocks. They show that positive preference shock which increases inflation decreases inflation risk premium. That is, as inflation increases inflation risk premium becomes more negative or larger. On the other hand, inflation term premium increases. Similarly, positive productivity shock decreases both inflation, inflation term premium, and the size of inflation risk premium (moves it closer to zero). Finally, positive monetary policy shock decreases inflation, inflation term premium and the size of inflation risk premium.

There seems to be a negative relationship between inflation term premia and inflation risk premia, a positive relationship between inflation term premia and expected inflation, and a negative relationship between inflation risk premia and expected inflation. This is confirmed in Table 11. These correlations are  $-0.99831$ ,  $0.96792$ , and  $-0.96200$ , respectively for  $n = 1$ . For longer maturities, they are a bit less in absolute value, but still highly significant. Notice also that nominal interest rates and average expected inflation are negatively correlated for short maturities, but positively correlated for long maturities.

Table 11 also reports that the real interest rates and expected inflation are significantly negatively correlated. This result was also obtained by Pennacchi (1991) who estimated both as a state-space system using observations on the term structure of nominal interest rates and NBER-ASA survey forecasts of inflation. Pennacchi also finds that real interest rates display greater volatility than expected inflation. Table 10 reports that both the standard deviation and coefficient of variation are significantly greater for the short-maturity real interest rates than for the expected inflation.

### *Sensitivity Analysis*

Tables 12–15 report selected correlations under different parameterizations. They reveal the robustness of our earlier conclusions:

1. Short-term real interest rates display greater volatility than expected inflation.
2. Nominal interest rates and expected inflation are negatively correlated for short maturities.
3. Inflation risk and term premia are very small and very constant.
4. Inflation risk premia are on average negative and inflation term premia are on average positive.
5. Short-term real interest rates and expected inflation are significantly negatively correlated.
6. Inflation risk premia and expected inflation are significantly negatively correlated.
7. Inflation term premia and expected inflation are significantly positively correlated.

Table 10: Main inflation statistics for real interest rates, average expected inflation, and inflation risk and term premia, benchmark case.

|              | Mean     | Standard Deviation | Correlation with Output |
|--------------|----------|--------------------|-------------------------|
| $r_{1,t}$    | 2.44323  | 3.84144            | -0.07976                |
| $r_{2,t}$    | 3.24540  | 3.34813            | -0.07399                |
| $r_{4,t}$    | 3.64921  | 2.54032            | -0.05532                |
| $r_{8,t}$    | 3.83640  | 1.64610            | -0.00476                |
| $r_{12,t}$   | 3.89609  | 1.19887            | 0.04803                 |
| $r_{16,t}$   | 3.92604  | 0.94661            | 0.09410                 |
| $r_{20,t}$   | 3.94399  | 0.78679            | 0.13243                 |
| $epi_{1,t}$  | 2.70201  | 2.59401            | 0.23127                 |
| $epi_{2,t}$  | 2.70201  | 2.27734            | 0.24525                 |
| $epi_{3,t}$  | 2.70200  | 1.81323            | 0.26987                 |
| $epi_{8,t}$  | 2.70195  | 1.26079            | 0.30932                 |
| $epi_{12,t}$ | 2.70193  | 0.96434            | 0.33665                 |
| $epi_{16,t}$ | 2.70194  | 0.78670            | 0.35395                 |
| $epi_{20,t}$ | 2.70196  | 0.66892            | 0.36427                 |
| $irp_{1,t}$  | 0.03125  | 0.00792            | -0.22185                |
| $irp_{2,t}$  | 0.05827  | 0.01088            | -0.23463                |
| $irp_{4,t}$  | 0.09122  | 0.01148            | -0.24944                |
| $irp_{8,t}$  | 0.10012  | 0.01175            | -0.19349                |
| $irp_{12,t}$ | 0.07833  | 0.01620            | -0.11236                |
| $irp_{16,t}$ | 0.05105  | 0.01802            | -0.09234                |
| $irp_{20,t}$ | 0.02706  | 0.01955            | -0.06929                |
| $itp_{1,t}$  | -0.13326 | 0.03596            | 0.21570                 |
| $itp_{2,t}$  | -0.13343 | 0.02834            | 0.22101                 |
| $itp_{4,t}$  | -0.12423 | 0.01934            | 0.22967                 |
| $itp_{8,t}$  | -0.10589 | 0.01222            | 0.22076                 |
| $itp_{12,t}$ | -0.09476 | 0.01074            | 0.17175                 |
| $itp_{16,t}$ | -0.08887 | 0.01040            | 0.14064                 |
| $itp_{20,t}$ | -0.08641 | 0.01033            | 0.12246                 |

