Expected inflation and other determinants of Treasury yields

Gregory R. Duffee
Johns Hopkins University

First version April 2013
Current version May 12, 2013

Highly preliminary—Comments welcome

Abstract

At the quarterly frequency from 1968 through 2012, shocks to expected average inflation over a bond's life account for between 10 to 15 percent of shocks to nominal Treasury yields. Shocks to real rates and term premia account for the remainder. Evidence from 1999 through 2012, when TIPS are available, suggest there is little difference between nominal and real term premia. Therefore nominal yield shocks are almost entirely real yield shocks. Efforts to link yield shocks to economic activity shocks or inflation shocks are not particularly successful.

Voice 410-516-8828, email duffee@jhu.edu. Address correspondence to 440 Mergenthaler Hall, 3400 N. Charles St., Baltimore, MD 21218. Thanks to participants at the Bank of Canada "Advanced in Fixed Income Modeling" conference for comments.

1 Introduction

In this paper I argue that shocks to expected inflation are a fairly small component of shocks to the nominal Treasury term structure. Shocks to inflation compensation also appear to contribute little. Instead, shocks to nominal Treasury yields are largely shocks to real yields.

This result is surprising because we know that nominal yields are closely related to expected future inflation. For example, Mishkin (1990) finds that the slope of the Treasury nominal term structure contains substantial information about the path of future inflation but very little information about real rates. Moreover, we know that inflation is highly persistent, thus shocks to inflation affect both short-maturity and long-maturity yields. Evidence from macro-finance dynamic term structure models such as Campbell and Viceira (2001) suggests that shocks to short-term real rates are much less persistent. Estimates from these highly structured models typically imply that shocks to long-term nominal yields are primarily associated with inflation, either directly through shocks to expected inflation or indirectly through shocks to the compensation investors require to face inflation uncertainty.

Nominal yields can be decomposed into the sum of three unobserved components: expected inflation, expected short-term real rates, and a nominal term premium. I use information from survey forecasts of future inflation and output to help infer these components with a dynamic factor model. In contrast to the approach embedded in most of the recent term structure literature, the factor model allows for shocks to yields that are independent of shocks to expected inflation at any future horizon. This channel turns out to be empirically important. Another departure from the standard literature is that no-arbitrage is not imposed.

An analysis of about 45 years of quarterly data reveals three important features of this decomposition. First, although expectations of future inflation are highly persistent, they fluctuate little over time. Estimates here imply that quarterly innovations in expected five-year inflation rates are about 25 basis points. Quarterly innovations in five-year nominal yields are around 70 basis points. Thus in a variance decomposition sense, inflation shocks explain less than 15 percent of yield shocks. Innovations to expected short-term real rates and term premia (along with their covariance) are the primary drivers of yield shocks.

Second, there is insufficient information in the data to disentangle the relative contributions of these two non-inflation components. In particular, different model specifications produce markedly different estimates of the persistence of short-term real rates. The uncertainty about persistence is consistent with asset-pricing research that predates the active use of dynamic term structure models. It is also consistent with recent work in the applied cointegration literature. This work typically produces a double negative: we cannot reject the hypothesis that inflation and nominal short-term yields are not cointegrated.

Third, most of the variation in short-term real rates and term premia is unrelated to economic activity or inflation. There are Taylor-rule fluctuations in real rates, but these are short-lived, affect primarily the short end of the yield curve, and are fairly small. More precisely, consider regressing bond yields on current economic activity and near-term expected inflation. Across bonds of various maturities, the residuals of these regressions move almost in lockstep. We can treat the common component of these residuals as a latent factor in a dynamic model of yields. The factor produces roughly parallel shifts in the shape of the term structure. Point estimates imply that this factor accounts for about 30 percent (50 percent) of the unconditional (conditional) variation of long-term nominal yields.

In the data this latent factor has no predictive power for future economic activity or inflation. Nor is it related to proxies for required risk compensation such as conditional variances of future GDP growth rates or conditional covariances between nominal bond returns and stock returns. In other words, it is an important component of bond yields that appears to be unrelated to the macroeconomy.

Such behavior is difficult to reconcile with macro models in which persistent shocks to real rates are reflected in the economy. One way to break the link between Treasury yields and the macroeconomy is with market segmentation. For example, prices of Treasury bonds may fluctuate in response to security-specific supply and demand. However, other evidence strongly contradicts this possibility. Yields on both six-month Eurodollars and Aaa-rated bonds move roughly one-for-one with the non-macro component of the nominal term structure. More importantly, yields on Treasury Inflation-Protected Securities (TIPS) also move one-for-one with this component. Therefore the non-macro component of nominal Treasury yields is also a real-yield component.

A huge literature documents every wiggle and twist observed in Treasury yields. Thus much of what appears in this paper has been foreshadowed elsewhere. Specific links to earlier work are mentioned throughout the text. The next section presents evidence for and against unit roots and cointegration. Section 3 discusses the observable variables that should be used to help infer real rates from short-term nominal yields. Section 4 constructs and estimates a dynamic model used to estimate the sources of shocks to nominal yields. Section 5 concludes.

2 A preliminary look at nominal Treasury yields

Fisher (1930) describes the decomposition of a short-term nominal interest rate into expected inflation and a real rate, while Macaulay (1938) interprets long-term yields in terms of expected future short-term yields. Decades of ensuing research has refined their intuition.

2.1 Notation and identities

The following notation helps clarify the relevant concepts.

$y_t^{(n)}$: Continuously compounded yield, nominal zero-coupon bond maturing at $t+n$.

π_t : log change in the price level from $t-1$ to t.

π_t^e : Period-t expectation of next period's inflation, $\pi_t^e \equiv E_t(\pi_{t+1})$.

r_t : one-period real rate for nominal bonds, $r_t \equiv y_t^{(1)} - \pi_t^e$.

Δx_t : first-difference of a variable, $\Delta x_t \equiv x_t - x_{t-1}$.

This one-period real rate (also known as the ex-ante real rate) differs from the yield on a one-period real bond owing to both Jensen's inequality and the compensation investors require to face uncertainty in next period's price level. These expectations should be thought of as investors' forecasts.

Yields on multiperiod bonds can be written as the sum of average expected short-term yields and term premia. Formally, the term premium on an n-period nominal bond, denoted $ntp_t^{(n)}$, satisfies

$$y_t^{(n)} \equiv \frac{1}{n}\sum_{j=0}^{n-1} E_t\left(y_{t+j}^{(1)}\right) + ntp_t^{(n)}. \tag{1}$$

Given the yield, the term premium depends on the expectations. We treat the expectation operator in (1) as investors' expectations and thus the term premium is investors' perception of the term premium. Standard manipulations express this nominal yield in a variety of useful forms. One replaces the expected short-term nominal yield in (1) with its components:

$$y_t^{(n)} = \frac{1}{n}\sum_{j=0}^{n-1} E_t\left(r_{t+j}\right) + \frac{1}{n}\sum_{j=0}^{n-1} E_t\left(\pi_{t+j}^{e}\right) + ntp_t^{(n)}. \tag{2}$$

Nominal yields are the sum of expected average inflation and average real rates over the life of the bond, plus a term premium.

Another manipulation emphasizes the relation between the level of multi-period yields and the short-term yield:

$$y_t^{(n)} = y_t^{(1)} + \frac{1}{n}\sum_{j=1}^{n-1}(n-j) E_t\left(\Delta y_{t+j}^{(1)}\right) + ntp_t^{(n)}. \tag{3}$$

Finally, the level of multi-period yields can be linked to the levels of real rates and expected inflation:

$$y_t^{(n)} = \left\{ r_t + \frac{1}{n}\sum_{j=1}^{n-1}(n-j) E_t\left(\Delta r_{t+j}\right) \right\} + \left\{ \pi_t^{e} + \frac{1}{n}\sum_{j=1}^{n-1}(n-j) E_t\left(\Delta \pi_{t+j}^{e}\right) \right\} + ntp_t^{(n)}. \tag{4}$$

Again, the expectations are from the perspective of investors.

2.2 Unit roots and cointegration

Fama (1975) initiates the asset-pricing approach to studying the dynamics of the real rate. He infers properties of the real rate from its ex-post counterpart constructed with Treasury bill yields and CPI inflation. The early literature, most prominently Nelson and Schwert (1977), Garbade and Wachtel (1978), Mishkin (1981), and Fama and Gibbons (1982), concludes that the real rate varies through time and is highly persistent. However, over the samples they examine, variations in this rate are small relative to variations in inflation. Thus variations in Treasury bill yields are largely explained by variations in inflation.

Early research on the real rate process notes that both short-term nominal Treasury yields and U.S. inflation appear to have unit roots.[1] This work struggled to find econometric tools appropriate to analyze a real rate process that is derived from two highly persistent processes (bill yields and inflation) and obscured by substantial noise (inflation shocks embedded in ex-post real rates).

