Revisions to Short Rate Expectations: Policy Shocks and Macroeconomic News*

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Abstract

How do financial markets react to monetary policy actions and macroeconomic news? This paper develops a coherent framework to capture the impact of monetary policy actions and macroeconomic news on the term structure of interest rates, based on a new affine-yield model that allows shock variances and covariances to differ between news events. We focus on the revisions to the entire path of future expected short rates, which the model allows to parsimoniously describe by means of the factor shocks, because these revisions completely characterize any news event. By integrating the different sources of volatility in one common framework we can assess and compare the differential impact of monetary policy and macro news on the term structure. The key findings are that policy actions have effects on the entire term structure, and that this impact varies greatly between policy actions but on average is hump-shaped, which contrasts with previous results in this literature. Furthermore, the revisions resulting from macroeconomic announcements show clear evidence for policy inertia, and they confirm the excess-sensitivity puzzle. Finally, there are important differences in comovement of forward rates between policy and macro news, which we attribute to the dimensionality of new information released on a given news event. The model also allows us to construct a horizon-specific measure for monetary policy shocks, and to consistently estimate the term structure of announcement effects.

Keywords: Monetary policy shocks, macroeconomic announcements, term structure of interest rates, policy inertia, excess-sensitivity puzzle

JEL Classifications: E43, E44, E52, G12

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1 Introduction

How do monetary policy actions affect the term structure of interest rates? Because of its high relevance to both market participants and policymakers, this question has commanded considerable interest among researchers. The Fed controls the overnight interest rate (the federal funds rate), but the monetary transmission mechanism works through changes in interest rates at all maturities. Hence the effectiveness of monetary policy crucially depends on whether and how the Fed can impact interest rates other than the short rate.

In his seminal paper Kuttner (2001) employs federal funds futures to measure monetary policy surprises on FOMC meeting days and finds a significant impact on yields at short and medium maturities, which however declines quickly with maturity. Other studies that come to similar conclusions are Poole and Rasche (2000); Rigobon and Sack (2004); Hamilton (2008). Gürkaynak et al. (2005a) show that policy surprises have two dimensions, due to the additional information conveyed to market participants in the FOMC statement, and explain more yield variation for longer maturities by including a second factor that is extracted from near-term money market futures. In their yield regressions as well, response coefficients and explanatory power decline with maturity. We can gather from the results of the regression approach in this literature that policy surprises do affect interest rates, that the impact seems to decline with maturity, and that to measure these surprises one factor is not sufficient.

A closely related question is how macroeconomic news affect the term structure. There exists an extensive literature that attempts answers, prominent contributions being Fleming and Remolona (1997), Balduzzi et al. (2001) and Faust et al. (2007). The focus of these studies is to ask which announcements affect interest rates and what the sign and size of the responses are. They find that some macro news have an important impact on yields whereas others do not, and that the effects vary according to the maturity of the yields considered.

The approach that is usually taken to assess the impact of news on the term structure is to regress yield changes on one or more surprise measures, and to re-estimate the equation for a number of different maturities. I argue that this does not give satisfactory answers to the questions of interest, since it does not recognize the multidimensional nature of news to the term structure: A particular policy action or macroeconomic announcement leads to a revision of the entire path of expected future short rates, and we need to model and understand this entire revision across maturities in order to understand the impact of the news. The finance literature on term structure models provides the right apparatus to achieve this. However, the regression approach described above neither provides a model of the short rate nor imposes no-arbitrage, both necessities to consistently model changes in interest rates, and hence does not

constitute the appropriate methodology to assess the impact of news on the term structure.

For the case of monetary policy analysis, the regression approach is particularly problematic. The surprise measures are derived from changes in money market futures rates, which are changes in average forward rates. The yield changes on the left hand side of the regression are of course also determined by changes in average forward rates, thus the regressions simply estimate, in a crude way, the comovement between forward rates at different maturities. Viewed in this light and given that the short rate has transitory components, the findings of decreasing explanatory power in the yield regressions of Kuttner (2001) and Gürkaynak et al. (2005a) are not surprising at all. The conclusion is that we do not yet have a satisfactory answer to the question about the effects of monetary policy on the term structure of interest rates.

Another shortcoming is that the two separate strands of literature are not integrated, which they would need to be in order for us to understand how the different types of news differ with regard to their impact on the term structure. What are the most important sources of volatility? How are rates at short, medium and long maturities affected by different news, and are there important differences in comovement of rates across maturities? These questions can only be answered if we integrate news about monetary policy and the macroeconomic situation in a common framework.

In this paper I propose a new approach to study how policy and macro news affect the term structure. The object of interest is the *revision to the entire expected future path of the short rate*, since this is what characterizes a particular news event.[1] Importantly the revision is an infinite-dimensional object, because it describes changes to the expectations for the short rate at any horizon. In order to capture the impact of news, we thus need to summarize the revision in a parsimonious way. I achieve this with the help of an affine term structure model, which allows to reduce the dimensionality to the number of underlying factor shocks, of which there are three in my model. By defining and putting at the focus of attention the revision, and by applying methods from modern financial theory, I am thus able to give more satisfactory answers to the questions about the impacts of monetary policy and macroeconomic news than previous studies have been able to.

The key to integrating in a coherent framework the news about monetary policy actions and the various kinds of macroeconomic news is to explicitly recognize the heterogeneity of these different sources of interest rate volatility. The shocks to the term structure factors need to be allowed to differ in variability and comovement depending on the type of news event.

[1] Since changes in risk premia also play an important role, we will focus on the changes in expectations under the risk-neutral measure.

Thus the paper takes a *conditional approach* to term structure modeling: The properties of the factor shocks, more specifically their second moments, are conditional on the "news regime" on a given day, where importantly the regime is observable based on the policy and news announcement calendar of the market participants. This is a simple but very effective way to describe similarities and uncover differences in yield dynamics. The conditional structure of the model allows to assess and compare the differential impact of policy actions and different macro news on interest rates.

The modeling and estimation approach developed in this paper also is a contribution to the term structure literature, for two reasons: First, the conditional approach allows to identify and describe the different sources of volatility to the term structure. News about monetary policy and about the economy are the main drivers of changes in interest rates, however existing term structure models usually treat all trading days in the same way.[2] The conditional character of my term structure model tells us what really moves the market, and in which way it moves the market. The literature on the term structure of volatility has so far not taken this conditional perspective. Second, the concept of a revision facilitates solving the term structure model, and a straightforward estimation procedure can be implemented based on changes in money market futures, which are equal to the average revision over the time period covered. Specifically I use Federal fund futures and Eurodollar futures to estimate the model.

The paper shows that monetary policy generally has strong effects on the entire term structure. The volatility curve on policy days shows that short rates move just as much as longer rates, and its hump shape indicates that one- to two-year-ahead forward rates have the highest variability. Importantly the revisions caused by policy actions show various different shapes: Some actions of the FOMC only move the short end of the yield curve and barely have an impact on longer rates, some have a hump-shaped impact, yet others leave the short end unchanged and move only long rates. These findings show that the impact of monetary policy does not decline with maturity as suggested by previous studies (Kuttner, 2001; Gürkaynak et al., 2005b,a), but that this impact entirely depends on the type of policy event, can have a variety of shapes, and on average is hump-shaped.

The great variety of revisions that can be caused by policy events is equivalent to the finding that these effects on the term structure are not sufficiently well captured by just one factor. This has previously been noted by Gürkaynak et al. (2005b), however these authors base their conclusion on results from a model-free factor analysis, whereas I draw upon an

[2]This also holds for regime-switching models such as Bansal and Zhou (2002) and Monfort and Pegoraro (2007), since they do not condition on observable information, i.e. do not distinguish between trading days.

analysis of the comovement of the shocks to the term structure factors. So then how do we measure a monetary policy shock? My approach allows to parsimoniously capture what happens on a policy day to the entire term structure, namely by describing the revision to the entire path of expected short rates caused by the policy action. This description of policy shocks is an important improvement upon the target and path factors that Gürkaynak et al. (2005b) use to describe policy events, since it fully characterizes the effects on the entire term structure and enables us to predict the changes to yields and forward rates at any maturity that are consistent with the absence of arbitrage. This suggests a horizon-specific policy shock measure based on predicted rate changes. Based on the insight that the effects of monetary policy depend strongly on the horizon under consideration, I develop this new shock measure and show its empirical success in predicting changes in the yield curve for U.S. treasury securities.

Comparing news resulting from monetary policy and from different macroeconomic announcements I uncover important differences in the behavior of the term structure. First, the term structure of volatility looks a lot different when macro news take place: Vol curves are steeply increasing at short maturities up to a year, and a lot more back-loaded than on policy days. Markets evidently revise their short rate expectations much less for short horizons than for medium and long horizons, because they expect the Fed to only sluggishly adjust the short rate in response to the new information. This is clear evidence of policy inertia, contrasting the negative evidence of Rudebusch (2006) on this issue. Second, among the different types of news I consider, new employment reports are by and far the most important source of interest rate volatility. Third, revisions resulting from macro news show much stronger comovement across horizons than policy-induced revisions, meaning that a specific macro news release usually causes a revision of a specific shape. Hence one factor is essentially enough to describe the revision in this case, which accords with intuition since there is only one piece of new information, the data surprise. On policy days, on the other hand, there are several pieces of news – the current target choice and the information in the FOMC statement – which independently affect the market's short rate expectations.

The paper is structured as follows: The term structure model is introduced and estimated in section 2. In section 3 the model is employed to estimate the term structure of volatility conditional on the type of news – monetary policy actions and specific macroeconomic news, namely about the labor market, the price level, and aggregate demand. Furthermore I show how the comovement differs between policy news and macro news. In section 4, after illustrating some instances of policy action and its effects, I develop a new measure for monetary policy shocks and document its empirical success. In section 5 I estimate the effects of macroe-

conomic data surprises on the term structure. Section 6 provides some concluding remarks and directions for future work.

2 Term structure model and estimation

2.1 Risk-neutral dynamics

Denote the rate for an overnight default-free loan between days t and $t+1$, the short rate, by x_t. It is assumed to be determined by three latent factors: $x_t = x_{1t} + x_{2t} + x_{3t}$. The modeling approach of this paper is to specify the factor dynamics under the risk-neutral measure $\mathbb{Q}$, and we choose them as follows:

$$\begin{aligned} x_{1t} &= \theta_1 x_{1,t-1} + \theta_2 x_{1,t-2} + \xi_{1t}^{\mathbb{Q}}, \qquad |\theta_2| < 1, \quad \theta_2 + \theta_1 < 1, \quad \theta_2 - \theta_1 < 1, \\ x_{2t} &= \rho x_{2,t-1} + \xi_{2t}^{\mathbb{Q}}, \qquad |\rho| < 1, \\ x_{3t} &= x_{3,t-1} + \xi_{3t}^{\mathbb{Q}} \end{aligned}$$

Thus under the $\mathbb{Q}$-measure, the first factor follows a stationary[3] AR(2) process, the second factor follows a stationary AR(1) process, and the third factor is a random walk. The motivation for this particular choice stems from some common empirical findings about term structure dynamics. First, as noted by Backus et al. (1999), yield dynamics are hump-shaped, meaning that forward rates at medium maturities are more volatile and responsive than those at short and long maturities.[4] Including an AR(2) process can account for this behavior, since it has a hump-shaped impulse-response function, provided that the roots are sufficiently close to one.[5] An alternative to generate hump-shaped dynamics is to have one factor reverting to another, as in the central tendency model of Balduzzi et al. (1998). Second, there is ample evidence that one or more interest rate factors are close to non-stationary. The null of a unit root in the short rate can usually not be rejected.[6] A related finding is that far-ahead forward rates show a lot of variability (Gürkaynak et al., 2005b), which motivates our choice to include a factor that follows a unit-root process under the $\mathbb{Q}$-measure. Notably, if the short rate was to

[3] The indicated parameter restrictions ensure stationarity as shown in Marmol (1995).

[4] This is also evident from the shape of the term structure of volatility: It is described by Piazzesi (2005) to be snake-shaped, and the back and tail of the snake correspond to the hump-shape that other authors have noted.

[5] Another example of a term structure model that includes an AR(2) factor is the one of Startz and Tsang (2007).

[6] Rose (1988) notes that "the literature clearly indicates that the nominal interest rate is nonstationary" (p. 1098), and does not reject a unit root for different one-month nominal interest rates. More up-to-date evidence by Rapach and Weber (2004) also suggests that nominal interest rates are I(1).

be specified as stationary under $\mathbb{Q}$, far-ahead forward rates would be close to constant. Third, the number of factors is chosen to be three because this is now common in the literature and seems necessary to match the behavior of the term structure (Balduzzi et al., 1996). Compared to existing models, our factor dynamics are most similar to those of Christensen et al. (2007), with the only difference being that they choose a central tendency instead of an AR(2) factor to generate hump-shaped dynamics.