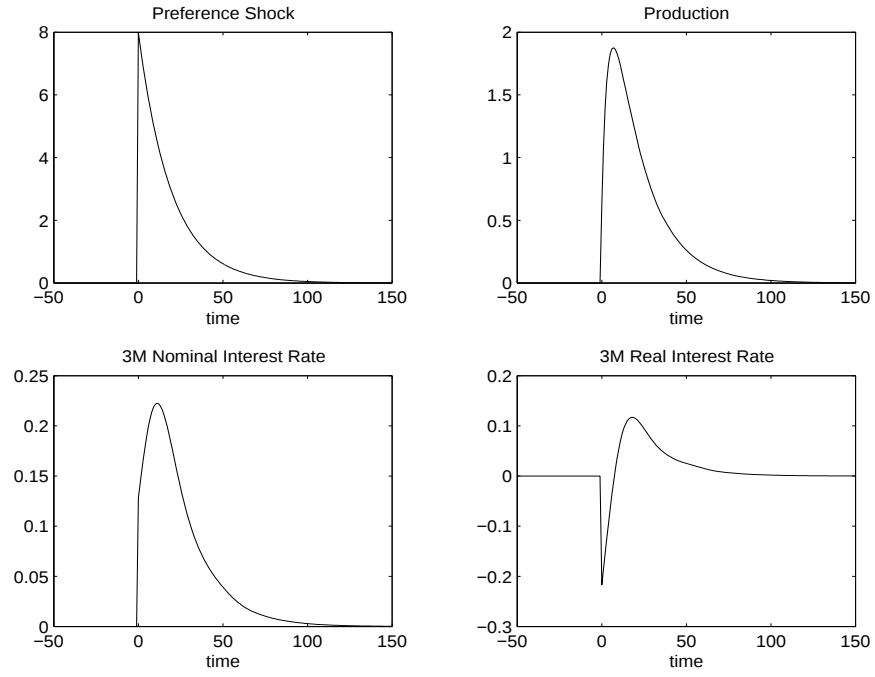


Figure 1: Impulse response functions to one standard deviation preference shock, benchmark case.