This literature takes a step forward with the development of cointegration. The decomposition of long-term yields in (3) shows that if short-term nominal yields have a unit root and term premia are stationary, then yields at all maturities are cointegrated. The earliest comprehensive empirical analysis of cointegration among nominal yields is in Campbell and Shiller (1987). The decomposition of (4) can be used to examine cointegration among yields, inflation, and real rates.[2] In particular, if both yields and inflation have unit roots, but they are not cointegrated, then either real rates or term premia must also have a unit root. Rose (1988) is the first to use cointegration logic to study the properties of real rates.

Exploring the properties of yields and inflation from the perspective of cointegration

[1] Fama (1975) reports the high autocorrelations of Treasury bill yields are consistent with nonstationarity. Nelson and Schwert (1977) make the same point about inflation. Schwert (1986) combines these observations, but does not use cointegration tools.

[2] This statement is a little loose. Real rates depend on expected inflation. As long as the inflation forecast error is stationary, expected and realized inflation have the same degree of integration.

helps to set the stage for more detailed analysis to follow. It also illustrates some important differences among various measures of inflation.

2.3 Yield and inflation data

For this exercise I use quarter-end observations for three-month Treasury bills and artificial zero-coupon Treasury bonds. The ten-year yield is constructed by bond constructed by staff at the Federal Reserve Board following the procedure of Gurkaynak, Sack, and Wright (2007). All other artificial yields are constructed by the Center for Research in Security Prices (CRSP). Yields are continuously compounded. The CRSP yields are available from 1952Q2 through 2012Q4. The ten-year yield is available from 1961Q2 through 2012Q4.

I examine two measures of realized inflation and one measure of expected inflation. The first two are quarter-to-quarter log changes in price indexes. One is the NIPA GDP price index and the other is the CPI. I use the CPI value for the last month of the quarter. These are available over the entire sample spanned by the yield data. Expected inflation is from the Survey of Professional Forecasters. It is the mean, across forecasters, of the prediction of next quarter's GDP inflation. I construct it following the procedure of Bansal and Shaliastovich (2012), which discards outlier responses from individual forecasters. The first observation of the survey data is 1968Q4.

2.4 Results

Table 1 displays test statistics and p-values for Augmented Dickey-Fuller (ADF) tests of unit roots. Results are reported for both the full sample of 1952Q2 through 2012Q4 and the shorter sample for which the survey data are available.

The first set of results shows that for both samples, the tests do not come close to rejecting the hypothesis of a unit root for any yield. The t-statistics decline with maturity, indicating that the evidence against unit roots shrinks as maturity increases.

By contrast, yield spreads are stationary. The second set of results evaluate the stationarity of differences between the five-year yield and the other yields. Most of the reported p-values are less than one percent. The standard interpretation of this result is that yields are cointegrated with a single cointegrating vector.[3] handbook treatment by Martin, Hall, and Pagan (1996) provide a handbook treatment of this evidence.

The third sets of results shows that for all combinations of inflation measure and sample period, the null hypothesis of a unit root cannot be rejected at the five percent level.[4] The results for the individual measures tell a story that will be important later. The evidence against a unit root is strongest for CPI inflation (for the full sample, rejection at the ten percent level), weaker for GDP inflation, and non-existent for expected inflation.

This ordering corresponds to the amount of transitory noise in the three measures. First consider a regression of CPI inflation on GDP inflation. For the full sample 1952Q2 through 2012Q4, the OLS results are (including the standard deviation and first-order serial correlation of the residual)

$$\pi_t^{CPI} = -0.10 + 1.12\pi_t^{GDP} + e_t, \quad \sigma(e) = 3.89,\ \rho(e_)) = 0.06. \tag{5}$$

The units are in annualized percentage points. Thus CPI inflation is basically GDP inflation plus a huge transitory residual. A similar but less dramatic description applies to GDP inflation relative to expected GDP inflation. For the shorter sample 1968Q4 through 2012Q4, the results are

$$\pi_t^{GDP} = -0.03 + 1.04\pi_t^{survey} + e_t, \quad \sigma(e) = 0.99,\ \rho(e_)) = 0.35. \tag{6}$$

The pattern of ADF test statistics in Table 1 tells us that the high mean reversion of the residuals in (5) and (6) partially obscures the underlying highly persistent process for

[3]Kozicki and Tinsley (2001) argue a more accurate characterization is that there is a single source of nonstationarity in all yields, but that this source is not $\mathcal{I}(1)$.

[4]For the full-sample tests, the starting point of the sample is not innocuous. Rose (1988) finds that tests tend to reject the null hypothesis of nonstationarity when pre-1950 data are included or post-1970 data are excluded.

expected inflation. Adjusting the number of lags used with the ADF test does not affect this result.

Panel A of Table 2 reports ADF tests of hypotheses that yields less inflation have a unit root. The alternative hypothesis is that the cointegration vector is $[1, -1]$. The main result is that the null hypothesis of no cointegration cannot be rejected. In the cointegration literature, Lardic and Mignon (2004) and Hjalmarsson and Österholm (2010) reach similar conclusions. Across different measures of inflation, the pattern of results is consistent with those in Table 1. The strongest evidence against a unit root uses the CPI measure of inflation. With this measure, two of the p-values in Table 2 are less than five percent. The evidence in favor of cointegration is weaker with GDP inflation and it is non-existent with survey expectations of inflation. As in Table 1, the high mean reversion of noise in realized inflation obscures the high persistence of the spread between yields and expected inflation.

Panel B of Table 2 reports results for the Engle-Granger cointegration test. Rather than assume a cointegrating vector of $[1, -1]$, this procedure first regresses yields on inflation, then applies the ADF test to the residuals. The critical values differ from standard ADF critical values. Using this test, the hypothesis of no cointegration cannot be rejected for any combination of yield and inflation measure.

How should we interpret these results from the perspective of modeling the term structure? If yields, inflation, and their difference are all $\mathcal{I}(1)$ processes, then either real rates and/or term premia must also be $\mathcal{I}(1)$. But since yield spreads are stationary (including the spreads between long-maturity bonds and the short rate), term premia must be stationary. Therefore real rates must be $\mathcal{I}(1)$.

But all we really know from these results is that there is insufficient time series evidence to determine whether real rates are stationary. From a modeling perspective, it is not critical if real rates are truly $\mathcal{I}(1)$, fractionally integrated, or $\mathcal{I}(0)$ but highly persistent. With finite samples there is no way to be sure. Thus the most important message is that models of the joint dynamics of inflation and bond yields should be sufficiently flexible to allow for two sources of persistent fluctuations in yields, only one of which is linked to inflation.

3 Yield projections

The identity (2) decomposes long-term nominal yields into average expected real rates, average expected inflation, and term premia. This section and the next discuss how to perform this decomposition empirically. There are two major difficulties. First, neither short-term real rates nor expected inflation are observed directly. Second, the joint dynamics of short-term real rates and expected inflation are not known.

3.1 Vector autoregression intuition

The simplest and most obvious econometric solution uses a vector auto-regression (VAR). The period-t vector of observables includes the period-t nominal short rate, inflation from $t-1$ to t, and possibly other information known to investors at t. The one-step-ahead VAR forecast produces an estimate of period-t expected inflation. With the maintained assumption that investors' forecasts correspond to VAR forecasts, the period-t real rate estimate is the nominal short rate less expected inflation. Paths of expected future inflation and real rates are given by the dynamic properties of the estimated VAR. Subtracting average expected future real rates and inflation from long-term yields produces term premia. Campbell and Shiller (1996) and Campbell, Shiller, and Viceira (2009) illustrate a slight modification of this approach.

This section discusses how to choose variables to include in the VAR. To forestall confusion, I note at the outset that the decomposition procedure adopted in the next section is *not* a VAR. Nonetheless, the logic that underlies the VAR variable choice carries over to the decomposition methodology of Section 4.

The accuracy of the VAR approach hinges on the information content of the variables included in the VAR. For example, if the history of realized inflation contains all information relevant to forecasting future inflation, the VAR will produce an accurate decomposition of long-term yields (at least in population) if enough lags of inflation are included in the vector of observables. Phillips curve logic suggests that expected inflation depends on both the history of realized inflation and current economic activity. If this is true, the VAR will produce an accurate decomposition by including this information in the observables.

However, overwhelming evidence shows that investors have more information about future inflation than is contained in the history of realized inflation and economic activity. In particular, surveys of professional forecasters can be aggregated to produce inflation forecasts that dominate, in a root mean squared error sense, all popular model-based forecasts. Recent evidence is in Ang, Bekaert, and Wei (2007). The handbook chapter of Faust and Wright (2012) carefully documents this result.

Therefore a VAR that uses only the nominal short rate, lags of realized inflation, and lags of economic activity will produce inaccurate decompositions of long-term yields, even in population. The nominal short rate contains both investors' information about future inflation and the current real rate. The VAR cannot disentangle them because it does not contain independent information about these pieces.