The key novelty of this term structure model is the inclusion of observable variance regimes, which will enable us to uncover differences in yield curve dynamics resulting from particular events. Let $\xi_t^{\mathbb{Q}} = (\xi_{1t}^{\mathbb{Q}}, \xi_{2t}^{\mathbb{Q}}, \xi_{3t}^{\mathbb{Q}})'$ and assume that under the $\mathbb{Q}$-measure we have $\xi_t^{\mathbb{Q}} \sim N(0, V_t)$ and $E(\xi_t^{\mathbb{Q}} \xi_s^{\mathbb{Q}\prime}) = 0$, for all $t \neq s$, that is $\xi_t^{\mathbb{Q}}$ is a martingale difference sequence (m.d.s.) under $\mathbb{Q}$ with time-varying variance-covariance matrix. Now V_t is assumed to be constant conditional on the regime, which is observable based on t: With R different regimes, let V_t be equal to one of $V^1, V^2, \ldots, V^R$ according to the regime on day t. Specifically, we will set $R = 4$, the four regimes being FOMC announcement days, BLS employment report days, CPI/PPI days, and days with new retail sales data.

Note the difference between this approach and "regime-switching" term structure models such as the ones of Bansal and Zhou (2002) and Monfort and Pegoraro (2007): Those models treat the state variable that determines the regime (in the language of Hamilton, 1994, chap. 22) as unobservable, whereas in our context the researcher can observe which type of news event takes place on a given day and thus knows the value of the state variable. This greatly simplifies modeling and estimation.

An implicit assumption is that only one event takes place on a given day, whereas in reality some days might have both a policy action and a macroeconomic announcement. I account for this by excluding those few days in my sample with more than one event. Another issue is that other macroeconomic announcements, which I do not consider here, sometimes take place on the days in my sample. Robustness checks (not reported here) indicate that this is unproblematic since it does not change the qualitative results. The use of intraday data is a way to improve the precision of the estimates, however I leave this to future work.

Having specified the factor dynamics under the $\mathbb{Q}$-measure, we should note that infinitely many real-world dynamics under the $\mathbb{P}$-measure are consistent with it. If we were to specify a pricing Kernel, this would pin down the change of measure. However, since this paper is not concerned with identifying and estimating risk premia, we can abstain from choosing a pricing Kernel. The advantages are that we do not need to specify which factors impact risk premia, and that the parameters for the prices of risk do not need to be estimated, which gives parsimony and thus helps the precision of our estimation and prediction. The way we

will pin down the $\mathbb{P}$-dynamics is by imposing identifying assumptions on the distribution of $\xi_t^{\mathbb{Q}}$ under $\mathbb{P}$, as will be shown below.

2.2 Revisions to short rate expectations

Since we assumed the existence of a risk-neutral probability measure, there exist no arbitrage opportunities by the Fundamental Theorem of Asset Pricing. We can find forward rates by taking expectations under $\mathbb{Q}$ of future short rates: For the forward rate at date t for a loan from $t+n$ to $t+n+1$ we have $f_t^n = E_t^{\mathbb{Q}} x_{t+n}$, up to Jensen inequality terms.[7] Yields are simply average forward rates, so that for the time t yield for a maturity of n days we have $y_t^n = n^{-1} \sum_{\tau=0}^{n-1} E_t^{\mathbb{Q}} x_{t+\tau}$. The term structure of interest rates can be characterized by either forward rates or yields, however the forward rate curve gives a cleaner picture of short rate expectations at the various forecast horizons and how they change.

New information that moves the term structure is captured by the revision to the expected short rate path under $\mathbb{Q}$, that is $\{(E_t^{\mathbb{Q}} - E_{t-1}^{\mathbb{Q}}) x_{t+n}\}_{n=0}^{\infty}$, which I simply call a "revision". The changes on a given day in forward rates and yields across all maturities are determined by the revision on that day, which incorporates changes in short rate expectations under the physical measure as well as changes in forward risk premia. The model implies the following relationship between factor innovations and the revisions:

$$(E_t^{\mathbb{Q}} - E_{t-1}^{\mathbb{Q}}) x_{t+n} = \begin{cases} \frac{\phi_1^{n+1} - \phi_2^{n+1}}{\phi_1 - \phi_2} \xi_{1t}^{\mathbb{Q}} + \rho^n \xi_{2t}^{\mathbb{Q}} + \xi_{3t}^{\mathbb{Q}} & \phi_1 \neq \phi_2 \\ (1+n)\phi_1^n \xi_{1t}^{\mathbb{Q}} + \rho^n \xi_{2t}^{\mathbb{Q}} + \xi_{3t}^{\mathbb{Q}} & \phi_1 = \phi_2, \end{cases} \tag{1}$$

where ϕ_1 and ϕ_2 are the roots of the characteristic equation of the AR(2) process. We will see that the restriction $\rho = \phi_1 = \phi_2$ is not rejected by the data, thus the theoretical exposition will from now on consider only this case. The revision is equal to the sum of the impulse-response functions of the three factors. A shock to the AR(2)-factor x_{1t} leads to a hump-shaped revision (given that ϕ_1 is close enough to one), shocks to x_{2t} die out exponentially, and shocks to the unit root factor x_{3t} lead to a parallel shift in the term structure. Different combinations of values for the shocks can lead to a large variety of shapes of revisions.

The revision is a m.d.s. under the $\mathbb{Q}$-measure, but what about its real-world dynamics?

[7] The Jensen inequality terms can be large for long maturities if the short rate is non-stationary, in fact they diverge for $n \to \infty$ in this case. However, we will exclusively consider the *daily changes* in forward rates, $f_t^n - f_{t-1}^{n+1}$. Thus we ignore only the difference in the Jensen inequality terms for maturities n and $n+1$, which is negligibly small.

Denote the forward risk premium in f_t^n by Π_t^n. We have for the revision at horizon n

$$\begin{aligned} f_t^n - f_{t-1}^{n+1} &= (E_t^{\mathbb{Q}} - E_{t-1}^{\mathbb{Q}})x_{t+n} \\ &= (E_t - E_{t-1})x_{t+n} + \Pi_t^n - \Pi_{t-1}^{n+1}. \end{aligned}$$

First note that $(E_t - E_{t-1})x_{t+n}$ is of course a m.d.s. under the $\mathbb{P}$-measure since it contains the new information about expected future short rates. However, the term $\Pi_t^n - \Pi_{t-1}^{n+1}$ might have a non-zero mean and be partly predictable, depending on the risk premium specification: For the case of constant risk premia this term is a constant, possibly non-zero. If forward risk premia are on average increasing with maturity, which is intuitively and empirically plausible, we have $E(\Pi_t^n - \Pi_{t-1}^{n+1}) < 0$. In general we cannot assume that either mean or serial correlation are zero.

With regard to the mean specification, we allow the revision to have a non-zero mean, which can depend on the horizon n. With regard to serial correlation, note that the sample used in this paper consists of days with particular events, namely monetary policy actions and certain macroeconomic announcements. Since there are usually numerous days without any events between two event days, and these are not included, rate changes in my sample are essentially serially uncorrelated. Hence we can get away without modeling the serial correlation in $\Pi_t^n - \Pi_{t-1}^{n+1}$. Evidence on rate changes in money market futures, which I do not show for sake of brevity, indicates that a significantly negative mean and a lack of serial correlation characterizes the revisions in my sample.

Our identifying assumptions for the distribution of the revision under the $\mathbb{P}$-measure boil down to assuming that

$$f_t^n - f_{t-1}^{n+1} = (E_t^{\mathbb{Q}} - E_{t-1}^{\mathbb{Q}})x_{t+n} = a_n + b_n'\xi_t, \quad b_n = ((1+n)\rho^n, \rho^n, 1)' \tag{2}$$

where a_n is a constant depending on the maturity n, b_n are the loadings for that maturity, and $\xi_t = (\xi_{1t}, \xi_{2t}, \xi_{3t})'$ is a Gaussian m.d.s. with a variance-covariance matrix depending on the particular regime on day t, as described above.

Revisions are closely related to the term structure of volatility, the empirical volatilities of yield changes or forward rate changes across maturities, also called "vol curve". Throughout this paper, we focus on the vol curves for forward rates (more specifically for futures rates, which are essentially average forward rates). For now leaving aside the volatility of pricing errors, the vol curve on a given day is equal to the square root of the revision variance across horizons:

$$\sigma_{t,n} = [Var(E_t^{\mathbb{Q}} - E_{t-1}^{\mathbb{Q}})x_{t+n}]^{.5} = (b_n' V_t b_n)^{.5}$$

where $\sigma_{t,n}$ is the volatility of $f_t^n - f_{t-1}^{n+1}$. Thus the loadings and the shock covariance matrix together determine the term structure of volatility. By allowing V_t to vary depending on the regime on day t, we effectively allow different vol curves for each of these regimes. The covariance between rate changes at different maturities, say n and m, is equal to $b_n' V_t b_m$, regime-dependent through V_t just like the vol curve. Thus our conditional approach also allows the comovement of the term structure to differ between regimes.

2.3 Money market futures

This paper uses data on money market futures, in particular on Federal funds futures and Eurodollar futures, to estimate model parameters, to infer the unobserved factor shocks from observed rates, and to assess variability, comovement and news-responses of risk-neutral short rate expectations.

Federal funds futures, which were introduced by the Chicago Board of Trade (CBOT) in October 1988, settle based on the average effective fed funds rate over the course of the contract month. Changes in the rate of a futures contract thus reflect changes in the expected average fed funds rate over the relevant period, plus changes in the risk premium.[8] Since we model short rate dynamics under the risk-neutral measure, we do not need to worry about changes in the risk premium: The change in the futures rate, assuming no arbitrage and no pricing errors, is precisely equal to the average revision to short rate expectations under the $\mathbb{Q}$-measure.[9] Let $d(t)$ denote the day of the month of calendar day t and take N to be the number of days in a month (for simplicity assumed to be 31). The daily change in the rate of the i-month-ahead contract is

$$\begin{aligned}
\Delta f_t^{(i)} &= N^{-1} \sum_{n=iN-d(t)+1}^{(i+1)N-d(t)} (E_t^{\mathbb{Q}} - E_{t-1}^{\mathbb{Q}}) x_{t+n} \\
&= N^{-1} \sum_{n=iN-d(t)+1}^{(i+1)N-d(t)} a_n + b_n' \xi_t \\
&= c_i + h_i{}' \xi_t, \qquad (3)
\end{aligned}$$

[8] Hamilton (2007) has argued theoretically and found empirical evidence that changes in risk premia in near-term fed funds futures are negligible at a daily frequency. Piazzesi and Swanson (2004), although arguing that these risk premia should not be neglected, admit that they vary "primarily at lower, business-cycle frequencies" [p. 17]. However we cannot ignore them since we consider maturities up to several years, and risk premium variation is likely to be sizeable at longer horizons.

[9] Note that we ignore the effect of marking-to-market, i.e. the fact that payments are made before maturity of the contract, however the evidence of Piazzesi and Swanson (2004) indicates that this effect is likely to be negligible in our context.

where c_i is the average of a_n over the relevant horizon, and h_i is the vector of loadings on the three shocks for contract i, which depends on the day of the month of calendar day t, denoted by $d(t)$. An exact expression for the loadings is given in appendix A. We will use the one- to six-month-ahead fed funds futures contracts, denoted by FF1 to FF6.

Federal funds futures are helpful to assess the impact of the Fed's actions and macroeconomic announcements on the expected path of monetary policy only for horizons up to several months, since open interest in contracts further out dwindles quickly. On the other hand Eurodollar futures show deep liquidity for contracts expiring several years in the future.[10] When it comes to predicting the future fed funds rate for horizons longer than several months, Eurodollar futures show the best performance of all financial instruments (Gürkaynak et al., 2007). This is because these contracts settle based on the three-month Libor rate, which strongly correlates with the fed funds rate, at least prior to August 2007. Thus we can expect changes in Eurodollar futures rates to signal changes in short rate expectations.

In order for Eurodollar futures rates to be given by average risk-neutral short rate expectations, we need one simplifying assumption about credit risk premia. Both intra-bank loans that are the basis for Libor quotations as well as loans in the federal funds market are unsecured. However a three-month loan at Libor is much riskier than rolling over daily loans at the federal funds rate. Thus Libor contains a significant credit risk premium. We assume that daily changes in this credit risk premium are negligible. This is a reasonable assumption for the data set we consider: The Libor-OIS spread (evidence not shown), which captures this credit risk premium, has for the period before August 2007 been small and much less variable than federal funds and Libor rates.

Under this assumption changes in Eurodollar futures are given by the same formula as for fed funds futures, equation 3, with N being the number of days in the quarter (taken to be 91 throughout this paper), and $d(t)$ being the day of the quarter for calendar day t. The contracts considered are the ones that settle on the last day of the current and the next 15 quarters, denoted by ED1 to ED16.[11]

2.4 Estimation and Results

The sample contains days between October 1988 (when Fed funds futures started trading) and June 2007 (just before the recent turmoil in financial markets began) that fall into one

[10] In September 2006, the open interest for all Eurodollar futures contracts expiring over the coming four years was above 100,000 (Stigum and Crescenzi, 2007, p.728). In terms of open interest, Eurodollar futures contracts are the most liquid futures contracts worldwide.