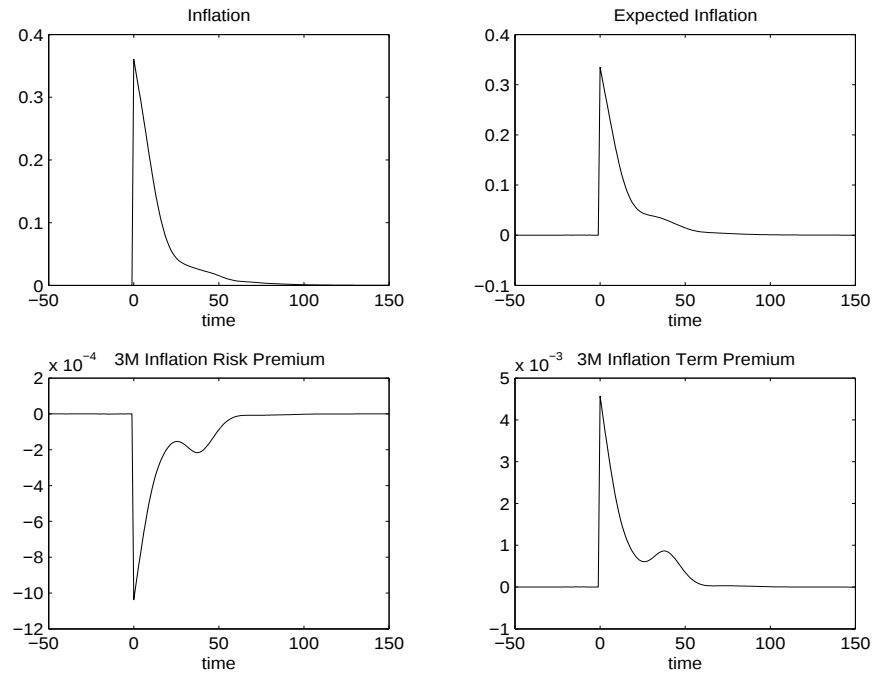


Figure 2: Impulse response functions to one standard deviation preference shock, benchmark case.

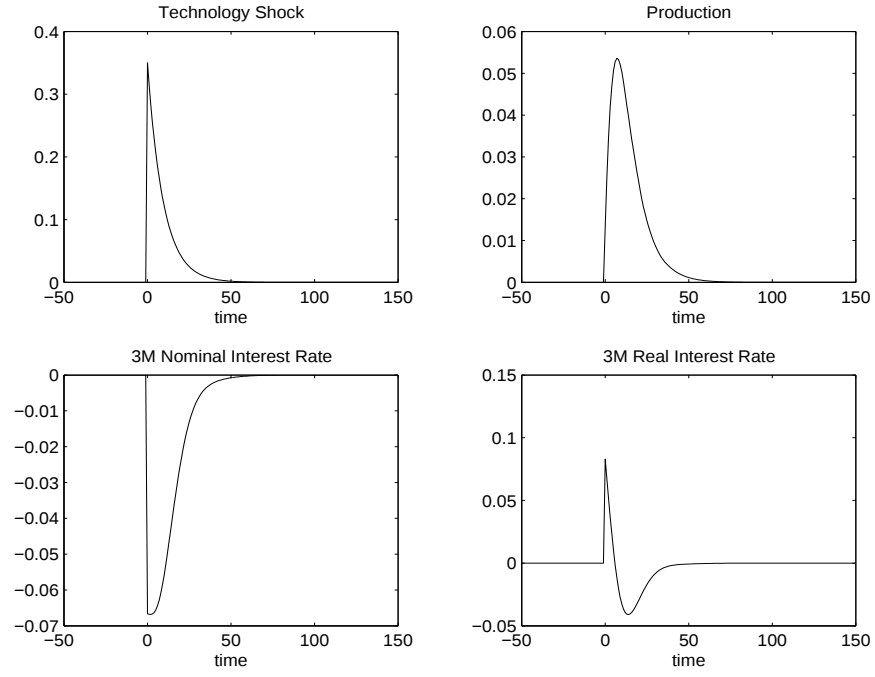


Figure 3: Impulse response functions to one standard deviation productivity shock, benchmark case.