If we are confident that short-term real rates are have low persistence, a potential solution is to include long-maturity yields in the VAR. Long-term yields will be insensitive to real rates if shocks die out quickly and if term premia do not vary with real rates. But the results of the previous section indicate that this approach will not work.

A better solution includes expected inflation from surveys in the vector of observables. Survey forecasts for different horizons help to pin down the dynamics of expected inflation. The long-term yield decomposition (2) also requires the dynamics of real rates. The intuition of the Taylor rule suggests that both current and expected future economic activity (as well as current and expected infltion) contain information about expected future real rates.

We want to avoid a kitchen-sink approach that throws any plausible observable into the VAR. A reasonable approach, although ad hoc, uses results from cross-sectional regressions of long-term yields on candidate observables. Observables that contain substantial information about expected future inflation and/or real rates will have substantial explanatory power in such regressions. Higher R^2s should accompany vectors of observables that have more accurate information about expected inflation and real rates. (Higher R^2s may also reflect a better fit of term premia, which is why this metric is ad hoc.)

3.2 Empirical implementation

This subsection discusses cross-sectional projections of nominal yields on observables that should contain information about expected future inflation and real rates. For a given vector of observables z_t, the regression is

$$y_t^{(n)} = \beta_{0,n} + \beta_n' z_t + e_{n,t}. \tag{7}$$

Panel A of Table 3 lists the set of observables that are included in various versions of z_t. The quarter-t state of the business cycle is proxied by log real per capita GDP less the mean of the same variable for quarters $t-1$ through $t-16$. Change in economic activity is measured by two variables: first-differenced log real per capita GDP and the Chicago Fed's National Activity Index (CFNAI). Quarter-t realized inflation is measured by the log change in the GDP price index from $t-1$ to t. Inflation forecasts from the Survey of Professional Forecasters are described in Section 2.3. Near the beginning of the second month in quarter t, forecasts are made for inflation from $t-1$ to t, t to $t+1$, through $t+3$ to $t+4$. Forecasts of real GDP growth are available for the same time period and same forecast horizons. As with the inflation forecasts, outlier responses are dropped following Bansal and Shaliastovich (2012).

Output and inflation measures are available on both a revised and real-time basis. Revised data are those currently available from the National Income and Product Accounts. Real-time data were publicly available by the end of the second month in quarter t. The

CFNAI is released monthly. It is available on a real-time basis since 2000. I define the revised quarter-t value as the average of the three monthly values in quarter t as currently reported by the Chicago Fed. The real-time value is the average of the three values that were released in each month of quarter t. For observations prior to 2000, I proxy for real-time value by assuming monthly values are released with a one-month lag. Survey forecasts are unrevised, and thus are real-time versions. All regressions are estimated over the sample 1968Q4 through 2012Q4, which is the period for which survey expectations are available.

Adjusted R^2s for different choices of z_t and different bond maturities are reported in Panel B of Table 2. Regressions are estimated for seven different maturities, five of which are reported in the table. There are four conclusions to draw from the results.

First, yields are better explained by real-time data than revised data. The relevant comparison is between the first two rows in Panel B. Both report adjusted R^2s for regressions of yields on the state of the business cycle, lags zero through four of GDP growth, and lags zero through four of realized inflation. Yields are observed at the end of the last month of the quarter. With revised data, the adjusted R^2s range from about 40 percent at the long end of the yield curve to 60 percent at the short end. With real-time data, the adjusted R^2s are about five percent higher. Thus the remaining regressions all use real-time data.

Second, real-time data do not explain mid-quarter yields better than they explain end-quarter yields. The real-time data are available by the end of the second quarter. This suggests that the real-time data are more closely related to yields at the end of the second month rather than the end of the third month. The regressions summarized in row three are identical to those in row two, aside from replacing the dependent variables with yields as of the end of the second month. The adjusted R^2s reported in the two rows are almost identical. Nonetheless, because the intuitive justification for using mid-quarter yields is strong, the remaining regressions all use mid-quarter yields.

Third, including forecasts of future inflation and output raises substantially the adjusted R^2s. The regressions summarized in row four include all of the observables in row three, and adds all of the survey data. (In other words, these regressions use the entire set of observables.) The adjusted R^2s increase by around 15 percent.

Fourth, substantially more parsimonious sets of observables capture almost all of the explanatory power of the entire set. The regressions in row four use nine measures of inflation: lags zero through four of realized (real-time) inflation and forecasts for five separate horizons. Row five discards six of these. It includes only the current real-time realization of GDP inflation (which is realized inflation for quarter $t-1$), and survey forecasts for $t-1$ to t and $t+2$ to $t+3$. The adjusted R^2s are slightly lower for the more parsimonious regression, but the largest difference across maturities is only one percent.

Similarly, the regressions in row six discard many of the economic activity variables. Row six uses the inflation measures from row five, and just three measures of economic activity. The adjusted R^2s are within a percent of those in row five. Finally, the regressions in row seven use only two observables for economic activity and two for expected inflation. Again, the adjusted R^2s are within a percent of those in the row five.

These results support the conclusion that a VAR should include survey expectations of inflation and a couple of observables related to macroeconomic activity. In the remainder of the paper I work with the final two sets of observables used in Panel B. From the perspective of Panel B these two sets have very similar explanatory power for yields. But as we will see, estimated dynamic models motivated by these two sets have substantially different properties.

I refer to the first set as the expanded set. The observation at t is a length-six vector. The elements are the quarter-t state of the business cycle (log real per capita GDP less the 16-quarter mean), the CFNAI, the survey forecast of GDP growth from $t-1$ to t, realized inflation in quarter $t-1$, and survey forecasts of GDP inflation for quarters t and $t+3$. I refer to second set as the baseline set. It is a length-four vector that excludes both the CFNAI and realized inflation in quarter $t-1$.

This subsection focused on choosing an appropriate set of macroeconomic variables to use in estimating inflation and real rate dynamics. The next two subsections focus on the variation in yields that is orthogonal to these variables.

3.3 What does existing theory tell us about the residuals?

Between 25 and 30 percent of the variation of nominal yields is not explained by the expected inflation and economic activity measures. This subsection reviews what existing theory says about the residuals. The next subsection takes a detailed empirical look at the residuals.

Many term structure models imply that for the specifications that include survey expectations, the only role of the residual in (7) is to absorb measurement error. The Taylor rule model of Ang, Dong, and Piazzesi (2007) illustrates the logic. There are three key ingredients. First, yields are an affine function of a state vector. The state includes real variables, inflation, and a latent factor. Second, real variables and inflation are affine functions of the state. Third, the state vector has VAR dynamics, thus expectations of future real variables and inflation are also affine functions of the state. At first glance it might seem that the latent factor corresponds to the residual of (7). But without loss of generality the state vector in models such as Ang et al. (2007) can be rotated to replace the latent factor with expected future values of inflation. Thus when these expectations are included among the regressions' explanatory variables, residuals should be identically zero.

Term structure models without affine mappings or with non-VAR dynamics relax this tight restriction, but only in the sense that the residual also absorbs model misspecification. For example, in the quadratic term structure model of Ang, Boivin, Dong, and Loo-Kung (2009), the state consists of the output gap, inflation, and time-varying coefficients in the Taylor rule. Expectations of future inflation in (7) pick up part of the contributions of time-varying coefficients. (Given contemporaneous output and inflation, different Taylor rule coefficients imply different expectations of inflation.) However, the functional form of (7) does not match the true functional form, putting some misspecification error into the residual. Similarly, a regime-switching model such as Ang, Bekaert, and Wei (2008) has non-VAR dynamics, thus expected future values of inflation are nonlinear functions of the state vector.

It is possible to construct a model in which a state variable shows up only in the residual of (7), even when expected inflation is included as an explanatory variable. Gallmeyer, Hollifield, Palomino, and Zin (2008) describe an exchange economy in which output (consumption) and inflation have exogeneous dynamics, and an independent state variable drives the willingness of investors to bear risk. This state variable affects bond yields and thus appears in the residual. Similarly, Bansal and Shaliastovich (2012) build a long-run risk model in which risk premia depend on time-varying second moments that are unrelated to first moments.

However, this result does not appear robust to weakening the assumption of exogeneous consumption and inflation dynamics. Gallmeyer, Hollifield, Palomino, and Zin (2008) emphasize that when inflation is endogeneous (e.g., there is a Taylor rule), then variations in risk premia affect inflation. In a production economy with New Keynesian price stickiness, such as the economy modeled by Rudebusch and Swanson (2012), inflation dynamics cannot be disentangled from firms' marginal profits and thus output dynamics. With endogenous capital as in van Binsbergen, Fernández-Villaverde, Koijen, and Rubio-Ramírez (2011), investment will depend on investors' willingness to bear risk. These models have nonlinearities that put misspecification into the residual of (7). Nonetheless, the main action in yields is in real activity and expected inflation.