[11] For more information on Eurodollar futures contracts please refer to the Chicago Mercantile Exchange's web site at http://www.cme.com/trading/prd/ir/eurodollar.html (accessed 09/10/2008).

of four regimes. The first regime consists of days with FOMC announcements[12] and without news releases for those macroeconomic news considered in the other three regimes. The second regime contains days with a BLS employment report that had no FOMC announcement and no other news. The third regime contains days with a CPI or PPI release, and without an FOMC announcement or other news. The fourth regime contains days when the retail sales numbers are released by the U.S. Census bureau, again without FOMC announcement or other news. This results in a sample with 799 days, with 148 days in the first, 215 days in the second, 316 days in the third, and 120 days in the fourth regime. We choose these four regimes in order to see differences between rate dynamics resulting from policy actions and from macroeconomic news, and to assess how news about the employment situation, about inflation, and about aggregate demand differ in their impact on the yield curve.

The focus on the revisions and the use of changes in futures rates allows for a straightforward estimation procedure based on Maximum Likelihood. As is common in term structure model estimation, we introduce idiosyncratic errors, because otherwise a low-dimensional factor model predicts a singular covariance matrix for higher-dimensional data. Denote by Δf_t the vector with daily changes in the futures rates, measured in basis points, which has dimension $k \times 1$. We include 6 fed funds futures contracts and 16 Eurodollar futures contracts, thus $k = 22$. Our empirical specification is

$$\underset{(k\times 1)}{\Delta f_t} = \underset{(k\times 1)}{\mu} + \underset{(k\times 3)}{H_t'}\underset{(3\times 1)}{\xi_t} + \underset{(k\times 1)}{\varepsilon_t}, \tag{4}$$

where $\mu = (c_1, \ldots, c_k)$, and the matrix $H_t = (h_1(t), \ldots, h_k(t))$ contains the loadings for the futures contracts as predicted by our model (which depend on t through the day of the month and the day of the quarter).[13] The pricing errors are assumed to be Gaussian, with contemporaneous covariance matrix R that is diagonal (since the three common factors are the source of comovement), and serially uncorrelated (since rate changes are serially uncorrelated in our sample, as mentioned above).

Under these assumptions Δf_t is serially uncorrelated and multivariate normal with mean μ and covariance matrix $\Sigma_t = H_t' V^{i(t)} H_t + R$, where $i(t)$ denotes the regime on day t. The

[12] Until December 2004 these are identified by Gürkaynak et al. (2005a). For the remaining period we take the days of the FOMC press release.

[13] For ease of exposition we here index c_i and h_i from 1 to k, differing slightly in notation from equation 3, since the meaning is obvious.

log-likelihood function is

$$\mathcal{L} = \sum_{t=1}^{T} -\frac{1}{2}\{T\log(2\pi) + \log(|\Sigma_t|) + \Delta(f_t - \mu)'\Sigma_t^{-1}\Delta(f_t - \mu)\}.$$

The four shock-covariance matrices V^1 to V^4 each have six unique elements, which amounts to 24 parameters. The other parameters to estimate are ϕ_1, ϕ_2, and ρ, as well as the 22 error variances and 22 means. The benchmark specification imposes $\phi_1 = \phi_2 = \rho$ and thus has 69 free parameters. We reparameterize to ensure that the estimates are within the admissible parameter space: A Cholesky decomposition ensures positive definiteness of V in each regime. For the autoregressive root we take $\rho = \lambda^2/(1+\lambda^2)$ and for the volatilities of the idiosyncratic shocks $\sigma_{\varepsilon,i} = e^{\zeta_i}$.

Table 1 and figures 1 and 2 show the estimation results. The table reports the estimates for ρ and for the shock volatilities and correlations in each of the four regimes, with standard errors in parentheses. It also reports the energy contents of the three principal components for each of the shock covariance matrices V^1 to V^4, as well as the log-likelihood for the benchmark version of the model and for more and less restricted versions. The graphs show estimates for the means and pricing error volatilities for each of the 22 futures contracts, including 95%-confidence intervals. I make use of robust Quasi-Maximum Likelihood standard errors as suggested by White (1982), with numerical approximations for gradient and Hessian.

The shocks ξ_{1t}, ξ_{2t} and ξ_{3t} show important differences in variability and comovement across regimes. The shock variances on policy days are lower than on employment report days, higher than on CPI days and about as high as on retail sales days. The release of a new employment report seems to have a bigger impact on short-rate expectations than any other type of news. In section 3.1 we will show the implied volatility curves and see exactly the differences between regimes in terms of variability.

The differences in comovement are even more striking. The correlation between the shocks is a lot higher on days with economic news than on policy days. This becomes particularly clear when we decompose the covariance matrix in each regime into its principal components (PCs) and show the energy content of each one: The first PC on policy days accounts for about 85% of the variance of revisions, and the second component for about 15%. For news days however the first PC accounts for 92-97% of the variability. The revisions across maturities are more strongly correlated on news days. This means that on news days revisions tend to have more similar shapes than on policy days. Section 3.2 will go into more detail about the differences in comovement that are implied by these estimates.

What causes the differences in comovement between regimes? If a particular news event is

characterized by the occurrence of several pieces of new information, then comovement in rate changes should be lower than for a news event that delivers only one piece of new information to markets: The separate pieces of information can create revisions of more varied shapes than one single piece of information. This intuition is confirmed by our estimation results: On policy days markets learn the new target rate chosen by the Fed, as well as infer the Fed's intentions about future policy from the FOMC statement. The communication independently creates news, thus causing more varied shapes of revisions and lower comovement than on news days. We can even venture one step further and interpret the differences in comovement between the news events: Employment report days have news about the unemployment rate, non-farm payroll employment numbers, and average hourly earnings. The fact that the comovement is lower than for the other news events can probably be ascribed to the separate pieces of new data. The fact that CPI/PPI news events show lower comovement than retail sales days probably stems from pooling two slightly different types of news releases, and thus different revision shapes, in one category. The cleanest news event, the publication of new retail sales numbers, has only one piece of new information and thus the strongest comovement: The data releases always affect the term structure in about the same way, i.e. revisions vary little in shape for this news event.

That the differences between the regimes are significant is evident from the log-likelihood value under the restriction that V_t is constant, which can be found under "equal V's" on the bottom of the table. Imposing this restriction leads to a significantly worse fit for the data. The log-likelihood is lower by about 187, which implies a likelihood-ratio statistic of 374, leading to a minuscule p-value. We strongly reject the null of equal covariance matrices across regimes.

For the AR(1) coefficient ρ we obtain an estimate of 0.9973. It is close to one because otherwise shocks to the transitory components would die out very quickly, however $\rho = 1$ is rejected. The restriction that the roots of the AR(2) process, ϕ_1 and ϕ_2, are equal to ρ is not rejected, as is evident from the equal log-likelihood value for the unrestricted version of the model (reported on the bottom as "different roots"). That these roots are sufficiently close to one leads to a hump-shaped impulse response function for the shock ξ_{1t}.

The mean rate changes, shown in figure 1 are all significantly negative, and range from -0.2 to -1. This supports our intuition that forward risk premia are on average increasing with maturity, and that hence the drift in forward rates should be negative. The restriction that the mean rate change across futures contract is the same ("equal means") leads to a likelihood-ratio statistic of $2(-31,422 + 31,447) = 50$ and is thus rejected, since the 5% critical value of the χ^2_{21}-distribution is 32.7. The restriction that $\mu = 0$ leads to a test statistic of 58 and

hence, given the critical value of 33.9, is rejected as well.

The estimated volatilities of the pricing errors are shown in figure 2. They are all significantly different from zero and decrease with maturity: The model fits the observed rate changes increasingly well for longer maturities.

2.5 Reality check: Persistence of the federal funds rate

Does the specification of the short rate as difference stationary make empirical sense? Do the parameter estimates imply dynamic properties for the short rate that accord with the evidence? As a reality check for the plausibility of model specification and estimation results I compare the model's implications with the empirical properties of the effective federal funds rate. The empirical autocovariance function of quarterly changes in the average fed funds rate, measured in basis points, is calculated over the sample horizon Oct-1988 to Jun-2007 – using quarterly averages avoids the problems that come with the discrete nature of changes in the target. The model-implied autocovariance function of quarterly changes in the average short rate is calculated by means of a simulation based on the model specification and estimates.[14]

Figure 3 shows the result. It turns out that the model-implied variability and persistence properties correspond well to those of the actual short rate. The variance is roughly the same, around 2000. The first autocovariance is a bit higher in the data, but in the ball-park of the one implied by the model – both are between 1000 and 1500. Both autocovariance series remain positive until five lags and then turn negative. In short the specification of the short rate that I choose in this paper seems very plausible in view of the empirical properties of the fed funds rate. Not only signs but even magnitudes of autocovariances are in accordance with the data on the fed funds rate, although the estimates are obtained based entirely on money market futures data.

2.6 Inference about latent shocks and the revisions

Having estimated the parameter of the model we are able to infer from observed rate changes the values of the latent shocks and thus the entire revision to short rate expectations for any given day. Optimal inference about the latent shocks implies finding the conditional

[14] There are some caveats, neither of which undermine the usefulness of this exercise: First the model needs to be estimated on all trading days. The slight serial correlation of rate changes that was mentioned above is ignored in this estimation – its magnitude is very small and not economically significant anyways. Furthermore when re-estimating the model I only use one variance regime for simplicity, since here we only care about the average short rate dynamics across regimes. Finally the change of measure is ignored: The short rate process is simulated as if the risk-neutral and physical measure coincide.

expectation of the shock vector given the observed future rate changes on day t, $E(\xi_t|\Delta f_t)$. Because of the normality assumption it can be calculated from a linear projection:

$$\begin{aligned}\hat{\xi}_t = E(\xi_t|\Delta f_t) &= Cov_t(\xi_t, \Delta f_t)[Var_t(\Delta f_t)]^{-1}(\Delta f_t - \hat{\mu}) \\ &= V_t H_t (H_t' V_t H_t + R)^{-1}(\Delta f_t - \hat{\mu}) \end{aligned} \tag{5}$$

The fitted values for the futures rate changes are $H_t'\hat{\xi}_t + \hat{\mu}$. The estimated revision to the expected short rate path under the $\mathbb{Q}$-measure is given by equation 1, where we substitute the estimated shocks for the unobserved errors. Note that we also have an estimate for the long-run revision $\lim_{n\to\infty}(E_t^{\mathbb{Q}} - E_{t-1}^{\mathbb{Q}})x_{t+n} = \xi_{3t}$

Now we are in the position to describe in a parsimonious way how particular news events affect the term structure: The values of the three shocks capture the entire revision. The reduction in dimensionality, from an infinitely-dimensional object to just three shock values, is made possible by specifying a term structure model which imposes the absence of arbitrage and a factor structure. Section 4 introduces a new measure of policy surprises that is based on the revision resulting from policy actions. In section 5 I estimate and predict revisions resulting from macroeconomic data surprises. First though we now turn to describing the model-implied properties of the revisions in terms of variability and comovement.

3 Differential effects of news on the term structure

This section characterizes the effects of news on the term structure by describing the variability and comovement of revisions that result from policy actions and the different macroeconomic news. As we argued above, the effects of news events are completely captured by the revisions to short rate expectations. Hence an analysis of the characteristics of the revisions, conditional on the type of news event that caused them, will give us insights into the differential impacts of news on the term structure interest rates.

3.1 Term structures of volatility

We first consider the variability of short rate expectations. A conditional assessment of the term structure of volatility will enable us to distinguish and compare the different sources of volatility, by telling us about the different average magnitudes and shapes of the revisions caused by each news event.

Figure 4 shows for each of the four different news events that we consider the empirical and model-implied volatilities of money market futures rates. The first row shows vol curves for

Eurodollar futures, the second row for fed funds futures. Each of the four columns corresponds to a specific news event. The panels show sample standard deviations of daily rate changes in basis points (bp) for each contract, together with 95% confidence intervals based on a Chi-square approximation. The thick black lines are the model-implied volatilities.[15]

The term structure model successfully captures the empirical volatilities: The shapes of the vol curves are closely replicated by the model, with model-implied vol curves almost throughout lying within the confidence intervals of the empirical vol curves, and generally being close to the point estimates for the sample standard deviations, particularly for medium and longer maturities. The model specification, although very parsimonious, allows enough flexibility to capture important empirical facts such as hump-shaped dynamics (the back and the tail of the snake, see Piazzesi, 2001) and high volatilities of long forward rates (Gürkaynak et al., 2005b).

3.1.1 The effects of monetary policy

The shape of the first vol curve tells us about the average variability of the policy-induced revisions at different horizons. Since the effects of monetary policy are multi-dimensional, describing this variability for the entire maturity spectrum is crucial to understanding the character of monetary policy's effects on the term structure.

Monetary policy actions have a *significant impact on interest rates*: The variability of revisions on policy days is similar in magnitude to that resulting from news about the price level (third column) or aggregate demand (fourth column) – the average level of the vol curves are similar. Furthermore the Fed, by means of its actions and words, can affect rates *across the entire maturity spectrum*. This is evident from the sizeable variation in rates even for maturities of several years – the longest Eurodollar futures contract (ED16) has a maturity of about four years and shows similar variability as the fed funds futures contracts, which represent the short end of the vol curve. Most importantly, the impact of policy actions on short rate expectations is *strongest at a horizon of one to two years*, resulting in a distinct hump-shape.