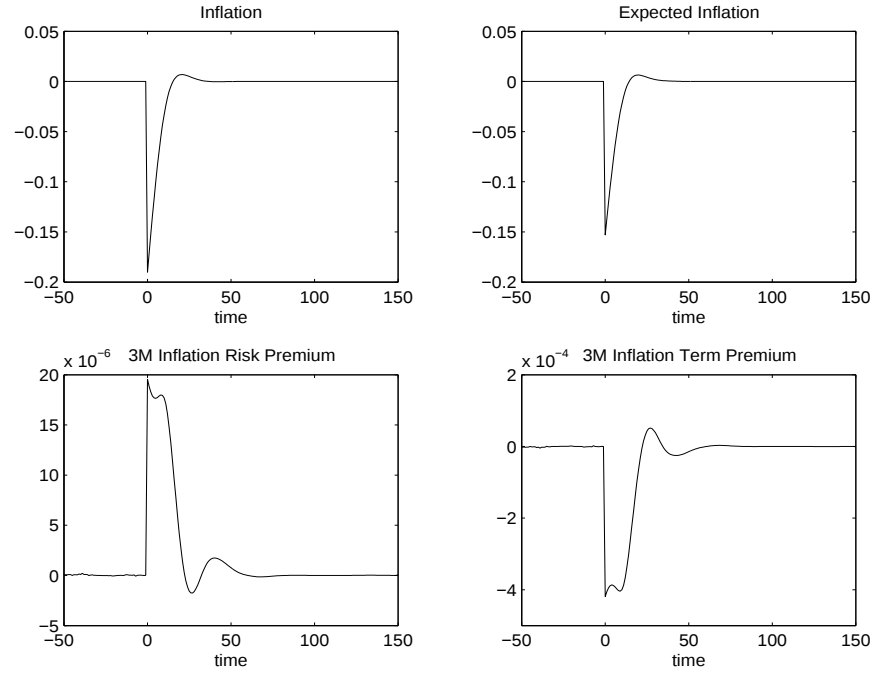


Figure 4: Impulse response functions to one standard deviation productivity shock, benchmark case.

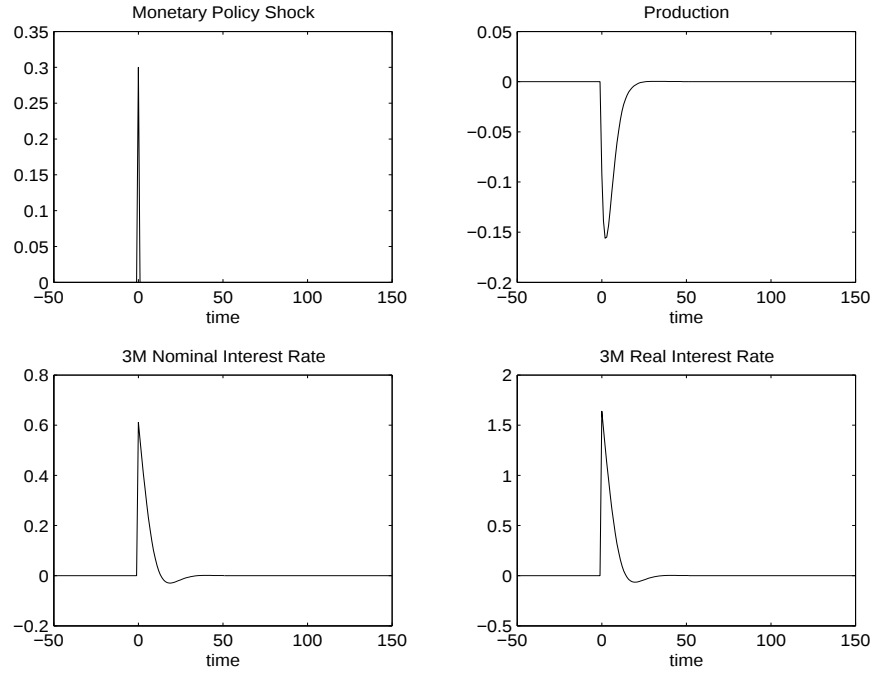


Figure 5: Impulse response functions to one standard deviation monetary policy shock, benchmark case.