The residual can play a larger role when we step outside the perfect markets framework of no-arbitrage models. Market imperfections lead to idiosyncratic variations in yields that have nothing to do with real activity or inflation. Research beginning with Park and Reinganum (1986) and Amihud and Mendelson (1991) shows that yields on Treasury securities have idiosyncratic components related to security-specific maturity dates and liquidity. Related evidence is in Krishnamurthy and Vissing-Jorgensen (2012), who document a common component in Treasury yields that is linked to the supply of Treasury securities. They argue this component reflects changes in the equilibrium price of liquidity and safety.

3.4 The residuals in practice

Figure 1 displays estimated residuals for regressions of yields on the expanded set of explanatory described in Section 3.2. Residuals for regressions that use the baseline set of explanatory variables are not displayed because they are almost identical. The figure shows that the residuals are volatile and highly correlated across yields. Sample standard deviations of the residuals are between 1.4 and 1.6 annualized percentage points.

Following the spirit of Litterman and Scheinkman (1991), term structures are often decomposed into principal components that are labeled level, slope, and curvature. Figure 2 displays the first three principal components of both the projected values (Panel A) and the residuals of the regressions (Panel B). The two panels are strikingly similar. In both cases, the first principal component is a level factor that captures almost all of the total variation. The level factor in Panel A (Panel B) explains almost 99 percent (95 percent) of the total variation in fitted (residual) yields.

Yet behind the pictures are very different stories. Expected inflation accounts for almost all of the level component of projected yields. The sample correlation between the level component and the survey forecast of inflation from $t+2$ to $t+3$ is 0.95. (The statistics in this paragraph are not reported elsewhere.) By construction, the level component of the yield residuals is orthogonal to expected inflation. The two level factors also exhibit substantially different persistence, at least in sample. Sample autocorrelations of the level factor in yield projections exceed 0.5 for more than five years, while those for yield residuals exceed 0.5 for only four quarters. Although residuals exhibit more mean reversion in sample, it is not sufficient to reject the null of a unit root with an ADF test.[5]

It is difficult to justify the view that the yield residuals are picking up time-varying risk premia. The most obvious reason is apparent from Figure 2. Variations in risk premia should

[5]With two lags, the ADF test has a p-value of 0.25. This p-value is not adjusted for sampling uncertainty in the parameter estimates of the yield regressions (7).

not show up at the short end of the yield curve, yet the yield residuals move in parallel. I performed additional checks for a risk premium channel. In unreported regressions, I included conditional variances and covariances in the yield regressions. If these conditional second moments have incremental explanatory power for yields, they also have explanatory power for yield residuals that are constructed without using second moments as explanatory variables. No statistically or economically significant explanatory power was uncovered for conditional variances of changes in yields, conditional covariances between stock and bond returns, or conditional variances of investors' forecasts of output and inflation.

My preferred interpretation is that the yield residuals correspond to variations in real rates that are orthogonal economic activity and expected inflation, or at least orthogonal to the measures of activity and inflation used in Table 3. The parallel shift in the yield curve is consistent with highly persistent real rates. It is also consistent with real rates that are highly persistent under the equivalent-martingale measure but not under the physical measure. I do not attempt to distinguish between these possibilities in this paper.

Variations in real rates should show up in yields of Treasury Inflation Protected Securities (TIPS). Yields on artificially-constructed zero-coupon TIPS bonds are available for maturities between five and ten years for the sample 1999Q1 through 2012Q12.[6] I regress these yields on the first principal component of the yield residuals (the level component), as in

$$y^n_{tips,t} = b_{0,n} + b_{1,n}\text{resid-level}_t + e_{t,n}. \tag{8}$$

The results are displayed in Panel A of Figure 3. The black line and black circles in the figure are copies of the first principal component of the nominal residuals, as displayed in Panel B of Figure 2. They represent the sensitivity of nominal yields to a unit change in the level factor of the residuals. The blue circles are the estimated coefficients from OLS estimation of (8). Plus and minus two standard error bounds are represented by the blue

[6] I use yields as of the end of the middle month in the quarter, which matches the timing of the nominal yields.

x's.[7]

In this sample, the sensitivities of TIPS yields to the level of nominal yield residuals are almost identical to the sensitivities of nominal yields. This pattern is precisely what we would see if the nominal yield residuals represent fluctuations in real rates. This pattern looks nothing like what we would see if the nominal yield residuals have something to do with inflation. For example, it strains credulity to view the residuals as the product of a misspecified relation between nominal yields and inflation, or time-varying compensation for inflation risk.

Related evidence is in Panel B of the figure. It displays components of nominal and TIPS yields for the sample 1999Q1 through 2012Q4. The black dashed-dotted line at the top of the panel and the blue dashed line are the fitted and residual components of the five-year nominal yield. The regression used to produce these components is estimated over the 1968Q4 through 2012Q4 sample, using the expanded set of explanatory variables described in Section 3.2. The solid black line is the five-year TIPS yield, normalized to have the same mean as the nominal yield's residuals over the 1999Q1 to 2012Q4 period.

The TIPS yield closely tracks the residual, aside from the post-Lehman failure period when TIPS yields temporarily jumped. The effect of the bankruptcy on the TIPS market is discussed by Campbell et al. (2009). Inflation is stable over much of this sample, thus the fitted component of the nominal yield has a lower standard deviation (about 70 basis points) than the residual (about 120 basis points).

The post-crisis period is illuminating because fitted and actual nominal yields sharply move in opposite directions. From 2009Q3 to 2012Q4, the fitted component of the nominal yield increases substantially (2.5 percent), while both the residual component and the TIPS yields decrease substantially (4.2 and 3.0 percent respectively). Careful examination of yield behavior post-crisis is beyond the scope of this paper. Here I simply note that changes of

[7] The standard errors are adjusted for generalized heteroskedasticity and seven lags of serial correlation in the residuals (no downweighting). The lag choice is motivated by inspection of the sample autocorrelations of the residuals. The standard errors are not adjusted for the generated regressor. **To be corrected in a less preliminary version, using a slightly different regression.**

similar magnitude in the residuals and TIPS yields appear elsewhere in the sample. From 2000Q4 through 2002Q3, the residual drops by about 3.0 percent, while the TIPS yield drops by about 2.25 percent.

An alternative to the real-rate view is that the residual level factor captures some Treasury-specific feature, such as aggregate supply and demand for securities issued by the Treasury. If so, variations in Treasury yields should not be matched by variations in non-Treasury yields. I investigate this hypothesis using six-month Eurodollar deposit rates and Moody's Aaa-rated seasoned corporate bond yield.[8] These yields are available for the full 1968Q4 through 2012Q4 sample.

The estimated regression has the same form as (8). I also include the first principal component of fitted yields as an explanatory variable. Its role is to reduce the standard deviation of the regression residuals and therefore tighten the standard errors. (By construction, the two level principal components are orthogonal.) The estimated coefficients on the level factor of nominal yield residuals are displayed in Panel A of Figure 3. The red circles are the estimated coefficients from OLS estimation, and two standard error bounds are represented by red x's.[9] (The Moody's yield is for coupon bonds, thus I arbitrarily place the results for this yield at the eleven-year zero-coupon maturity.)

As with TIPS yields, the sensitivities of non-Treasury nominal yields to the level of nominal Treasury yield residuals are almost identical to the sensitivities of nominal Treasury yields. This variation in nominal Treasuries is matched almost one-for-one with both variation in indexed Treasuries and variation in non-Treasury nominal yields.

4 Yield dynamics

This section estimates a joint dynamic model of nominal yields, macroeconomic activity, and expected inflation. The main use of the model is to decompose nominal long-term yields into

[8]Both series are monthly averages of daily yields. Because these are not month-end yields, I use values for the third month of the quarter rather than the second.

[9]See footnote 7. Standard errors are adjusted for ten lags of serial correlation.

expected inflation, expected real rates, and term premia. The model dynamics then tell us how to decompose the variance of yields into variances and covariances among these parts.

One of the main results is that shocks to expected inflation account for only a small fraction of shocks to long-term yields. Part of the the empirical intuition behind this result is easy to see with a couple of OLS regressions. Expected inflation from surveys for three quarters ahead is a mean-reverting process with a sample standard deviation of quarterly shocks of about 30 basis points. A simple AR(1) regression confirms these properties. Therefore the shock to expected average inflation over the next five years has a standard deviation less than 30 basis points. The yield on a five-year nominal bond has a standard deviation of quarterly shocks of about 70 basis points. (Regress the yield on the previous quarter's values of the yield and expected inflation.) Thus a variance decomposition attributes less than 20 percent of the overall variance of five-year yield shocks to expected inflation shocks.

These calculations do not tell us the full variance decomposition. In particular, they do not indicate whether inflation has an indirect role through its covariance with expected future real rates or term premia, as in Ang and Ulrich (2012). A richer dynamic model is required.