These findings contrast with the conclusion suggested by Kuttner (2001) and Gürkaynak et al. (2005a) that the impact of monetary policy declines with maturity. These authors perform regressions of yields at different maturities on policy surprise measures, and find that regression coefficients and explanatory power (R^2) decline with maturity. However, this

[15] For the covariance matrix of the futures rate changes on day t in regime i we have $\Sigma_t = H_t V^i H_t' + R$. Since the loadings H_t and thus Σ_t depend on the day of the month and on the day of the quarter, these need to be averaged out in order to obtain Σ^i.

regression approach does not describe the impact of policy actions on the term structure, rather it simply estimates the correlation of rate changes at different maturities: The surprise measures are scaled changes in near-term money market futures and thus vary with the average change in forward rates (i.e. the average revision) at the short end. The dependent variables are yield changes, which are equal to the average changes in forward rates over the horizon of the yield maturity. Thus these regressions are simply a crude way to measure comovement in forward rates. That it decreases with maturity of the yields is not surprising: Since the short rate has transitory components (under both probability measures), revisions to expectations and thus changes in forward rates are less correlated the further apart the maturities of the forward rates are. Hence this result does not help answering the question about the impact of monetary policy. My approach on the other hand does provide answers, by recognizing that it is the entire revision which represents the effects of monetary policy, and by characterizing its properties.

3.1.2 Policy news vs. different types of macro news

A comparison of the impact of the different news events shows that short rate expectations are most volatile on days of a new employment report release. Evidently new information about the labor market causes bigger changes in policy expectations and risk premia than news about either policy actions, the price level, or aggregate demand. The vol curves for the other news regimes are at a similar level as the vol curve on policy days, with the variability on CPI/PPI days being slightly lower than for days with new retail sales. Employment news are far and beyond the most important source of volatility in the term structure.

There is a striking difference between revisions caused by policy actions and those caused by macroeconomic news: On days with macro news, they are much more steeply increasing in magnitude at the short end, as well as more back-loaded, meaning the long-end of the vol curve is at a significantly higher level than the short end. Thus, in response to new macro data, market participants revise their short rate expectations much less over the next several months and even quarters than over longer horizons. This constitutes evidence for policy inertia, the concept that changes in the stance of monetary policy are implemented by the Fed by slowly adjusting the target rate towards the new desired level, since markets clearly expect the short rate to change by much less over the next months than over the next years. Piazzesi (2001) showed how the back of the snake can be attributed to policy inertia in the context of a term structure model that incorporates monetary policy. My evidence about the impact of macro news on short rate expectations, with a very pronounced hump-shape, i.e. back of the snake, is distinctly in favor of policy inertia.

Notably my evidence stands in contrast to findings by Rudebusch (2006). We start from the same premise, namely that "changes in the path of expected future interest rates following the release of news about the state of the economy should reveal the degree of interest rate smoothing because financial markets will expect an inertial central bank to distribute the policy rate changes over several periods" (p.26). The vol curves I uncover thus support the notion of policy inertia. Rudebusch has a different approach: He calculates the ratio of 3-by-3-month forward rate to 3-month yield, based on intraday data on U.S. Treasury securities, for days with either a new employment report or new CPI data. In the case of policy inertia, the forward rate should move more strongly than the yield, and hence the ratio should usually be above one. Since the median and mean of this ratio are essentially equal to one in his sample, he concludes that "the case of little or no inertia is the relevant one" (p.29). I present comparable evidence in table 2, using the rate changes in the Eurodollar futures contracts ED2 to ED4 relative to the change in the contract ED1. The median and mean of this ratio is in all subsamples far above one. Hence for the futures rate changes in my sample, the evidence is strongly in favor of policy inertia also using Rudebusch's approach, indicating that policy inertia is a fact rather than fiction.[16]

Policy days show a less steep increase at the short end of the vol curve than news days. For fed funds futures in particular, the volatilities are about equal for all six contracts considered, notably with higher volatility for the nearest contracts than we see for any type of macro news. This makes a lot of intuitive sense, since the fed with its choice of the target, which inevitably contains surprises from time to time, creates variability at the very short end of the term structure. This is of course an important aspect of monetary policy actions. However I argue that it has been overemphasized in the literature and that considering the entire revision to the expected short rate path is the only way to satisfactorily characterize the effects of monetary policy on interest rates.

3.2 Comovement

The effects of news on the term structure are characterized not only by the variability of revisions, but also by the comovement of rate changes at different horizons. If rate changes

[16]How can the differences in our evidence be explained? Adjusting the sample window to the one used by Rudebusch does not change the qualitative results. The use of intraday data as opposed to my daily data is no likely candidate explanation, since the rate variation on the days under consideration is certainly caused to a large extent by the news event. The features of the yield data is the most likely explanation: Possibly 3-month and 6-month U.S. treasury securities move much more in lock-step than indicated by the expectations hypothesis, because of phenomena such as flight-to-security or hedging motives. The use of money market futures appears more likely to deliver reliable results.

caused by a news event strongly correlate across maturities, then one variable can sufficiently well describe the effects of these news, since the resulting revisions are always of very similar shape. However, if the correlation is not as strong, one factor is not enough anymore, since the revisions can have a variety of shapes.

My evidence indicates that macro news fall in the former category, whereas policy actions can cause more varied revisions and thus fall in the latter category. One piece of evidence was shown already in section 2.4, namely that the term structure shocks are much more strongly correlated in the case of macro news than in the case of policy actions, with the first principal component of the shock covariance matrix accounting for 92-97% of total variation in the first case, as opposed to only about 85% in second case. A principal component analysis of the model-implied covariance matrix of futures rate changes Σ (or of the empirical covariance matrix for that matter) leads to the same conclusion (evidence not shown). Stopping rules that help in determining the number of components describing common variance (Peres-Neto et al., 2005) indicate throughout that to describe variation in revisions one component suffices on news days, but that we need at least two on policy days. This evidence is in the vein of Gürkaynak et al. (2005a), who find that two factors are required to describe the variation in yields on days with policy actions. However I draw a different lesson from this evidence: We need to capture the entire revisions that result from policy actions, and the right way to do this is not by using the first two principal components of yield changes, but by parsimoniously describing the revision to short rate expectations by means of a term structure model.

Before going into more detail in section 4 about capturing monetary policy surprises with the help of my model, I will shed some more light on the regression approach that is common in the literature (Kuttner, 2001; Poole and Rasche, 2000; Gürkaynak et al., 2005b,a). I argued above that regressions of yield changes on near-term fed funds futures do not assess the impact of monetary policy on the term structure, but simply estimate comovement of rate changes in a crude way. Since the term structure model captures not only variability but also comovement of rate changes, it implies results for these regressions. I assess whether the predictions accord with the sample regression coefficients and what we can learn from comparing the regression results between the different news regimes.

Let's consider regressions of rate changes in Eurodollar futures (instead of yield changes) on a fed funds futures contract. I will use the 3-months-ahead fed funds futures contract (FF3), since it always has at least one FOMC meeting before delivery[17] and generally is a stronger measure of near-term policy surprises than the shortest contracts – admittedly the choice is

[17]Because the fed funds rate has a step-function character and only changes its level essentially every six weeks, the specification for the shortest fed funds futures contracts suffers from the problem that no rate change might occur until delivery.

slightly arbitrary. I refer to it as the near-term policy surprise. Figure 5 shows, separately for each news regime, the estimated response coefficients with 95%-confidence intervals based on White standard errors for all Eurodollar futures contracts, together with model-implied response coefficients. For details on the calculation of the model-implied coefficients please refer to appendix B. Also shown are the coefficients of determination (R^2) for each regression.

The model estimates lead to predictions that closely correspond to the empirical regression results. This holds for regressions not only for Eurodollar futures rates but also for yields (as in Kuttner, 2001) and forward rates (as in Gürkaynak et al., 2005b), as evidenced by additional calculations which I do not report here for sake of brevity. Thus, by capturing well the characteristics of revisions in terms of variability and comovement, the model in a sense encompasses the regression approach common in the literature. The advantage is that by imposing a factor structure and the absence of arbitrage, my approach delivers results that are more precise and more plausible, since it smoothes out noise due to institutional features and other phenomena in prices of individual financial instruments.

The correlation between the near-term policy surprise and other rates, and hence the explanatory power of the regressions, always decreases with maturity. As mentioned before, this is to be expected given the partly transitory nature of the short rate. It decreases much more quickly for revisions caused by policy actions than for macro news, which is just a different perspective on our previous finding of lower comovement of rate changes resulting from policy events. Interestingly however, in the case of policy surprises the regression coefficients are essentially decreasing with maturity, whereas for macro news they show a distinct hump-shape and hence reflect the shape of the vol curve on these days. Policy actions lead to revisions that are on average hump-shaped, as evidenced by the vol curve in the upper-left panel of figure 3.1, but this hump-shape is not reflected by the responses of longer rates to the near-term policy surprise. These results give another perspective on the finding that the effects of monetary policy are not decreasing with maturity: This erroneous conclusion from the regression approach simply stems from the fact that near-term policy surprise measures cannot signal the entire revision that results from policy actions. However, the near-term surprise measure apparently does a decent job in signaling the entire revision resulting from macro news, since on these days the hump-shaped variability pattern is reflected by the response coefficients. Consequently near-term fed funds futures, while of limited use in measuring policy surprises, could be useful in predicting what happens to the rest of the term structure in response to macroeconomic data surprises.

The key conclusions of this section were about the differential impact of policy actions and macroeconomic news on the term structure of interest rates, both in terms of variability and

comovement of revisions to short rate expectations across the maturity spectrum. I arrived at these conclusions by recognizing that the effects of news are multidimensional, and that they can only be described and understood if we capture them in their entirety and represent them in a parsimonious way by means of a term structure model. In the next section I will use this apparatus to develop a new measure of monetary policy shocks.

4 Measuring monetary policy shocks

A monetary policy shock is a revision to short rate expectations that is caused entirely by policy actions and not by news about the economy. Hence the shock is an inherently multidimensional object, and we need to describe it in a parsimonious way in order to make sense of it. As was shown above, the term structure model of this paper achieves this, and thus provides the right framework to measure policy shocks.

4.1 Revisions resulting from policy actions

One way to measure the shocks is to use the values of the factor shocks and depict the revision on days with a policy shock. Figure 6 shows examples of policy shock: On four different dates, each of which saw an increase in the target federal funds rate by 25 basis points, I show actual changes in Eurodollar futures rates and fitted changes implied by the revision on that day, which are obtained by backing out the values of the latent shocks using equation 5. Also shown are the estimated long-run revisions, which are simply equal to $\hat{\xi}_{3t}$, indicating how the long-run expectation of the short rate might have changed in response to the policy action. On the dates shown in the top row, the one-month ahead fed funds futures contract rate increased by 10 and 8 bps respectively, whereas on the dates shown in the bottom row it did not change at all.

The revisions resulting from the policy actions on these dates are of very different shapes, indicating that the impact of monetary policy on the term structure differed significantly. Since Kuttner (2001) we know that the target rate change is no useful measure for the policy shock, and our graphs confirm this. Furthermore, the change in a near-term fed funds futures contract is not a good indication of what happens to the term structure either, evidenced by the significantly different revisions in the left and right column, since for each row the rate change of FF1 was about the same. This exemplifies the conclusion of Gürkaynak et al. (2005a) and our evidence from the previous section. Now the strength of my model is that it provides us with an estimate of the entire revision that resulted from a policy action,

i.e. an estimate of the policy shock. We see that the rate changes implied by the estimated revision in general correspond well to the actually observed changes, with noise due to market microstructure and other influences getting smoothed out. The model captures the revision on these days very well.

4.2 A horizon-specific measure for policy shocks

Although we can describe the revision resulting from policy actions graphically, many situations will require a numeric measure that summarizes the policy shock. The state of the art seems to be the approach of Gürkaynak et al. (2005a), namely providing two numbers, the "target factor" and the "path factor", which are derived from near-term money market futures. These are simply the first two principal components of the futures rate changes, rotated such that the target factor has a unit impact on the nearest-term futures contract and that both factors have the same impact on the furthest out futures contract. This approach has several shortcomings: First, by being simply a statistical summary of rate changes at the short end, it lacks the advantages of a term structure model. In particular, it does not imply changes of rates at arbitrary maturities that follow from no-arbitrage. Second, the measure is hard to interpret – it is not at all obvious what a specific number for the path factor means intuitively. Third, it leaves open the question how we would have to combine the two measures were we in need of a univariate summary of the policy shock for a certain purpose. All of these disadvantages are related to the fundamental flaw that this approach does not capture the entire revision to short rate expectations.