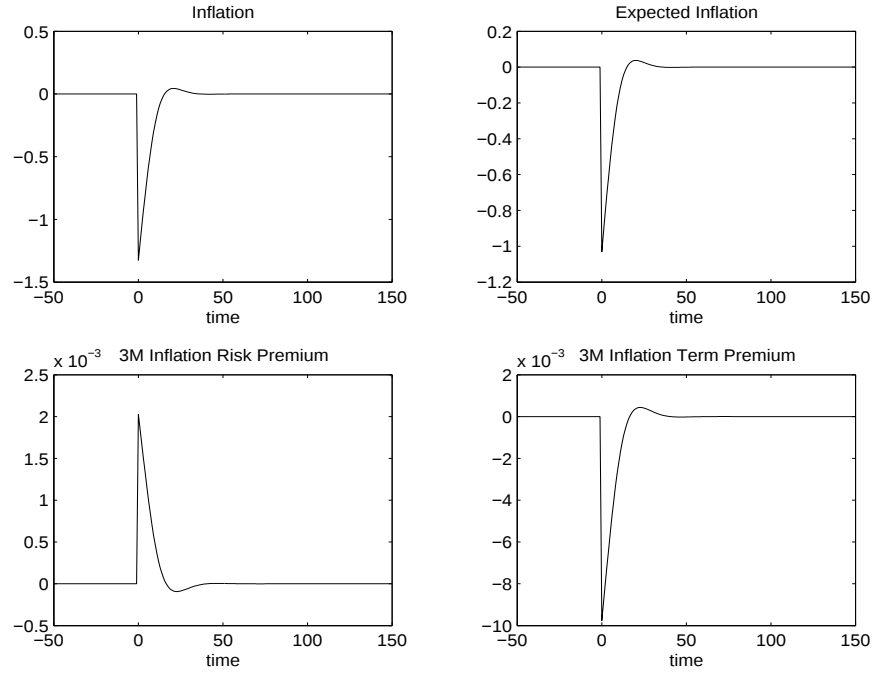


Figure 6: Impulse response functions to one standard deviation monetary policy shock, benchmark case.

Table 11: Correlations between selected variables, benchmark case.

|                              | $n = 1$  | $n = 2$  | $n = 4$  | $n = 8$  | $n = 12$ | $n = 16$ | $n = 20$ |
|------------------------------|----------|----------|----------|----------|----------|----------|----------|
| $\rho(r_{n,t}, R_{n,t})$     | 0.79443  | 0.77924  | 0.71054  | 0.64143  | 0.64166  | 0.66613  | 0.69209  |
| $\rho(r_{n,t}, epi_{n,t})$   | -0.90508 | -0.89273 | -0.84064 | -0.69445 | -0.52287 | -0.36678 | -0.24002 |
| $\rho(R_{n,t}, epi_{n,t})$   | -0.46075 | -0.41324 | -0.21622 | 0.10656  | 0.31825  | 0.44948  | 0.53452  |
| $\rho(irp_{n,t}, epi_{n,t})$ | -0.96200 | -0.95162 | -0.82097 | -0.44215 | -0.21947 | -0.18939 | -0.17546 |
| $\rho(itp_{n,t}, epi_{n,t})$ | 0.96792  | 0.96517  | 0.90958  | 0.75572  | 0.53398  | 0.40181  | 0.35814  |
| $\rho(irp_{n,t}, itp_{n,t})$ | -0.99831 | -0.99450 | -0.96585 | -0.82293 | -0.75916 | -0.72576 | -0.63868 |

8. Inflation term premia and inflation risk premia are significantly negatively correlated.

The exceptions to the above results are as follows (the last result holds always).

1. There are no monetary policy shocks ( $\sigma_{mp} = 0$ ) or monetary policy responds to output ( $\omega_y = 0.1$ ).
2. There are no monetary policy shocks ( $\sigma_{mp} = 0$ ) or monetary policy responds to output ( $\omega_y = 0.1$ ) or the degree of interest rate smoothing is reduced ( $\chi = 0.7$ ).
3. Prices are less sticky ( $\theta_p = 0.5$ ) or the volatility of monetary policy shocks is doubled ( $\sigma_{mp} = 0.006$ ).
4. There are no monetary policy shocks ( $\sigma_{mp} = 0$ ).
5. There are no monetary policy shocks ( $\sigma_{mp} = 0$ ) or monetary policy responds to output ( $\omega_y = 0.1$ ) or the degree of interest rate smoothing is reduced ( $\chi = 0.7$ ).
6. There are no monetary policy shocks ( $\sigma_{mp} = 0$ ) or monetary policy responds to output ( $\omega_y = 0.1$ ).
7. There are no monetary policy shocks ( $\sigma_{mp} = 0$ ).

Finally, Table 14 shows that the current inflation and expected inflation are significantly positively correlated under all parameterizations.