4.1 A state-space setting

State-space models are standard in the dynamic term structure literature.[10] A vector of observables are linked through their loadings on a vector of common factors, where there are more observables than factors. The common factors have VAR(1) dynamics. The general framework is

$$\begin{pmatrix} \text{activity measures}_t \\ \text{inflation measures}_t \\ \text{nominal yields}_t \end{pmatrix} = A + Bx_t + \eta_t, \qquad \eta_t \sim MVN(0, H), \tag{9}$$

[10]The first use of these models in the real-rate literature is Hamilton (1985), although his motivation differs from that in the dynamic term structure literature.

$$x_{t+1} = \mu + Kx_t + \Sigma\epsilon_{t+1}, \qquad \epsilon_{t+1} \sim MVN(0, I). \tag{10}$$

I examine two specifications, motivated by the baseline and expanded set of macro variables discussed at the end of Section 3.2.

4.2 A baseline specification

This specification uses two economic activity observables and two expected inflation observables. I use the notation $E_t^s(z_{\{j\}})$ to indicate a survey expectation observed in the second month of quarter t, where the participants are asked to predict the value of z in quarter $t + j$. Hats over variables indicate observables, which contain the transitory component η_t. The observables are

$$\text{activity measures}_t = \begin{pmatrix} \widehat{\text{cycle}}_t & \widehat{E_t^s}(\Delta y_{\{0\}}) \end{pmatrix}', \tag{11}$$

$$\text{inflation measures}_t = \begin{pmatrix} \widehat{E_t^s}(\pi_{\{0\}}) & \widehat{E_t^s}(\pi_{\{3\}}) \end{pmatrix}', \tag{12}$$

$$\text{nominal yields}_t = \begin{pmatrix} \hat{y}_t^{(1)} & \hat{y}_t^{(4)} & \hat{y}_t^{(8)} & \hat{y}_t^{(12)} & \hat{y}_t^{(16)} & \hat{y}_t^{(20)} & \hat{y}_t^{(40)} \end{pmatrix}'. \tag{13}$$

The baseline specification uses a length-five state vector. The five factors are designed to pick up common variation in the four activity and inflation variables, along with the common component of the yield residuals. Without loss of generality, the state vector can be rotated, translated, and scaled to equal

$$x_t = \begin{pmatrix} \text{cycle}_t & E_t^s(\Delta y_{\{0\}}) & E_t^s(\pi_{\{0\}}) & E_t^s(\pi_{\{3\}}) & l_t \end{pmatrix}'.$$

There are no hats in this state vector, indicating that the factors are not the activity and inflation observables, but rather their versions without the η_t noise. The latent factor l_t mean zero and contemporaneously orthogonal to the other elements of the state vector, again without loss of generality. This normalization does not imply that the latent factor has no ability to forecast future economic activity or inflation expectations. It is scaled so that the loading of the four-year yield on the latent factor equals one.

I impose two restrictions on the dynamics of the state vector. First, the dynamics must be consistent with survey expectations of inflation. In practice, this requires that μ and K in (10) ensure that the quarter-t three-quarter ahead expectation $E^s_{t+3}(\pi_{\{0\}})$ equals the quarter-t expectation $E^s_t(\pi_{\{3\}})$. Recall the estimated model will be used to decompose yields into expected future inflation, expected future real rates, and term premia. Forcing the parameters to align with survey expectations helps align model-implied expectations with investors' beliefs.

Second, the latent factor l_t follows an autonomous process with shocks that are independent of shocks to the other factors. I refer to l_t as the "non-macro" factor. The autonomous assumption is motivated by empirical evidence. Survey forecasts of output growth and inflation at all horizons (contemporaneous through four quarters ahead) are close to orthogonal to the level of yield residuals constructed in Section 3.2.[11] Nor are the forecasts made in quarter $t + 1$ predictable with the level of the residuals in quarter t. No t-statistic exceeds one in absolute value.

As with the inflation-expectation restriction, imposing the assumption that l_t is autonomous helps to align model-implied expectations with investors' beliefs. This does not necessarily align the model with actual dynamics. Cieslak and Povala (2013) argue that investors make systematic errors in forecasting future nominal short rates that are correlated with errors they make in forecasting future economic activity. Thus l_t may not be autonomous in the true dynamic process. The empirical evidence in the next subsection presents some evidence supporting this view.

[11]This is true by construction for the forecasts of contemporaneous output and inflation, as well as the forecast of inflation three quarters ahead.

4.3 An expanded specification

This specification adds the CFNAI index to the economic activity measures and adds realized inflation in quarter $t-1$ (which is the most recent observed value) to the inflation measures. The observed yields are unchanged. An additional state variable is included, thus the state vector has six elements. Without loss of generality, the state vector can be transformed to

$$x_t = \begin{pmatrix} \text{cycle}_t & E_t^s(\Delta y_{\{0\}}) & \pi_{t-1} & E_t^s(\pi_{\{0\}}) & E_t^s(\pi_{\{3\}}) & l_t \end{pmatrix}'.$$

The same restrictions are imposed on the dynamics of the state. Here, the restriction on inflation expectations also includes the requirement that the one-quarter ahead model-implied expectation of π_{t-1} equals the current survey expectation $E_t^s(\pi_{\{0\}})$.

4.4 Results for expected inflation and other yield determinants

Maximum likelihood estimation uses the Kalman filter. To conserve space, only estimates related to yield decompositions are discussed. Given the parameter estimates and filtered estimates of the state vector for each quarter, the filtered n-quarter yield can be decomposed into expected real rates, expected inflation, and term premia using (4) and the model's estimated dynamics. "Filtered yield" means the yield implied by the filtered state, not the observed yield. According to the model these values differ owing to η_t in the measurement equation (9). Similarly, filtered shocks to the state vector can be calculated for each quarter (the filtered state at t less the one-step-ahead forecast as of $t-1$). Filtered shocks to yield are the sums of filtered shocks to the three components on the right of (4).

Panel A of Table 4 reports, for the baseline version of the model, the decomposition of the sample variance of these yield shocks. To illustrate how to read the table, consider the row labeled "One-yr." The figures in the row are the fractions of the sample variance of one-year yield shocks that are explained by the component variances and covariances. The rows sums to one. For example, eleven percent is attributed to the variance of shocks to average expected inflation over the next year and three percent is attributed to the covariance between the expected inflation and expected real-rate components. Panel B in Table 4 reports the sum of the columns in Panel A related to inflation expectations.

Square brackets in Panel A report [2.5 97.5] percent confidence bounds on the figures. They are based on an outer-product estimate of the covariance matrix of the parameter estimates. I use a Monte Carlo approach. For a given simulation, step one draws parameters from a normally-distributed distribution with mean equal to the parameter estimates and covariance matrix given by the outer-product estimate. This draw is discarded if the parameters imply nonstationary dynamics. Step two calculates the population variance decomposition of one-quarter-ahead yield shocks. Note that the confidence bounds are for a population decomposition rather than the sample decomposition used to construct the point estimates.

There are two broad lessons to draw from Table 4. First, shocks to average expected inflation contribute very little to the overall variance of yield shocks. The direct contribution of the variance of expected inflation is around 10 to 12 percent of the total variance. The indirect contribution—the covariance terms involving inflation—are negative, thus the total effect reported in Panel B is less than 10 percent. The confidence bounds on the variance decompositions are wide, but we can comfortably reject the hypothesis that the contribution of shocks to expected inflation exceeds 40 percent of the total variance of yield shocks.

Second, the combination of data and model do not allow us to determine reliably the relative contributions of shocks to average expected real rates and term premia. The point estimates indicate an overall breakdown of about half and half, with real rates mattering more for short maturities and term premia mattering more for long maturities. But the confidence bounds do not allow us to rule out much more extreme ratios.

The filtered shocks to the three yield components are displayed in Figure 4. (The shocks are for the baseline version of the model.) There are seven time series in both Panels A and B, for the seven yields used in estimation. There are six in Panel C since the one-quarter yield has no term premia.

Panel A illustrates the well-known fact that inflation expectations were more stable in the second half of the sample than in the first half. Although this may suggest instability in the variance decompositions, note that both real rate expectations and term premia were also more stable in the second half. Figure 4 indicates that the homoskedastic model of Section 4.1 is misspecified, but it does not show whether inflation expectations were relatively more important in the first half of the sample.

Table 5 reports separate sample variance decompositions of yield shocks for the split sample. The model is estimated only once—over the full sample—and sample variances of shocks are computed separately for the first and second halves. The point estimates in Panels A and B (the first and second halves, repectively) do not point to a substantially greater role for inflation in either sample. Over the first half, the direct contribution of inflation is a little larger than in the second half, but the indirect contribution through covariances is smaller.

More evidence about robustness is reported in Table 6. It repeats the variance decomposition in Table 4 using the expanded version of the model. The point estimates for the contribution of inflation are in line with those in Table 4. Confidence bounds are not reported. They are wider than the bounds in Table 4 owing to the greater flexibility of the expanded version of the model.