My approach suggests a new way to numerically summarize policy shocks. The key insight is that for different relevant horizons we should be using different measures of policy shocks, since the expected short rate does not change by the same amount across all horizons. We can measure the policy shock that is relevant for a particular horizon by using changes in near-term money market futures to infer the revision to short rate expectations, and then calculate the average revision over the horizon under consideration. Thus we would for example use the average change in the expected short rate over the next two years, which is the model-implied change in a two-year yield, to assess the impact of monetary policy on the two-year treasury note. Mathematically the policy shock measure on day t for the horizon starting n days ahead

and ending $n+m$ days ahead is

$$\begin{aligned} mp_t^m &= m^{-1} \sum_{\tau=n}^{n+m-1} (\hat{E}_t^{\mathbb{Q}} - \hat{E}_{t-1}^{\mathbb{Q}}) x_{t+\tau} \\ &= c_{n,m} + h'_{n,m} E(\xi_t | \Delta f_t), \\ &= c_{n,m} + h'_{n,m} \hat{\xi}_t, \end{aligned}$$

where Δf_t includes only near-term money market futures, $h_{n,m}$ is a vector of loadings, and $c_{n,m}$ is a constant.[18] The loadings correspond to an m-day yield change in the case of $n = 0$, and generally to an n-by-m forward rate change implied by the term structure model. Exact expressions for these loadings are provided in appendix C. I employ fed funds futures contracts FF1 to FF6 and Eurodollar futures contracts ED1 to ED4 in order to back out the factors and construct the shock measure. In short, the policy shock measure corresponds simply to the model-implied rate changes for yields or forwards rates over the specific horizon, given the particular factor estimates obtained from near-term money market futures. This is the policy shock measure that logically follows from the theoretical framework of this paper.

4.3 Empirical assessment

Using my new horizon-specific measure, I assess the reaction of treasury securities to monetary policy shocks. To contrast the results with those of previous studies, I construct target and path factor according to the methodology of Gürkaynak et al. (2005a) based on the same information set. Data on yields and forward rates are those of Gürkaynak et al. (2006). My sample contains the FOMC announcement dates from October 1988 to June 2007, excluding as before observations with employment reports, CPI/PPI news or new retail sales, and now also those that do not have yield data available. This gives us 148 observations.

Table 3 shows the results. Numbers in parentheses are White standard errors. The first three columns give regression coefficients and R^2 for for regressions using only the target factor. The next four columns show the same for regressions using both target and path factors. These results are comparable to table 5 of Gürkaynak et al. (2005a), differences result from different sample choice and the information set used to construct the factors. The first section of the table shows that in fact the target factor has a one-for-one impact on the one-month-ahead fed funds futures contract, that the factors are orthogonal, and that both factors have the same impact on the longest futures contract.

[18] Since we use the policy shock as a right-hand-side variable in different regressions, the constant is irrelevant, and we set it equal to zero.

In the last three columns we see how treasury securities react to the new horizon-specific measure of monetary policy shocks. First and foremost, the slope coefficients all statistically significant at the 1% level, and larger than those on either target or path factor. Treasury yields show a strong and significant response to policy shocks when the shock is measured as I suggest.

Furthermore the explanatory power of the univariate policy shock measure that I constructed is about as large as that of target and path factors taken together: A univariate regression with my horizon-specific measure for policy shocks as explanatory variable explains the same about of variation in yields and forward rates as a multivariate regression using the target and path factors of Gürkaynak et al. (2005a). This results from the construction of my policy shocks which is specific to the horizon under consideration. This in turn is made possible because my term structure model allows us to infer the entire revision to short rate expectations from any given subset of rate changes, in this case near-term money market futures.

Hence a horizon-specific shock measure does not only have intuitive appeal, but also is empirically successful. For these reasons it seems promising to take the route I suggest here when measuring monetary policy shocks.

5 The impact of macroeconomic data surprises

Although there is agreement in the literature that macroeconomic announcements have an important impact on interest rates, "few studies examine their impact on the yield curve as a whole," as noted by Fleming and Remolona (1999, p. 1). These authors fill this gap by estimating the impact of announcements on yields of different maturities. They find hump-shaped responses and attribute this to policy inertia. More recently Gürkaynak et al. (2005b) performed a similar analysis but using forward rates instead of yields, which gives a cleaner picture of how short rate expectations (and possibly risk premia) at different horizons react to data surprises. The hump shape is clearly visible in their results, furthermore long forward rates react significantly to announcements. This is puzzling in the context of modern macro-models, and is thus termed "excess-sensitivity puzzle".

In order to really understand the impact of macro news on the term structure, the regression approach of separately regressing each rate on a surprise measure, which is conventionally followed in the literature, is unsatisfactory: As in the case of monetary policy shocks, we need to capture the revision to the entire expected short rate path that results from a specific macroeconomic data surprise. After analyzing the variability and comovement of revisions

caused by macro news in section 3, we now employ the framework of this paper to estimate the response of the expected short rate path to different macroeconomic announcements, i.e. the term structure of announcement effects.

My theoretical framework allows us to uncover the term structure of announcement effects in a very simple way: In a first step we determine the values of the factor shocks that are associated with a one-unit surprise in any data series. Regressions for each of the three shocks (which are inferred from money market futures as described above) on the data surprises do the job. Then in a second step we use these values to calculate the implied revision. Note that this is different from the usual regression approach where rates of different instruments are separately regressed on the surprise measure: By estimating the response of the factor shocks to the surprises I take into account that the whole term structure moves according to the revisions to short rate expectations, thus my approach is consistent with the absence of arbitrage and a particular short rate process.

I use data on six different macroeconomic data releases: Non-farm payroll employment, the unemployment rate, hourly earnings, Core CPI and Core PPI (Bureau of Labor Statistics, BLS) as well as retail sales (Department of Commerce). The sample consists of all days with at least one data release between October 1988 and June 2007, which did not have a policy action, i.e. an FOMC announcement. The surprise component in the data release is calculated as the difference between the actually released number and the value expected by the market. To measure the market expectation I take the median market forecast, which is compiled by Money Market Services the Friday before the announcement.[19] The impact of the data surprises is estimated by including a constant and all six surprise measures on the right-hand-side of the regressions, thus if there are several news releases on one day, their impact is singled out by estimating partial effects.

Table 4 shows the numerical results, including the response coefficients for the futures contracts FF2 and ED4 as well as for the two-year yield. The last three columns display responses of the factor shocks, which for each news announcement completely characterize the implied revision. The response of $\hat{\xi}_{3t}$ to the surprise measures the long-run impact of the news. Numbers in parentheses are White standard errors. Figure 7 shows the term structure of announcement effects. Results from unrestricted regressions for each Eurodollar futures contract, which correspond to the conventional regression approach, are shown together with the model-implied rate changes (the solid line) which follow from the specific revisions associated with the news release. These rate changes reveal the term structure of announcement

[19] Rigobon and Sack (2006) advance some points why this surprise measure might be contaminated with a considerable amount of noise. It might pay off to use intra-day data in this context, and possibly to address the measurement bias problem with new econometric tools. I relegate both issues to possible future work.

effects that is consistent with the absence of arbitrage and my model specification. Also I include the implied long-run revision (the dashed line).

The table shows that all announcements have a significant effect on the short end of the term structure, evidenced by the response of the FF2 contract. Also, all announcements with the exception of Core PPI lead to significant responses of ED4 and the two-year yield. From this evidence alone we would conclude that there is a significant impact of these macro news on the term structure. However, to the question about announcement effects, this is an insufficient and even misleading response. A correct and much more accurate answer is obtained by considering in detail the effects across the term structure, to which I now turn.

First of all the figure shows that the model leads to results consistent with the empirical announcement effects: The model-implied responses correspond closely to the unrestricted estimates of the response coefficients. The increase at the short end, the hump-shape and the leveling out towards a long-run response are all captured by the predicted response curve. The predicted responses are always very close to the point estimate of the response for each contract. Hence, once again, we see that the restrictions of my model are empirically plausible, which enables us to capture the impact of macroeconomic news on the term structure by describing the revisions to the expected short rate path that the announcements cause.

One important pattern in the term structure of announcement effects, as is evident from looking at figure 7, is a distinct hump-shape. Most announcements show this pattern, leading to increasing responses up to maturities of one to two years, with a decreasing response thereafter. Since it is the shock to the first short rate component, ξ_{1t}, that gives us hump-shaped dynamics, we see a strong hump-shape in those cases where this shock responds significantly to the data surprise. As was discussed above, increasing responses to macro news are evidence for policy inertia: The Fed is expected to act in response to the news, but not to immediately and fully adjust the target in response to the new information. Rather it will implement the new stance of monetary policy over a number of FOMC meetings, thus near-term responses are increasing in the horizon. The results here about the impact of macro news on short rate expectations add to the evidence on the term structures of volatility in section 3.1 and make our case for policy inertia even stronger.

The other important aspect in this context is whether a specific news release moves the long end of the term structure. My model allows us to assess this systematically by considering whether the release leads to a significant long-run revision, i.e. whether it significantly affects the shock to the unit-root component of the short rate, ξ_{3t}. As we see in the right-most column of table 4 this is the case for all announcements but the unemployment rate and hourly earnings. These two releases only move short rate expectations up to medium maturities,

then their impact dies out. The unrestricted responses in figure 7 also give some indication about the long-run impact of a specific announcement, however my approach allows a rigorous assessment of whether there are long-run effects, by testing whether the announcement has a significant impact on the persistent shock to the short rate, i.e. causes a non-zero long-run revision.

Importantly most releases do lead to a significant long-run revision. This fact is consistent with the finding of Gürkaynak et al. (2005b) that far-ahead forward rates significantly respond to most macroeconomic announcements, which they term the "excess-sensitivity puzzle." One reason that the volatility and sensitivity of long forward rates constitutes a puzzle is that conventional macro models predict that forward rates revert towards the natural rate with increasing horizon. From a different point of view, if the short rate was mean-reverting under the risk-neutral measure, we would have a zero long-run revision and far-ahead forward rates that are close to constant. Our finding corroborates the evidence of these authors that forward rates do not revert to the natural rate. Furthermore it strongly indicates that the short rate under $\mathbb{Q}$ is not mean-reverting. Note that we are not saying that the short rate is necessarily non-stationary under $\mathbb{P}$: The variability in long rates could well (and probably does) come from changing risk premia, and future research should assess their role in this matter by decomposing the variability and responses of long forward rates.

In sum, my approach leads to a clearer and more differentiated answer about the impact of macroeconomic data announcements on short rate expectations across horizons than the regression approach that is common in the literature. We have shown the term structure of announcement effects for selected news releases which is consistent with the absence of arbitrage and our specification of the short rate process. Its hump-shape indicates an important role for policy inertia in how market participants revise their expectations. Furthermore, the significant long-run revision implied by most of these announcements, corresponding to a response of the persistent component in the risk-neutral short rate, is clear evidence for the existence of the excess-volatility puzzle.

6 Conclusion

This paper introduces a coherent framework to describe and understand the impact of news on the term structure. The key question is: What are the effects of monetary policy shocks and macroeconomic announcements on interest rates? My term structure model, which allows for heterogenous sources of volatility, and the concept of the revision to the entire expected short rate path under the risk neutral measure together enable us to provide more satisfactory

answers to this question than previous studies have been able to give.

The take-aways are: (1) The conventional regression approach of separately estimating the impact of some surprise measure on the rate of each instrument is not the right apparatus to assess the impact of news on the term structure. (2) Monetary policy actions affect the entire term structure, with the strongest impact at medium maturities. (3) Different policy actions vary greatly in their impact on interest rates, with these differences intuitively resulting from the independent pieces of information that markets receive. When measuring policy shocks, we thus need to take into account the relevant maturity (or investment) horizon. (4) Macroeconomic announcements differ in their impact on short rate expectations, but most lead to a strongly hump-shaped response and a significant long-run revision. (5) The evidence is clearly in favor of policy inertia: Market participants revise their expectations of the short rate in accordance with the Fed sluggishly adjusting its policy rate. (6) Long forward rates move more strongly than suggested by conventional macro-models or by a term structure model that imposes mean-reversion of the short rate under the risk-neutral measure, confirming the existence of an excess-volatility puzzle.

Two directions for future work are the use of intraday data to improve the precision of the estimates, and in particular the identification of the impact of news on risk premia. The first point seems to be a fruitful task because in particular for monetary policy shocks we would like to make sure that the revision we estimate is the one caused by the policy action, and that there are no other confounding impacts. By looking at short time windows around the actual policy announcements we could corroborate our results about the effects of policy shocks on the term structure.

With regard to risk premia, the obvious next step is to disentangle the effects of news on short rate expectations and risk premia. We could answer additional questions which are of great policy relevance, and in fact were suggested to me by the Fed Chairman Ben Bernanke himself.[20] The first and most important question is about the general direction of responses in term premia to Fed actions. Furthermore, if the responses vary, a characterization of the regimes or conditions that lead to particular responses would give us important new insights. More generally we would like to describe the impact of different kinds of news on term premia. My framework can be generalized to incorporate a risk premium specification explicitly: By specifying a pricing Kernel and decomposing the revisions to short rate expectations under $\mathbb{Q}$ into the revisions under $\mathbb{P}$ and changes in the forward risk premium, we would be able to provide answers to the questions above, and obtain an even more differentiated characterization of the impact of news on the term structure.

[20] Personal conversation at the Federal Reserve Board, September 2008.