#### *Mundell-Tobin Effect*

According to Mundell-Tobin effect, higher inflation reduces demand for money and increases demand for interest-bearing assets.<sup>12</sup> Therefore, required return on bonds and/or marginal productivity of capital falls and real interest rate declines. Mundell-Tobin effect has been confirmed in cross-sectional empirical studies by Monnet and Weber (2001) and Rapach (2003).

Bai (2005) presents the possibly first general equilibrium model with long-lived consumers and a quantitatively significant Mundell-Tobin effect. We obtain the same result. Table 16 shows

<sup>12</sup>Mundell (1963) used bonds and Tobin (1965) real capital.

Table 12: Sensitivity of real interest rate and expected inflation statistics to different parameter values. BM = benchmark.

|                                                     | $E[r_{1,t}]$ | $\sigma(r_{1,t})$ | $\rho(r_{1,t}, Y_t)$ | $E[epi_{1,t}]$ | $\sigma(epi_{1,t})$ | $\rho(epi_{1,t}, Y_t)$ |
|-----------------------------------------------------|--------------|-------------------|----------------------|----------------|---------------------|------------------------|
| BM                                                  | 2.44323      | 3.84144           | -0.07976             | 2.70201        | 2.59401             | 0.23127                |
| $b = 0$                                             | 3.91091      | 3.85959           | -0.34255             | 2.70305        | 2.70596             | 0.48602                |
| $\gamma = 1.5$                                      | 1.57240      | 4.01566           | -0.09344             | 2.70586        | 2.98997             | 0.32506                |
| $\chi = 0.7$                                        | 3.15546      | 1.88062           | 0.00681              | 2.93799        | 1.29973             | 0.36158                |
| $\pi_{ss} = 1.0$                                    | 2.58478      | 3.98113           | -0.07987             | -0.31087       | 2.82735             | 0.20949                |
| $\pi_{ss} = 1.01$                                   | 2.38704      | 3.80035           | -0.08064             | 3.70419        | 2.53410             | 0.24241                |
| $\omega_y = 0.1$                                    | 1.41685      | 4.43245           | -0.05063             | 2.03919        | 5.10894             | -0.27850               |
| $\omega_\pi = 3.0$                                  | 3.00102      | 2.64209           | -0.03573             | 2.94862        | 1.29731             | 0.17075                |
| $\omega_\pi = 1.2$                                  | 2.15903      | 4.61458           | -0.09958             | 2.18798        | 3.55571             | 0.25169                |
| $\theta_p = 0.5$                                    | 3.01132      | 5.14716           | -0.05187             | 2.77138        | 4.81021             | 0.13592                |
| $\sigma_d=0,$<br>$\sigma_a=0.01$                    | 2.70905      | 3.91251           | -0.53361             | 2.71190        | 2.60253             | 0.43339                |
| $\sigma_a = 0$                                      | 2.46048      | 3.88249           | -0.08605             | 2.71528        | 2.57105             | 0.23886                |
| $\sigma_{mp} = 0$                                   | 3.62740      | 0.70511           | -0.12057             | 2.98589        | 0.96212             | 0.45681                |
| $\sigma_{mp} = 0.006$                               | -1.13281     | 8.31457           | -0.12515             | 2.12654        | 5.34492             | 0.20446                |
| $\rho_d=\rho_a=0.99,$<br>$\sigma_{mp}=0, \chi=0.95$ | 3.26258      | 0.54433           | -0.31659             | 2.96822        | 0.65423             | 0.36379                |

Table 13: Sensitivity of inflation risk and term premia statistics to different parameter values. BM = benchmark.