The decompositions in Tables 4, 5, and 6 are for quarterly shocks to yields. Expected inflation plays a much greater role in variance decompositions of levels of yields, at least for the 1968 through 2012 sample. The evidence is in Table 7. For both the baseline version of the model (Panel A) and the expanded version (Panel B), the direct contribution of inflation is the largest single component of yield variances. Including the indirect covariance effects, the point estimates imply that inflation accounts for between 50 and 60 percent of yield variances.

The obvious reason why inflation plays a greater role unconditionally than it does conditionally is that inflation shocks are more persistent than other shocks. Point estimates of unconditional persistence are reported in Table 8. (For the moment, ignore the final column in this table.) The model-implied correlation between one-quarter-ahead expected inflation at t and one-quarter-ahead expected inflation six years later exceeds 0.5. The corresponding correlation for the expected real rate is 0.25 with the baseline version and only 0.07 with the expanded version. The term premium on a ten-year bond is also less persistent than inflation. Term premia on other bonds behave similarly.

There are no standard errors or confidence bounds included in Tables 7 and 8 because they are easy to summarize: there is enormous uncertainty in the properties of unconditional variances of yields. Slight changes in the elements of the feedback matrix K in (10) can reverse the relative persistence of the yield components. Thus it is plausible that unconditionally, expected real rates and term premia both contribute more than expected inflation to the overall variance of nominal yields.

In Table 8, the expanded version of the model tells us that shocks to real rates die out quickly. At the eight-quarter horizon, the estimated population serial correlation is less than 0.2. Estimates for the baseline model imply higher persistence: at the eight-quarter horizon the serial correlation exceeds 0.5. Uncovering the features of the data that drive this disagreement illustrates the sensitivity of macro-finance models to the choice of observables and assumptions about measurement error.

In some sense, the ultimate source of the disagreement is model misspecification. Equation (9) says that the observables have common, persistent components (the factors) and idiosyncratic, white-noise components η_t. The baseline version (and perhaps the expanded version) has too few common factors. Therefore truly common factors also show up in estimates of the η_t shocks. shocks are non-common, completely transitory shocks.

Panel A of Figure 5 displays the observed survey expectation of GDP growth from $t-1$ to t. It also displays the baseline version's filtered value of this time series, which strips out the η_t part. The estimated baseline version of the model treats much of the variation in survey expectations as driven by η_t, and thus irrelevant to explaining the joint variation of macro variables and yields. Inspection of Panel A shows that the non-η_t part of the survey expectation is much more persistent than is the raw surve expectation. The factor driving the survey expectation also drives real rates, thus real rates are persistent.

Panel B displays the same two time series for the expanded version of the model. This estimated model treats almost all of the variation in the survey expectations as part of the common variation in macro variables and yields. The differences between Panels A and B are driven primarily by the inclusion of CFNAI among the expanded set of observables. The correlation between the survey expectation of GDP growth and the CFNAI exceeds 0.8. Thus the likelihood of the expanded model is maximized by capturing their joint variation with a common factor rather than by attributing it to independent noise. This common factor has low persistence, producing low persistence in the real rate. The baseline model would produce the same result if we hard-wired the standard deviation of η_t to equal zero for the survey expectation of GDP.

This comparison does not imply that the expanded version is a more accurate description of yields than the baseline version. The expanded version may be misspecified as well. If so, the more parsimonious baseline model may describe yield dynamics better than the expanded version, at the cost of producing a poor cross-sectional fit to the macro data. The more robust message is that both the choice of observables and specifications of the non-common component can have substantial effects on the estimated model's yield dynamics.

4.5 Macro and non-macro components of yields

Here we take a brief look at the contribution of the "non-macro" factor to the variation of nominal yields. This factor has dynamics that are independent of inflation and economic activity. Thus by construction, it cannot affect average expected inflation. The only components of nominal yields that it can affect are affect average expected real rates and term premia. Although the factor is independent of the other factors in population, maximum likelihood estimation does not impose that independence in a finite sample.

Table 9 decomposes the sample variances of yield shocks into macro and non-macro components. The point estimates are for the baseline version of the model. In sample, the macro and non-macro shocks are correlated, thus the sample variances of yield shocks are partially explained by sample covariances between the macro and non-macro components. The 95th percent confidence bounds on the variance decompositions are calculated following the procedure in Section 4.4. These are bounds on population variance decompositions, which depend on population dynamics rather than sample dynamics. Therefore no bounds are reported for the covariance contribution.

According to the point estimates, the relative importance of the macro and non-macro factors depends on maturity. For short maturities, the macro factors dominate the variance decomposition. The role of the non-macro factor increases with maturity such that at the ten-year maturity, the non-macro factor explains half of the variance of yield shocks. However, the confidence bounds for all maturities are large. For three-month yields, the bound for the macro factors ranges from less than half to more than 90 percent. For ten-year yields, the corresponding bound ranges from less than 15 percent to more than 80 percent.

Loadings of yields on the non-macro factor are close to parallel across maturities. The loadings are not displayed in any figure because they are similar to the first principal component of the yield residuals displayed in Panel B of Figure 2. The effect of this factor on the three-month yield is entirely a real-rate effect, since the three-month yield has no term premium. The effect of the factor on longer-maturity yields is a function of its persistence. Persistence near that of a random walk implies that a non-macro shock to the real rate is nearly permanent. In this case, a level shock to the term structure is largely explained by a real rate shock. Low persistence implies that a non-macro shock to the real rate has little effect on long-term yields. Hence a level shock to the term structure is primarily a term premium shock at long maturities.

According to the baseline model, the non-macro factor is highly persistent. Point estimates of serial correlation are reported in the final column of Table 8's Panel A. The half-life is about four years. As a consequence, the effects of shocks to this factor on term premia and average expected real rates are approximately equal at the ten-year maturity. (The precise numbers are not reported in any table.) Estimates of the expanded version of the model imply a less-persistent process for the non-macro factor. Panel B of Table 8 indicates that shocks have a half-life of about two years. Thus for this model, almost all of the non-macro variance of shocks to the ten-year bond yield is attributed to term premia shocks.

4.6 Nominal and TIPS yields

Figure 6 displays the five-year TIPS yield. The black line duplicates the black line in Panel B of Figure 3. Also displayed in Figure 6 is the five-year nominal yield less average expected five-year inflation, as implied by estimates of the baseline model. (Estimates of the expanded model produce a very similar time series.) Over the sample period 1999Q1 through 2012Q4, their correlation exceeds 0.9. Aside from aftermath of the Lehman bankruptcy, the two series move almost in lockstep.

Put differently, over this sample the nominal yield is approximately expected inflation plus the real yield. Nominal yields have a nominal term premia component, while TIPS yields have a real term premia component. This figure suggests that outside of crisis periods, the difference between the two premia does not fluctuate substantially.

Similar evidence is in Table 10, which reports correlations between daily changes in nominal and TIPS yields. The correlations are broken down by calendar year and maturity. Campbell et al. (2009) argue that the high correlations at the daily frequency are a consequence of unusually stable inflation expectations during this sample period. It is true that inflation expectations were less volatile post 1998 than before. But as discussed in Section 4.4, the other components of nominal yields were also less volatile. The evidence here is that shocks to inflation expectations were small relative to real-rate shocks and term premia shocks throughout the 1968Q4 through 2012Q4 sample.

5 Concluding comments

This paper studies the joint dynamics of nominal yields and inflation expectations from 1968 through 2012. For this sample, quarterly shocks to nominal yields are primarily shocks to real rates and term premia. Over the shorter 1999 through 2012 period during which TIPS are available, the difference between nominal and real term premia appears small.

This is a surprising result, at least based on much of the recent macro-finance dynamic term structure research, but it is not raise any problems from a theory perspective. More troubling is the evidence that in the sample, around half of the variance of quarterly shocks to longer-term yields is driven by real-yield shocks that are unrelated to macroeconomic activity or inflation expectations. A few potential explanations for such shocks are considered and rejected.

References

Amihud, Yakov, and Haim Mendelson, 1991, Liquidity, maturity, and the yields on U.S. Treasury securities, *Journal of Finance* 46, 1411-1425.

Ang, Andrew, Geert Bekaert, and Min Wei, 2007, Do macro variables, asset markets or surveys forecast inflation better?, *Journal of Monetary Economics* 54, 1163-1212.

Ang, Andrew, Geert Bekaert, and Min Wei, 2008, The term structure of real rates and expected inflation, *Journal of Finance* 63, 797-849.

Ang, Andrew, Jean Boivin, Sen Dong, and Rudy Loo-Kung, 2009, Monetary policy shifts and the term structure, Working paper, Columbia University.

Ang, Andrew, Sen Dong, and Monika Piazzesi, 2007, No-arbitrage Taylor Rules, Working paper, Columbia University.

Ang, Andrew, and Maxim Ulrich, 2012, Nominal bonds, real bonds, and equity, Working paper, Columbia GSB.

Bansal, Ravi, and Ivan Shaliastovich, 2012, A long-run risks explanation of predictability in bond and currency markets, Working paper, Duke University.