References

Backus, David K., Chris I. Telmer, and Liuren Wu, "Design and Estimation of Affine Yield Models," GSIA Working Papers 5, Carnegie Mellon University, Tepper School of Business November 1999.

Balduzzi, Pierluigi, E. J. Elton, and T. C. Green, "Economic News and Bond Prices: Evidence from the U.S. Treasury Market," *Journal of Financial and Quantitative Analysis*, December 2001, *36* (4), 523–544.

_ , Sanjiv Ranjan Das, and Silverio Foresi, "The Central Tendency: A Second Factor In Bond Yields," *The Review of Economics and Statistics*, February 1998, *80* (1), 62–72.

_ , _ , _ , and Rangarajan Sundaram, "A Simple Approach to Three-Factor Affine Term Structure Models," *Journal of Fixed Income*, December 1996, pp. 43–53.

Bansal, Ravi and Hao Zhou, "Term Structure of Interest Rates with Regime Shifts," *Journal of Finance*, October 2002, *57* (5), 1997–2043.

Christensen, Jens H.E., Francis X. Diebold, and Glenn D. Rudebusch, "The affine arbitrage-free class of Nelson-Siegel term structure models," Technical Report 2007.

Faust, Jon, John H. Rogers, Shing-Yi B. Wang, and Jonathan H. Wright, "The high-frequency response of exchange rates and interest rates to macroeconomic announcements," *Journal of Monetary Economics*, May 2007, *54* (4), 1051–1068.

Fleming, Michael J. and Eli M. Remolona, "What moves the bond market?," *Economic Policy Review*, 1997, (Dec), 31–50.

_ and Eli M Remolona, "The term structure of announcement effects," BIS Working Papers 71, Bank for International Settlements June 1999.

Gürkaynak, Refet S., Brian P. Sack, and Eric T. Swanson, "Do Actions Speak Louder Than Words? The Response of Asset Prices to Monetary Policy Actions and Statements," *International Journal of Central Banking*, May 2005, *1* (1), 55–93.

_ , _ , and _ , "The Sensitivity of Long-Term Interest Rates to Economic News: Evidence and Implications for Macroeconomic Models," *American Economic Review*, March 2005, *95* (1), 425–436.

_ , _ , **and** _ , "Market-Based Measures of Monetary Policy Expectations," *Journal of Business & Economic Statistics*, April 2007, *25* (2), 201–212.

_ , **Brian Sack, and Jonathan H. Wright**, "The U.S. Treasury yield curve: 1961 to the present," Finance and Economics Discussion Series 2006-28, Board of Governors of the Federal Reserve System (U.S.) 2006.

Hamilton, James D., *Time Series Analysis*, Princeton University Press, 1994.

_ , "Daily Changes in Fed Funds Futures Prices," NBER Working Papers 13112, National Bureau of Economic Research, Inc May 2007.

_ , "Assessing monetary policy effects using daily federal funds futures contracts," *Federal Reserve Bank of St. Louis Review*, 2008, (Jul), 377–394.

Kuttner, Kenneth N., "Monetary Policy Surprises and Interest Rates: Evidence from the Fed Funds Futures Market," *Journal of Monetary Economics*, 2001, *47*, 523–544.

Marmol, Francesc, "The Stationarity Conditions for an AR(2) Process and Schur's Theorem," *Econometric Theory*, dec 1995, *11* (5), 1180–1182.

Monfort, Alain and Fulvio Pegoraro, "Switching VARMA Term Structure Models," *Journal of Financial Econometrics*, 2007, *5* (1), 105–153.

Peres-Neto, Pedro R., Donald A. Jackson, and Keith M. Somers, "How many principal components? stopping rules for determining the number of non-trivial axes revisited," *Computational Statistics & Data Analysis*, June 2005, *49* (4), 974–997.

Piazzesi, Monika, "An Econometric Model of the Yield Curve with Macroeconomic Jump Effects," NBER Working Papers 8246, National Bureau of Economic Research, Inc April 2001.

_ , "Bond Yields and the Federal Reserve," *Journal of Political Economy*, April 2005, *113* (2), 311–344.

_ **and Eric T. Swanson**, "Futures Prices as Risk-Adjusted Forecasts of Monetary Policy," Working Paper 10547, National Bureau of Economic Research 2004.

Poole, William and Robert H. Rasche, "Perfecting the Market's Knowledge of Monetary Policy," *Journal of Financial Services Research*, 2000, *18* (2/3), 255–298.

Rapach, David E. and Christian E. Weber, "Are real interest rates really nonstationary? New evidence from tests with good size and power," *Journal of Macroeconomics*, September 2004, *26* (3), 409–430.

Rigobon, Roberto and Brian Sack, "The impact of monetary policy on asset prices," *Journal of Monetary Economics*, November 2004, *51* (8), 1553–1575.

_ **and** _ , "Noisy Macroeconomic Announcements, Monetary Policy, and Asset Prices," NBER Working Papers 12420, National Bureau of Economic Research, Inc August 2006.

Rose, Andrew Kenan, "Is the Real Interest Rate Stable?," *Journal of Finance*, December 1988, *43* (5), 1095–1112.

Rudebusch, Glenn D., "Monetary Policy Inertia: Fact or Fiction?," *International Journal of Central Banking*, December 2006, *2* (4).

Startz, Richard and Kwok Ping Tsang, "The Yield Curve through Time and Across Maturities," Working Papers UWEC-2007-05, University of Washington, Department of Economics March 2007.

Stigum, Marcia and Anthony Crescenzi, *The Money Market*, fourth ed., McGraw-Hill, 2007.

White, Halbert, "Maximum Likelihood Estimation of Misspecified Models," *Econometrica*, January 1982, *50* (1), 1–25.

A Loadings of futures rate changes on factor shocks

For the loading of the i-period-ahead contract futures rate change on the first shock we have

$$\begin{aligned} h_i^1 &= N^{-1} \sum_{n=iN-d+1}^{(i+1)N-d} (1+n)\rho^n \\ &= \frac{(iN-d+2)\rho^{iN-d+1} - [(i+1)N-d+2]\rho^{(i+1)N-d+1}}{N(1-\rho)} + \frac{\rho^{iN-d+2}(1-\rho^N)}{N(1-\rho)^2}, \end{aligned}$$

where d is the day of the month. To see this we take the well-known summation formula for the geometric progression,

$$\sum_{k=m}^{n} r^k = \frac{r^m - r^{n+1}}{1-r},$$

and take the first derivative with respect to r to obtain

$$\sum_{k=m}^{n} kr^{k-1} = \frac{mr^{m-1} - (n+1)r^n}{1-r} + \frac{r^m - r^{n+1}}{(1-r)^2}.$$

This can be applied to the summation above. For the loading on the second shock we have

$$\begin{aligned} h_i^2 &= N^{-1} \sum_{n=iN-d+1}^{(i+1)N-d} \rho^n \\ &= \frac{\rho^{iN-d+1}(1-\rho^N)}{N(1-\rho)}. \end{aligned}$$

The loading on the third shock is unity. The vector with loadings is $h_i = (h_i^1, h_i^2, 1)'$. I suppress the dependence on the parameters and on the day of the month for notational simplicity.

B Regression coefficients and R^2 implied by the model

The population parameters for regressions of rate changes in Eurodollar futures contracts on rate changes in the 3-month-ahead fed funds futures contract (FF3) are equal to the covariance between the two variables, divided by the variance of the fed funds futures rate changes. The coefficient of determination is simply the squared correlation. The model parameters imply both variances and covariances, and hence predict the regression coefficients and R^2. Importantly, these depend on the news regime through the factor covariance matrix V^i. In regime i, the model-implied regression coefficients and coefficients of determination for a regression

of Eurodollar futures contract j on the contract FF3 are

$$\begin{aligned}
\beta_j &= \frac{Cov(\Delta f_t^j, \Delta f_t^{FF3})}{Var(\Delta f_t^{FF3})} = \frac{Cov(h_j'\xi_t, h_{FF3}'\xi_t)}{Var(h_{FF3}\xi_t + \varepsilon_t^{FF3})} = \frac{h_j' V^i h_{FF3}}{h_{FF3}' V^i h_{FF3} + \sigma^2_{\varepsilon,FF3}}, \text{and} \\
R_j^2 &= \frac{(Cov(\Delta f_t^j, \Delta f_t^{FF3}))^2}{Var(\Delta f_t^{FF3}) Var(\Delta f_t^j)} = \frac{(h_j{}' V^i h_{FF3})^2}{(h_{FF3}{}' V^i h_{FF3} + \sigma^2_{\varepsilon,FF3})(h_j{}' V^i h_j + \sigma^2_{\varepsilon,j})}.
\end{aligned}$$

Here $j = ED1, \ldots, ED16$, and ε_t^{FF3} stands for the pricing error of FF3, which has a variance of $\sigma^2_{\varepsilon,FF3}$, the square of the third diagonal element of R. The pricing error variances for the Eurodollar futures $\sigma^2_{\varepsilon,j}$ correspond to the squares of the 7th to 22nd diagonal elements of R.

The above notation ignores that the loadings of the futures depend on the day of the month and the day of the quarter, and hence the regression coefficient is a different one for each combination of these. To obtain an unconditional regression coefficient, I simply average out the day of the month/quarter.

C Loadings of yields and forward rates on factor shocks

For the loading of an m-day yield change on the first shock we have

$$\begin{aligned}
h_m^1 &= m^{-1} \sum_{n=0}^{m-1} (1+n)\rho^n \\
&= \frac{1-(m+1)\rho^m}{m(1-\rho)} + \frac{\rho - \rho^{m+1}}{m(1-\rho)^2}.
\end{aligned}$$

For the loading on the second shock we have

$$\begin{aligned}
h_m^2 &= m^{-1} \sum_{n=0}^{m-1} \rho^n \\
&= \frac{1-\rho^m}{m(1-\rho)}.
\end{aligned}$$

The loading on the third shock is unity. The vector with loadings is $h_m = (h_m^1, h_m^2, 1)'$.

For the loading of an m-day forward rate change starting n days ahead on the first shock

we have

$$\begin{aligned} h^1_{n,m} &= m^{-1} \sum_{h=n}^{n+m-1} (1+h)\rho^h \\ &= \frac{(n+1)\rho^n - (n+m+1)\rho^{n+m}}{m(1-\rho)} + \frac{\rho^{n+1} - \rho^{n+m+1}}{m(1-\rho)^2}. \end{aligned}$$

For the loading on the second shock we have

$$\begin{aligned} h^2_{n,m} &= m^{-1} \sum_{h=n}^{n+m-1} \rho^n \\ &= \frac{\rho^n(1-\rho^m)}{m(1-\rho)}. \end{aligned}$$

The loading on the third shock is unity. The vector with loadings is $h_{n,m} = (h^1_{n,m}, h^2_{n,m}, 1)'$.

Table 1: Maximum Likelihood Estimation of factor model

Parameter	policy days	empl. report	CPI/PPI	retail sales
$\sigma_{\xi,1}$	0.0415	0.0648	0.0379	0.0419
	(0.0038)	(0.0056)	(0.0028)	(0.0050)
$\sigma_{\xi,2}$	9.9291	11.3830	7.2834	9.9564
	(1.3795)	(0.9379)	(0.3755)	(1.3312)
$\sigma_{\xi,3}$	6.5434	10.0468	6.3384	8.2916
	(0.4992)	(0.6740)	(0.3060)	(0.9709)
$corr(\xi_{1t}, \xi_{2t})$	-0.3662	-0.5426	-0.4273	-0.3312
	(0.0662)	(0.0752)	(0.0596)	(0.0949)
$corr(\xi_{1t}, \xi_{3t})$	+0.2676	+0.5035	+0.2358	+0.2505
	(0.0883)	(0.0651)	(0.0565)	(0.0856)
$corr(\xi_{2t}, \xi_{3t})$	-0.6390	-0.8437	-0.8877	-0.9394
	(0.0962)	(0.0301)	(0.0223)	(0.0201)
Energy content:				
1st princ. comp.	85.37%	92.32%	94.50%	97.07%
2nd princ. comp.	14.63%	7.68%	5.50%	2.93%
3rd princ. comp.	$< 0.01\%$	$< 0.01\%$	$< 0.01\%$	$< 0.01\%$
ρ	0.9973			
Log-likelihood	-31,422			
Other models:				
unrestr. roots	-31,422			
equal V's	-31,609			
equal means	-31,447			
zero means	-31,451			

I use fed funds futures contracts FF1 to FF6 and Eurodollar futures contracts ED1 to ED16 to estimate the model (description see text). Sample: 10-1988 to 06-2007. The number of days is 799, with 148, 215, 316, and 120 days in each of the four regimes. Numbers in parentheses are Quasi-Maximum Likelihood standard errors. Also reported are the energy contents of the three principal components for each of the shock covariance matrices V^1 to V^4, as well as the log-likelihood for the benchmark version of the model and for more and less restricted versions as described in the text.