|                                                     | $E[irp_{1,t}]$ | $\sigma(irp_{1,t})$ | $\rho(irp_{40,t}, Y_t)$ | $E[itp_{1,t}]$ | $\sigma(itp_{1,t})$ | $\rho(itp_{1,t}, Y_t)$ |
|-----------------------------------------------------|----------------|---------------------|-------------------------|----------------|---------------------|------------------------|
| BM                                                  | 0.03118        | 0.00791             | -0.22202                | -0.13326       | 0.03596             | 0.21570                |
| $b = 0$                                             | 0.01183        | 0.00334             | -0.46988                | -0.05695       | 0.01882             | 0.46112                |
| $\gamma = 1.5$                                      | 0.02474        | 0.00844             | -0.32039                | -0.10765       | 0.03811             | 0.31329                |
| $\chi = 0.7$                                        | 0.00230        | 0.00154             | -0.39511                | -0.00980       | 0.00636             | 0.39513                |
| $\pi_{ss} = 1.0$                                    | 0.04075        | 0.00848             | -0.20000                | -0.17466       | 0.03933             | 0.19330                |
| $\pi_{ss} = 1.01$                                   | 0.02767        | 0.00772             | -0.23420                | -0.11831       | 0.03484             | 0.22804                |
| $\omega_y = 0.1$                                    | 0.08749        | 0.04018             | 0.29107                 | -0.37114       | 0.17383             | -0.28012               |
| $\omega_\pi = 3.0$                                  | 0.01250        | 0.00197             | -0.17014                | -0.05267       | 0.00872             | 0.16492                |
| $\omega_\pi = 1.2$                                  | 0.05052        | 0.01118             | -0.24147                | -0.21843       | 0.05263             | 0.23254                |
| $\theta_p = 0.5$                                    | 0.10231        | 0.01577             | -0.13378                | -0.51707       | 0.09585             | 0.12053                |
| $\sigma_d=0,$<br>$\sigma_a=0.01$                    | 0.02934        | 0.00710             | -0.39130                | -0.12698       | 0.03342             | 0.40043                |
| $\sigma_a = 0$                                      | 0.03207        | 0.00773             | -0.21817                | -0.13670       | 0.03512             | 0.21186                |
| $\sigma_{mp} = 0$                                   | -0.00275       | 0.00030             | 0.00166                 | 0.01095        | 0.00119             | 0.01463                |
| $\sigma_{mp} = 0.006$                               | 0.16828        | 0.04733             | -0.17461                | -0.71920       | 0.22571             | 0.16958                |
| $\rho_d=\rho_a=0.99,$<br>$\sigma_{mp}=0, \chi=0.95$ | 0.00013        | 0.00050             | -0.22447                | -0.00059       | 0.00203             | 0.22539                |

Table 14: Sensitivity of selected correlations to different parameter values. BM = benchmark.

|                                                     | $\rho(\pi_t, epi_{1,t})$ | $\rho(r_{1,t}, R_{1,t})$ | $\rho(r_{1,t}, epi_{1,t})$ | $\rho(R_{1,t}, epi_{1,t})$ |
|-----------------------------------------------------|--------------------------|--------------------------|----------------------------|----------------------------|
| BM                                                  | 0.99007                  | 0.79443                  | -0.90508                   | -0.46075                   |
| $b = 0$                                             | 0.99016                  | 0.79188                  | -0.92546                   | -0.50151                   |
| $\gamma = 1.5$                                      | 0.98668                  | 0.65870                  | -0.78859                   | -0.05678                   |
| $\chi = 0.7$                                        | 0.98009                  | 0.80360                  | -0.09781                   | 0.51371                    |
| $\pi_{ss} = 1.0$                                    | 0.98805                  | 0.77576                  | -0.92625                   | -0.48071                   |
| $\pi_{ss} = 1.01$                                   | 0.99065                  | 0.79249                  | -0.89165                   | -0.43052                   |
| $\omega_y = 0.1$                                    | 0.98219                  | 0.22357                  | -0.66846                   | 0.57540                    |
| $\omega_\pi = 3.0$                                  | 0.99322                  | 0.93120                  | -0.89752                   | -0.67503                   |
| $\omega_\pi = 1.2$                                  | 0.98857                  | 0.66538                  | -0.90977                   | -0.29547                   |
| $\theta_p = 0.5$                                    | 0.97207                  | 0.30724                  | -0.96350                   | -0.04133                   |
| $\sigma_d=0,$<br>$\sigma_a=0.01$                    | 0.99158                  | 0.85386                  | -0.94422                   | -0.63483                   |
| $\sigma_a = 0$                                      | 0.99024                  | 0.81989                  | -0.91598                   | -0.52131                   |
| $\sigma_{mp} = 0$                                   | 0.99320                  | 0.48591                  | -0.18627                   | 0.76821                    |
| $\sigma_{mp} = 0.006$                               | 0.97400                  | 0.88941                  | -0.96042                   | -0.72717                   |
| $\rho_d=\rho_a=0.99,$<br>$\sigma_{mp}=0, \chi=0.95$ | 0.97695                  | 0.60954                  | -0.06265                   | 0.75301                    |