Campbell, John Y., and Robert J. Shiller, 1987, Cointegration and tests of present value models, *Journal of Political Ecoomy* 95, 1062-1088.

Campbell, John Y., and Robert J. Shiller, 1996, A scorecard for indexed government debt, *NBER Macroeconomics Annual 1996*. Ben Bernanke and Julio Rotemberg, Eds., 155-208.

Campbell, John Y., Robert J. Shiller, and Luis M. Viceira, 2009, Understanding inflation-indexed bond markets, *Brookings Papers on Economic Activity*, Spring, 79-120.

Campbell, John Y., and Luis M. Viceira, 2001, Who should buy long-term bonds?, *American Economic Review* 91, 99-127.

Cieslak, Anna, and Pavol Povala, 2013, Expecting the Fed, Working paper, Kellogg SOM/University of Lugano.

Fama, Eugene F., 1975, Short-term interest rates as predictors of inflation, *American Economic Review* 65, 269-282.

Fama, Eugene F., and Michael R. Gibbons, 1982, Inflation, real returns and capital investment, *Journal of Monetary Economics* 9, 297-323.

Faust, Jon, and Jonathan H. Wright, 2012, Forecasting inflation, *Handbook of Forecasting*, forthcoming.

Fisher, Irving, 1930, *Theory of Interest.* New York: Macmillan.

Gallmeyer, Michael, Burton Hollifield, Francisco Palomino, and Stanley Zin, 2008, Term premium dynamics and the Taylor rule, Working paper, University of Michigan.

Garbade, Kenneth, and Paul Wachtel, 1978, Time variation in the relationship between inflation and interest rates, *Journal of Monetary Economics* 4, 755-765.

Gurkaynak, Refet S., Brian Sack, and Jonathan H. Wright, 2007, The U.S. Treasury yield curve: 1961 to the present, *Journal of Monetary Economics* 54, 2291-2304.

Hamilton, James D., 1985, Uncovering financial market expectations of inflation, *Journal of Political Economy* 93, 1224-1241.

Hjalmarsson, Erik, and Pär Österholm, 2010, Testing for cointegration using the Johansen methodology when variables are near integrated: size distortions and partial remedies, *Empirical Economics* 39, 51-76.

Kozicki, Sharon, and Peter A. Tinsley, 2001, Shifting endpoints in the term structure of interest rates, *Journal of Monetary Economics* 47, 613-652.

Krishnamurthy, Arvind, and Annette Vissing-Jorgensen, 2012, The aggregate demand for Treasury debt, *Journal of Political Economy* 59, 233-267.

Lardic, Sandrine, and Valérie Mignon, 2004, Fractional cointegration and the term structure, *Empirical Economics* 29, 723-736.

Litterman, Robert, and Jose Scheinkman, 1991, Common factors affecting bond returns, *Journal of Fixed Income* 1, 54-61.

Macaulay, Frederick, 1938, *The Movements of Interest Rates, Bond Yields, and Stock Prices in the United States since 1856.* New York: National Bureau of Economic Research.

Martin, Vance, Anthony D. Hall, and Adrian R. Pagan, 1996, Modelling the term structure, *Handbook of Statistics* 14, G.S. Maddala and C.R. Rao, Eds., 91-118.

Mishkin, Frederic S., 1981, The real rate of interest: an empirical investigation, *Carnegie-Rochester Conference Seies on Public Policy* 15, 151-200.

Mishkin, Frederic S., 1990, The information in the longer maturity term structure about future inflation, *Quarterly Journal of Economics* 105, 815-828.

Nelson, Charles R., and G. William Schwert, 1977, Short-term interest rates as predictors of inflation: On testing the hypothesis that the real rate of interest is constant, *American Economic Review* 67, 478-486.

Park, Sang Yong, and Marc R. Reinganum, 1986, the puzzling price behavior of Treasury bills that mature at the turn of calendar months, *Journal of Financial Economics* 16, 267-283.

Rose, Andrew K., 1988, Is the real interest rate stable?, *Journal of Finance* 43, 1095-1112.

Rudebusch, Glenn D., and Eric Swanson, 2012, The bond premium in a DSGE model with long-run real and nominal risks, *American Economic Journal: Macroeconomics* 4, 105-143.

Schwert, G. William, 1986, The time series behavior of real interest rates: A comment, *Carnegie-Rochester Conference Series on Public Policy* 24, 275-288.

van Binsbergen, Jules H., Jesús Fernández-Villaverde, Ralph S.J. Koijen, and Juan F. Rubio-Ramírez, 2011, The term structure of interest rates in a DSGE model with recursive preferences, Working paper, Stanford GSB.

Table 1. Tests of nonstationarity

The table reports results of augmented Dickey-Fuller tests that yields, yield spreads, and inflation have unit roots. The table reports t-statistics and their p-values under the hypothesis of a unit root. Yields are quarter-end observations. Yield spreads are all relative to the five-year yield. GDP inflation is the log change in the GDP index from quarter $t-1$ to quarter t. CPI inflation is the log change in the CPI index from the last month of quarter $t-1$ to the last month of quarter t. Expected inflation is from the Survey of Professional Forecasters. It is the mean forecast of GDP inflation from quarter t to quarter $t+1$. The first observation of the ten-year yield is 1961Q2. The first observation of all other yields is 1952Q2. The first observation of expected inflation is 1968Q4. All ADF tests use six lags.

	1952Q2–2012Q4		1968Q4–2012Q4	
Variable	Coef	p-val	Coef	p-val
Three-mon yield	−2.51	0.114	−2.17	0.223
One-yr yield	−1.96	0.313	−1.60	0.475
Two-yr yield	−1.64	0.455	−1.22	0.641
Three-yr yield	−1.45	0.540	−0.95	0.758
Four-yr yield	−1.36	0.580	−0.78	0.821
Five-yr yield	−1.27	0.619	−0.67	0.849
Ten-yr yield	−0.94	0.764	−0.47	0.892
Three-mon less five-yr	−4.79	0.001	−4.30	0.001
One-yr less five-yr	−4.53	0.001	−4.23	0.001
Two-yr less five-yr	−4.43	0.001	−4.14	0.001
Three-yr less five-yr	−3.95	0.003	−3.75	0.005
Four-yr less five-yr	−3.93	0.003	−3.77	0.004
Ten-yr less five-yr	−2.86	0.052	−3.12	0.027
GDP infl	−2.49	0.120	−2.06	0.270
CPI infl	−2.82	0.057	−2.46	0.128
Expected GDP infl			−1.57	0.488

Table 2. Tests of cointegration

Panel A reports results of augmented Dickey-Fuller (ADF) tests of the hypotheses that yields less inflation have unit roots. The panel reports t-statistics and their p-values under the hypothesis of a unit root. Panel B reports results of Engle-Granger tests (using ADF) that yields and inflation are cointegrated. For these tests yields are regressed on inflation. Data are described in Table 1. All ADF tests use six lags.

	Inflation	1952Q2–2012Q4		1968Q4–2012Q4	
Yield	measure	Coef	p-val	Coef	p-val
A.					
Three-mon	GDP	−2.51	0.114	−2.11	0.249
One-yr	GDP	−2.20	0.210	−1.80	0.385
Five-yr	GDP	−2.04	0.280	−1.62	0.463
Ten-yr	GDP	−1.85	0.362	−1.77	0.397
Three-mon	Expected			−2.42	0.138
One-yr	Expected			−1.94	0.324
Five-yr	Expected			−1.18	0.657
Ten-yr	Expected			−1.28	0.615
Three-mon	CPI	−2.78	0.063	−2.29	0.177
One-yr	CPI	−2.81	0.059	−2.31	0.169
Five-yr	CPI	−3.07	0.030	−2.56	0.105
Ten-yr	CPI	−2.94	0.043	−2.74	0.070
B.					
Three-mon	GDP	−2.49	0.299	−2.11	0.475
One-yr	GDP	−2.11	0.475	−1.71	0.660
Five-yr	GDP	−1.68	0.671	−1.13	0.875
Ten-yr	GDP	−1.27	0.839	−1.01	0.901
Three-mon	Expected			−1.92	0.562
One-yr	Expected			−1.73	0.647
Five-yr	Expected			−1.39	0.802
Ten-yr	Expected			−1.37	0.809
Three-mon	CPI	−2.30	0.335	−2.50	0.299
One-yr	CPI	−2.14	0.459	−2.12	0.472
Five-yr	CPI	−1.93	0.556	−1.34	0.820
Ten-yr	CPI	−1.68	0.672	−1.22	0.853

Table 3. Quarterly projections of yields on measures of economic activity and inflation

Nominal Treasury bond yields are regressed on various combinations of contemporaneous and lagged measures of economic activity and inflation. Yields are measured at either the end of the quarter (end) or the end of the second month in the quarter (mid). Panel B reports adjusted R^2s. Panel A lists the explanatory variables. Most of these variables are released with a lag and subject to revision. Regressions are estimated using both these revised versions of the data and real-time versions. The sample period for all regressions is 1968Q4 through 2012Q4.