Table 2: Summary statistics for ratio of near-term rate changes

News	$\Delta f_t^{ED2}/\Delta f_t^{ED1}$			$\Delta f_t^{ED3}/\Delta f_t^{ED1}$			$\Delta f_t^{ED4}/\Delta f_t^{ED1}$			
	median	mean	(s.e.)	median	mean	(s.e.)	median	mean	(s.e.)	obs.
Empl. report	1.83	2.30	(0.20)	2.25	3.08	(0.30)	2.32	3.35	(0.38)	136
CPI/PPI	1.63	1.98	(0.16)	2.00	2.74	(0.27)	2.33	3.30	(0.33)	185
Retail sales	2.11	2.46	(0.22)	3.33	3.80	(0.45)	3.75	4.33	(0.57)	61
Pooled	1.78	2.17	(0.11)	2.26	3.03	(0.19)	2.50	3.48	(0.23)	382

Medians, means, and standard errors for the means for relative rate changes. means Sample: 10-1988 to 06-2007. I include only observations for which the denominator rate change is non-zero (using unity for the ratio when the denominator is zero still results in medians and means far above one).

Table 3: Regressions of rate changes on different measures of monetary policy shocks.

	Target factor			**Target and path factors**				**Horizon-specific measure**		
	const.	target	R^2	const.	target	path	R^2	const.	shock	R^2
Futures										
FF1	0.17	1.00**	0.93	0.17	1.00**	0.00	0.93			
	(0.15)	(0.03)		(0.14)	(0.03)	(0.01)				
ED4	-0.64	0.59**	0.18	-0.09	0.59**	0.59**	0.98			
	(0.60)	(0.16)		(0.09)	(0.02)	(0.01)				
yields										
two years	-0.21	0.46**	0.21	0.15	0.46**	0.38**	0.86	-0.12	0.83**	0.84
	(0.47)	(0.12)		(0.20)	(0.05)	(0.02)		(0.21)	(0.03)	
five years	-0.27	0.26	0.07	0.11	0.26**	0.40**	0.76	-0.06	0.83**	0.75
	(0.51)	(0.15)		(0.25)	(0.08)	(0.03)		(0.28)	(0.04)	
ten years	-0.33	0.13	0.02	-0.03	0.13	0.32**	0.60	-0.14	0.70**	0.59
	(0.46)	(0.12)		(0.29)	(0.07)	(0.03)		(0.31)	(0.06)	
forward rates (6mo)										
two years	-0.18	0.30	0.06	0.27	0.30**	0.48**	0.80	0.08	0.83**	0.79
	(0.60)	(0.16)		(0.28)	(0.07)	(0.03)		(0.29)	(0.04)	
five years	-0.36	0.07	< 0.01	-0.03	0.07	0.35**	0.50	-0.12	0.77**	0.48
	(0.49)	(0.14)		(0.34)	(0.10)	(0.05)		(0.39)	(0.06)	
ten years	-0.45	-0.04	< 0.01	-0.28	-0.04	0.18**	0.20	-0.24	0.40**	0.17
	(0.47)	(0.07)		(0.42)	(0.06)	(0.04)		(0.42)	(0.08)	

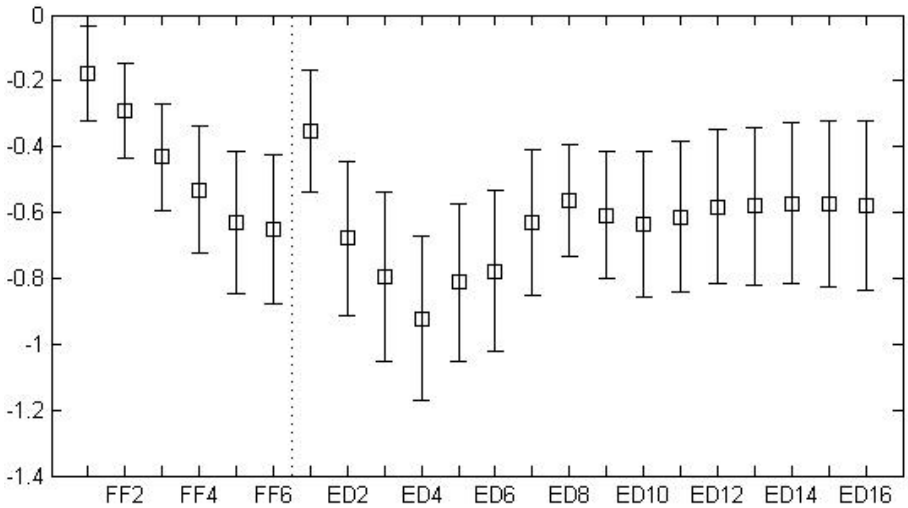
The number of observations is 148. Numbers in parentheses are White standard errors. * denotes statistical significance at the 1% level. Forward rates are for six-month loans ending at the specified maturities. For explanation of target and path factors refer to text and Gürkaynak et al. (2005a). Horizon-specific policy shock measure is calculated as average estimated revision over relevant horizons (details see text). Policy shock measures are inferred from information set including fed funds futures contracts FF1 to FF6 and Eurodollar futures contracts ED1 to ED4.

Table 4: Effects of macroeconomic announcements

News release	FF2	ED4	2y yield	$\hat{\xi}_{1t}$	$\hat{\xi}_{2t}$	$\hat{\xi}_{3t}$
Non-farm payroll empl.	2.94**	7.72**	5.53**	0.03**	-3.17**	3.53**
	(0.34)	(0.84)	(0.56)	(0.00)	(0.95)	(0.63)
Unemployment rate	-9.41**	-13.85*	-10.43**	-0.04	-6.86	-2.34
	(2.43)	(5.37)	(3.72)	(0.03)	(5.84)	(4.46)
Hourly earnings	5.39**	15.24**	11.73**	0.08**	-10.09	8.33
	(1.64)	(5.09)	(3.64)	(0.03)	(5.99)	(4.61)
Core CPI	8.59**	21.75**	17.52**	0.07**	-12.53**	15.33**
	(1.95)	(5.36)	(4.01)	(0.02)	(4.83)	(4.40)
Core PPI	1.57*	3.65	1.87	-0.00	-2.98	4.39**
	(0.65)	(2.04)	(1.66)	(0.01)	(1.92)	(1.62)
Retail sales	1.24**	4.65**	3.52**	0.03**	-3.08**	2.35**
	(0.34)	(0.96)	(0.73)	(0.00)	(0.91)	(0.82)

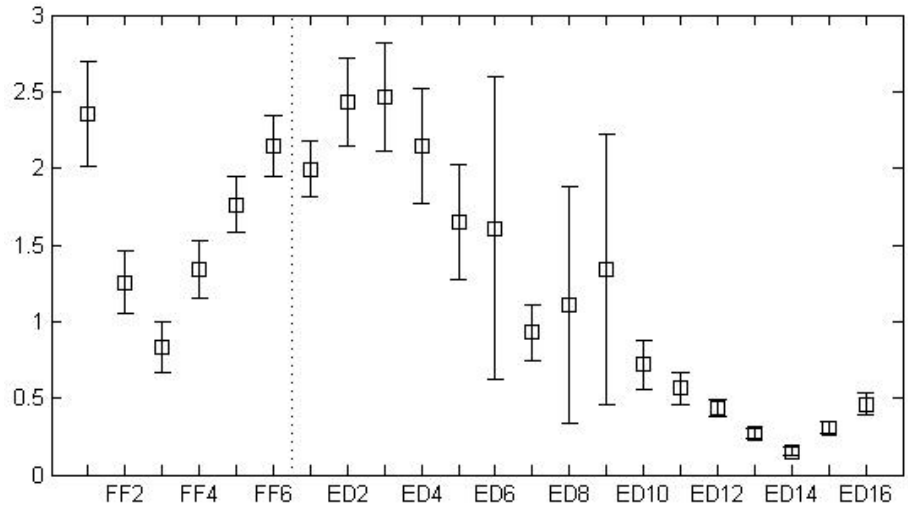
Sample: Days with at least one macroeconomic announcement but without policy action, Oct-1988 to Jun-2007, $N = 647$. Numbers in parentheses are White standard errors. * and ** denote significance at 5% and 1% level, respectively.

Figure 1: Estimated means of futures rate changes



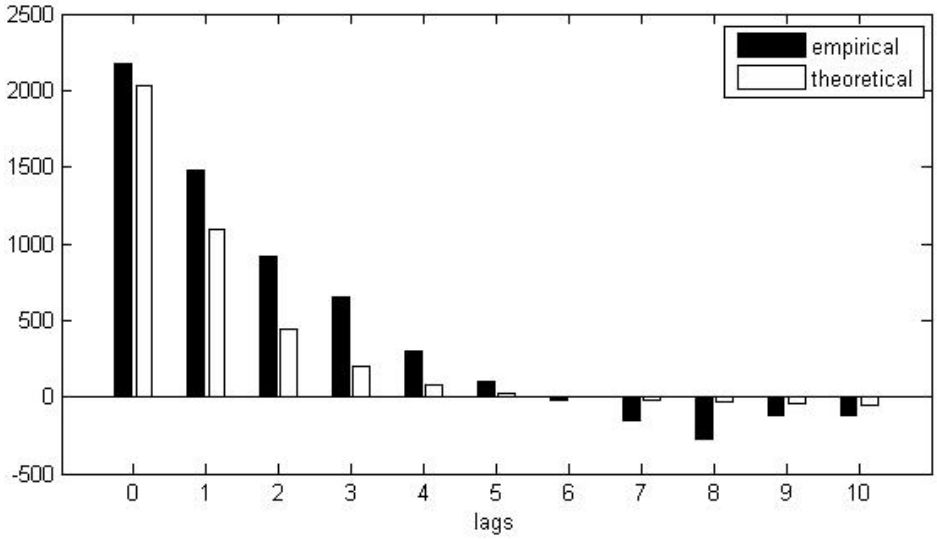
Estimated means of rate changes of money market futures, together with 95%-confidence intervals based on Quasi-Maximum-Likelihood standard errors, for benchmark specification of the model. Please refer to the text or table 1 for data description.

Figure 2: Estimated volatilities of pricing errors



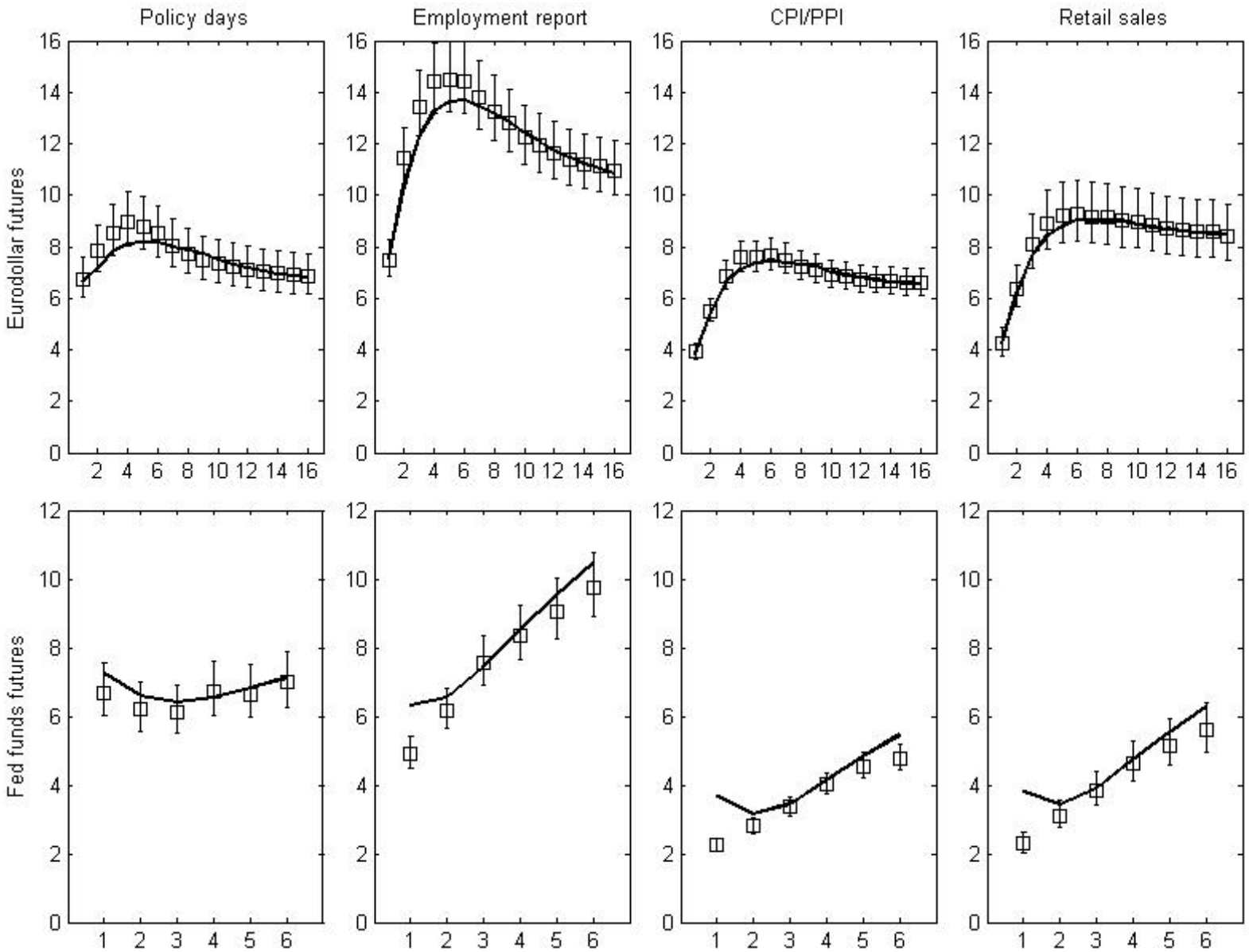
Estimated volatilities of pricing errors together with 95%-confidence intervals based on Quasi-Maximum-Likelihood standard errors, for benchmark specification of the model. Please refer to the text or table 1 for data description.