Table 15: Sensitivity of selected correlations to different parameter values. BM = benchmark.

|                                                     | $\rho(irp_{1,t}, epi_{1,t})$ | $\rho(itp_{1,t}, epi_{1,t})$ | $\rho(irp_{1,t}, itp_{1,t})$ |
|-----------------------------------------------------|------------------------------|------------------------------|------------------------------|
| BM                                                  | -0.96200                     | 0.96792                      | -0.99831                     |
| $b = 0$                                             | -0.98098                     | 0.97798                      | -0.99769                     |
| $\gamma = 1.5$                                      | -0.93459                     | 0.95022                      | -0.99626                     |
| $\chi = 0.7$                                        | -0.85067                     | 0.85618                      | -0.99977                     |
| $\pi_{ss} = 1.0$                                    | -0.95873                     | 0.96381                      | -0.99889                     |
| $\pi_{ss} = 1.01$                                   | -0.96235                     | 0.96965                      | -0.99774                     |
| $\omega_y = 0.1$                                    | 0.57540                      | 0.94390                      | -0.99827                     |
| $\omega_\pi = 3.0$                                  | -0.91935                     | 0.92941                      | -0.99910                     |
| $\omega_\pi = 1.2$                                  | -0.94245                     | 0.94969                      | -0.99780                     |
| $\theta_p = 0.5$                                    | -0.95004                     | 0.96228                      | -0.99499                     |
| $\sigma_d=0,$<br>$\sigma_a=0.01$                    | -0.95724                     | 0.96694                      | -0.99740                     |
| $\sigma_a = 0$                                      | -0.97168                     | 0.97521                      | -0.99848                     |
| $\sigma_{mp} = 0$                                   | -0.13088                     | 0.16868                      | -0.99889                     |
| $\sigma_{mp} = 0.006$                               | -0.86648                     | 0.88168                      | -0.99712                     |
| $\rho_d=\rho_a=0.99,$<br>$\sigma_{mp}=0, \chi=0.95$ | -0.76052                     | 0.76218                      | -0.99998                     |

Table 16: The effect of changes in the steady-state inflation rate on nominal and real interest rates and inflation.

|                     | $E[R_{1,t}]$ | $E[r_{1,t}]$ | $E[\pi_t]$ |
|---------------------|--------------|--------------|------------|
| $\pi_{ss} = 1.0$    | 2.09924      | 2.58478      | -0.31088   |
| $\pi_{ss} = 1.0075$ | 5.01198      | 2.44323      | 2.70201    |
| $\pi_{ss} = 1.01$   | 5.97292      | 2.38704      | 3.70419    |

Mundell-Tobin effect at work. Increase in the average level of inflation increases average level of nominal interest rates, but decreases average level of real interest rates.

## 7. Conclusions

We conclude that in our model:

1. Short-term real interest rates display greater volatility than expected inflation.
2. Nominal interest rates and expected inflation are negatively correlated for short maturities.
3. Inflation risk and term premia are very small and very constant.
4. Inflation risk premia are on average negative and inflation term premia are on average positive.
5. Short-term real interest rates and expected inflation are significantly negatively correlated.
6. Inflation risk premia and expected inflation are significantly negatively correlated.
7. Inflation term premia and expected inflation are significantly positively correlated.
8. Inflation term premia and inflation risk premia are significantly negatively correlated.
9. Current inflation and expected inflation are significantly positively correlated.
10. Mundell-Tobin effect holds.

Most of our results are quite robust to alternative parameterizations.

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