Figure 3: Empirical vs. model-implied autocovariances of federal funds rate



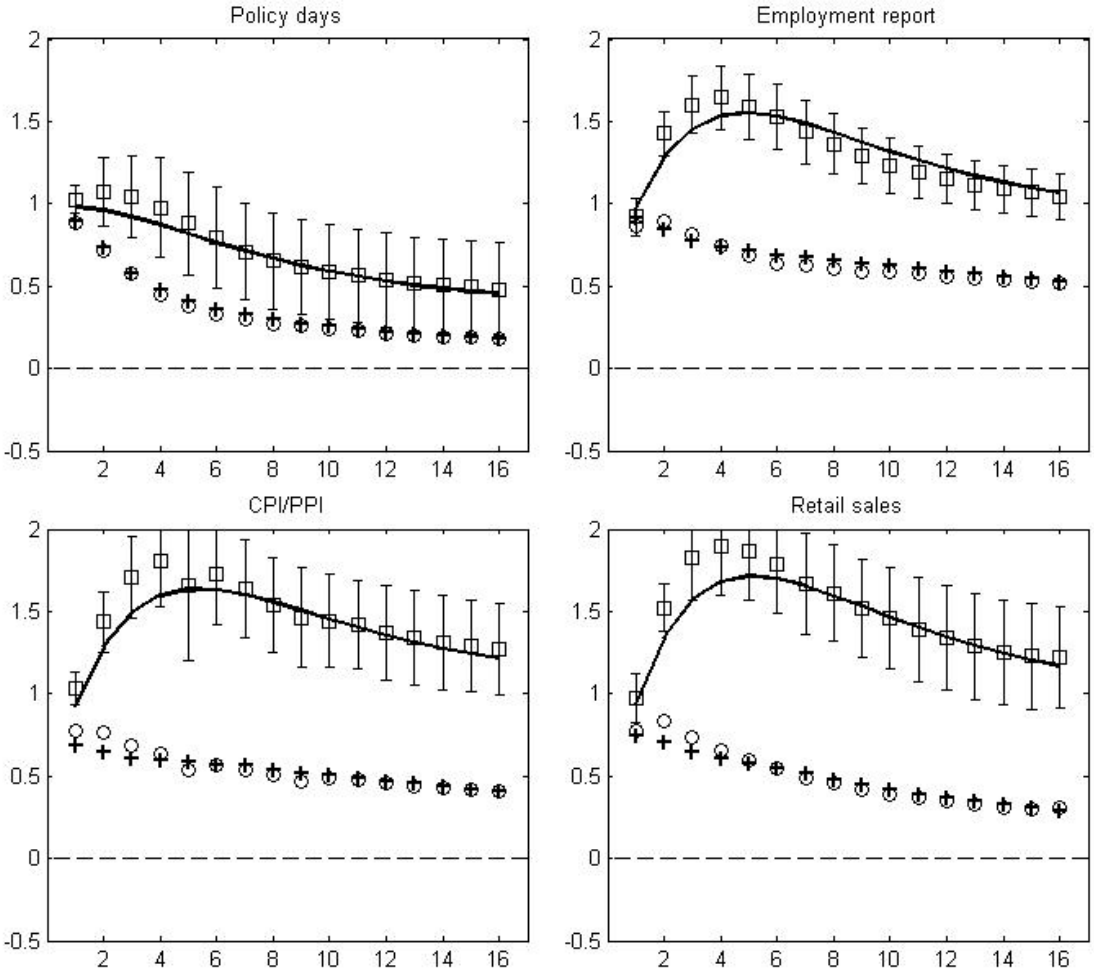
Autocovariances of the first differences in the average quarterly short rate. Empirical autocovariances for effective federal funds rate from Oct-1988 to Jun-2007. Model-implied autocovariances: see text.

Figure 4: Vol curves for different news events



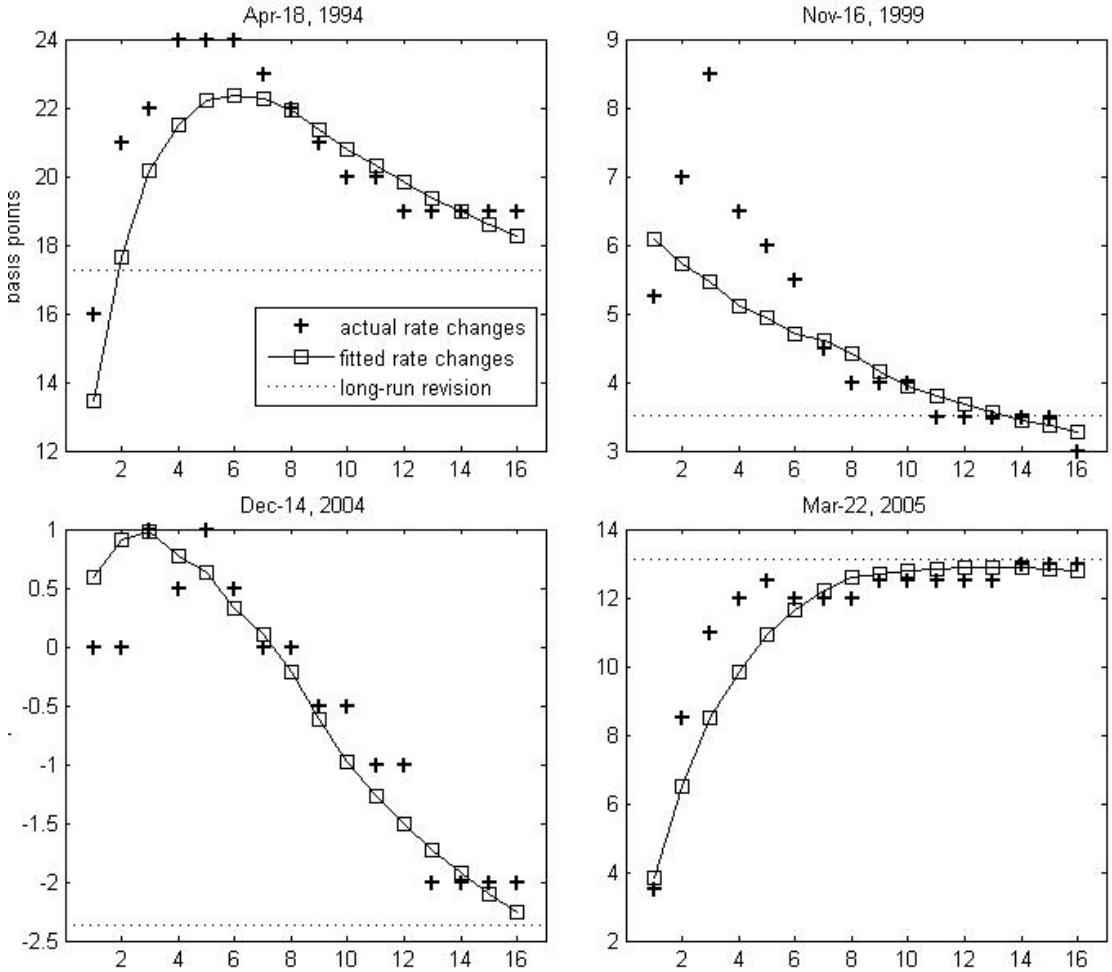
Empirical volatilities (sample standard deviations) with 95% confidence intervals based on a Chi-square approximation, and model-implied volatilities of daily rate changes, for Eurodollar futures and fed funds futures, for each of the four types of news events.

Figure 5: Empirical and model-implied results for the traditional regression approach



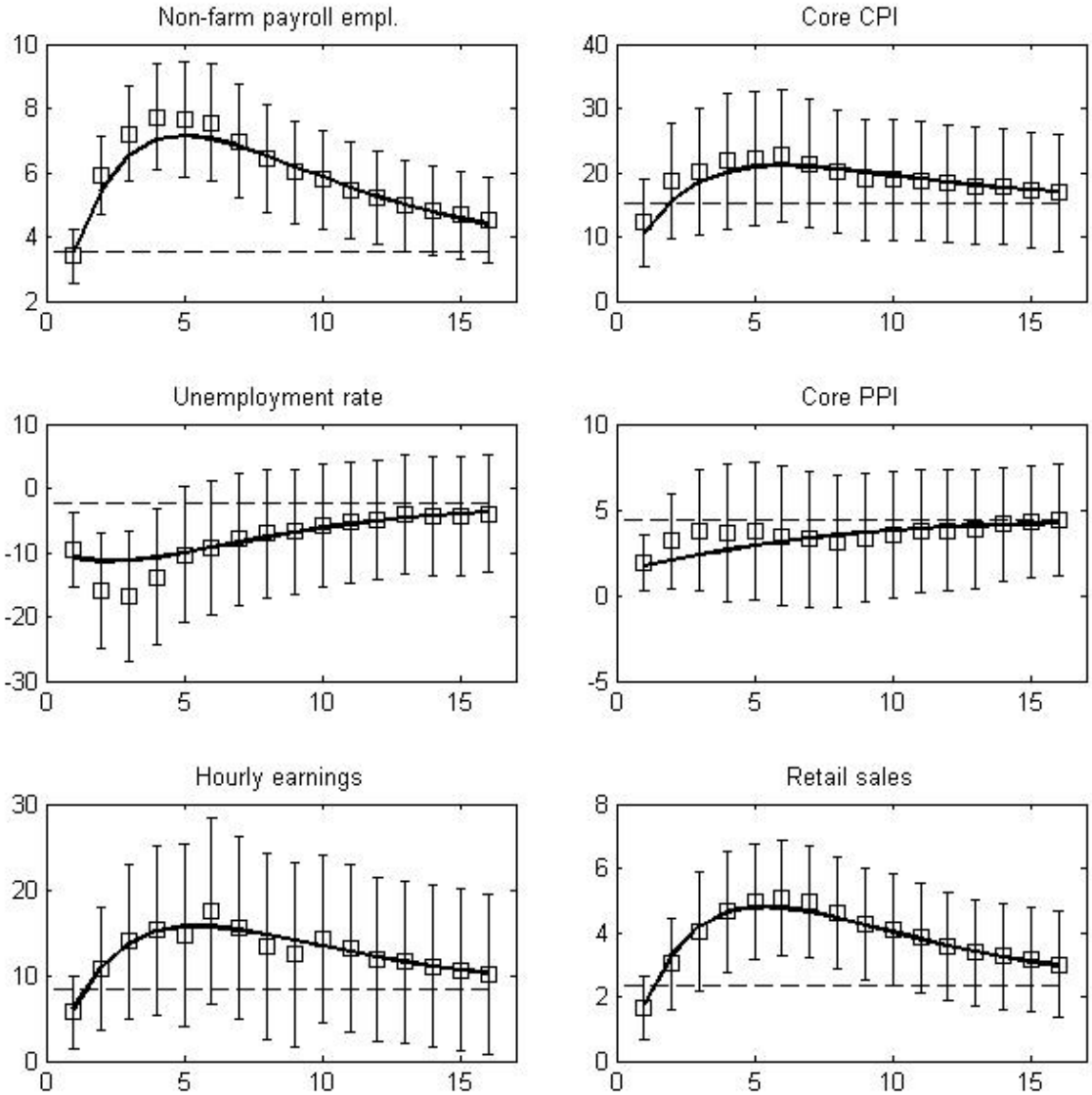
Regressions of changes in Eurodollar futures rates on changes in near-term federal funds futures rates (FF3) in different news regimes: Empirical response coefficients (squares) with 95% confidence intervals based on White standard errors, and model-implied response coefficients (thick line). Also shown are empirical coefficients of determination (circles) and the model-implied counterparts (thick plus signs).

Figure 6: Policy shocks: Examples of revisions resulting form policy actions



Actual changes in Eurodollar futures rates and fitted changes implied by revision on four days with monetary policy actions. Note: The target rate was increased by 25 bps in each of these cases. On the dates shown in the top row, the one-month ahead fed funds futures contract rate increased by 10 and 8 bps respectively, whereas on the dates shown in the bottom row it did not change at all.

Figure 7: The term structure of announcement effects



Actual changes in Eurodollar futures rates and fitted changes implied by revision on four days with monetary policy actions. Note: The target rate was increased by 25 bps in each of these cases. On the dates shown in the top row, the one-month ahead fed funds futures contract rate increased by 10 and 8 bps respectively, whereas on the dates shown in the bottom row it did not change at all.