A. Explanatory variables

ID	Description	Available vintages (revised/real-time)
[1]	log real per capita GDP less 16-quarter moving average	rev, r-t
[2]	First-difference of log real per capita GDP, and lags	rev, r-t
[3]	CFNAI, three-month moving average	rev, r-t
[4]	Quarter-to-quarter GDP index inflation, and lags	rev, r-t
[5]	Survey forecasts of GDP growth from $t+i-1$ to $t+i$, $i = 0, \ldots, 4$	r-t
[6]	Survey forecasts of GDP inflation from $t+i-1$ to $t+i$, $i = 0, \ldots, 4$	r-t

B. Adjusted R^2

Yields	Variables used	3 mon	1 yr	2 yr	5 yr	10 yr
end-Q	[1]; [2], lags 0-3; [3]; [4], lags 0-3. all rev.	57.6	57.2	53.6	46.1	38.9
end-Q	[1]; [2], lags 0-3; [3]; [4], lags 0-3. all r-t.	62.1	61.1	57.8	51.4	45.4
mid-Q	[1]; [2], lags 0-3; [3]; [4], lags 0-3. all r-t.	62.2	60.8	56.9	50.6	44.0
mid-Q	[1]; [2], lags 0-3; [3]; [4], lags 0-3; all r-t. [5],$i = 0, \ldots, 4$; [6],$i = 0, \ldots, 4$	76.2	76.4	75.2	72.6	71.6
mid-Q	[1]; [2], lags 0-3; [3]; [4], lag 0; all r-t. [5],$i = 0, \ldots, 4$; [6],$i = 0, 3$	75.1	75.6	74.5	72.2	71.0
mid-Q	[1]; [3]; [4], lag 0; all r-t. [5],$i = 0$; [6],$i = 0, 3$	74.4	74.9	74.1	72.0	71.4
mid-Q	[1]; r-t. [5],$i = 0$; [6],$i = 0, 3$	74.0	74.6	73.8	71.8	70.9

Table 4. Decompositions of sample variances of yield shocks

The table reports model-implied decompositions of sample variances of quarterly shocks to nominal Treasury bond yields. The model describes the joint dynamics of nominal yields, realized and expected inflation, and measures of economic activity. Yields are the sum of average expected inflation and short-term real rates over the life of the bond, plus a term premium. The sample period is 1968Q4 through 2012Q4. In Panel A, 95th percentile bounds are in brackets. Panel B reports the sum of columns 1, 4, and 5 in Panel A.

A. Full decomposition

	1. Average expected inflation	2. Average expected real rate	3. Term premium	2Cov([1], [2])	2Cov([1], [3])	2Cov([2], [3])
Three-mon	0.13	0.91	0.00	−0.04	0.00	0.00
	[0.06 0.47]	[0.49 1.38]	[0.00 0.00]	[−0.66 0.32]	[0.00 0.00]	[0.00 0.00]
One-yr	0.11	0.50	0.10	0.03	−0.05	0.32
	[0.06 0.33]	[0.25 0.98]	[0.03 0.56]	[−0.29 0.31]	[−0.38 0.14]	[−0.36 0.40]
Two-yr	0.10	0.39	0.20	0.04	−0.09	0.36
	[0.06 0.30]	[0.17 0.94]	[0.08 0.90]	[−0.27 0.33]	[−0.48 0.14]	[−0.61 0.45]
Three-yr	0.10	0.35	0.23	0.04	−0.09	0.37
	[0.06 0.30]	[0.13 0.94]	[0.10 1.01]	[−0.27 0.34]	[−0.47 0.14]	[−0.74 0.46]
Four-yr	0.10	0.32	0.24	0.04	−0.09	0.37
	[0.06 0.31]	[0.09 0.95]	[0.12 1.10]	[−0.27 0.36]	[−0.48 0.15]	[−0.86 0.45]
Five-yr	0.11	0.30	0.26	0.05	−0.09	0.37
	[0.06 0.33]	[0.07 0.95]	[0.13 1.18]	[−0.28 0.39]	[−0.53 0.17]	[−0.88 0.45]
Ten-yr	0.09	0.19	0.42	0.04	−0.09	0.34
	[0.03 0.40]	[0.03 0.90]	[0.23 1.38]	[−0.32 0.47]	[−0.72 0.18]	[−1.00 0.40]

B. Components related to inflation

	Point estimate	95th Percentile Bounds	
Three-mon	0.09	−0.38	0.51
One-yr	0.08	−0.17	0.42
Two-yr	0.05	−0.23	0.37
Three-yr	0.05	−0.24	0.36
Four-yr	0.06	−0.24	0.37
Five-yr	0.07	−0.25	0.39
Ten-yr	0.05	−0.34	0.35

Table 5. Decompositions of sample variances of yield shocks: subsamples

The table reports model-implied decompositions of sample variances of quarterly shocks to nominal Treasury bond yields. The model describes the joint dynamics of nominal yields, realized and expected inflation, and measures of economic activity. Yields are the sum of average expected inflation and short-term real rates over the life of the bond, plus a term premium. The model is estimated once, over the period 1968Q4 through 2012Q4. Parameters and fitted shocks to the state vector are used to construct decompositions of sample variances for the first and second halves of the sample.

A. 1969 through 1990

	1. Average expected inflation	2. Average expected real rate	3. Term premium	2Cov([1], [2])	2Cov([1], [3])	2Cov([2], [3])
Three-mon	0.13	0.91	0.00	−0.04	0.00	0.00
One-yr	0.10	0.48	0.11	0.02	−0.09	0.35
Two-yr	0.10	0.37	0.23	0.02	−0.10	0.39
Three-yr	0.10	0.33	0.27	0.01	−0.12	0.40
Four-yr	0.11	0.31	0.29	0.01	−0.13	0.40
Five-yr	0.12	0.30	0.31	0.01	−0.13	0.40
Ten-yr	0.10	0.18	0.48	0.01	−0.14	0.36

B. 1991 through 2012

	1. Average expected inflation	2. Average expected real rate	3. Term premium	2Cov([1], [2])	2Cov([1], [3])	2Cov([2], [3])
Three-mon	0.16	0.95	0.00	−0.11	0.00	0.00
One-yr	0.10	0.63	0.05	0.04	−0.04	0.21
Two-yr	0.08	0.47	0.11	0.08	−0.03	0.28
Three-yr	0.08	0.39	0.13	0.10	−0.01	0.32
Four-yr	0.08	0.35	0.15	0.10	0.00	0.33
Five-yr	0.08	0.31	0.16	0.10	0.01	0.33
Ten-yr	0.07	0.20	0.31	0.09	0.01	0.32

Table 6. Decompositions of sample variances of yield shocks, expanded model

The table reports model-implied decompositions of sample variances of quarterly shocks to nominal Treasury bond yields. The model describes the joint dynamics of nominal yields, realized and expected inflation, and measures of economic activity. Yields are the sum of average expected inflation and short-term real rates over the life of the bond, plus a term premium. Relative to the baseline version, the expanded version of the model has an additional state variable and is estimated using observations of two additional macro variables. The sample period is 1968Q4 through 2012Q4. Panel B reports the sum of columns 1, 4, and 5 in Panel A. Panel B also reports 95th percentile bounds.

A. Full decomposition

	1. Average expected inflation	2. Average expected real rate	3. Term premium	2Cov([1], [2])	2Cov([1], [3])	2Cov([2], [3])
Three-mon	0.15	1.01	0.00	−0.16	0.00	0.00
One-yr	0.12	0.59	0.06	−0.05	−0.04	0.32
Two-yr	0.11	0.36	0.18	−0.01	−0.08	0.44
Three-yr	0.11	0.24	0.29	0.01	−0.10	0.46
Four-yr	0.12	0.17	0.36	0.01	−0.11	0.44
Five-yr	0.12	0.14	0.40	0.02	−0.10	0.42
Ten-yr	0.14	0.07	0.50	0.04	−0.08	0.33

B. Components related to inflation

	Point estimate	95th Percentile Bounds	
Three-mon	−0.01	−3.51	0.55
One-yr	0.03	−0.45	0.48
Two-yr	0.02	−0.36	0.46
Three-yr	0.02	−0.48	0.45
Four-yr	0.02	−0.58	0.46
Five-yr	0.04	−0.69	0.48
Ten-yr	0.10	−0.95	0.53

Table 7. Decompositions of sample variances of yields

The table reports model-implied decompositions of sample variances of nominal Treasury bond yields. The model describes the joint dynamics of yields, realized and expected inflation, and measures of economic activity. Yields are the sum of average expected inflation and short-term real rates over the life of the bond, plus a term premium. Relative to the baseline version, the expanded version has an additional state variable and is estimated using observations of two additional macro variables. The sample period is 1968Q4 through 2012Q4.

	1. Average expected inflation	2. Average expected real rate	3. Term premium	2Cov([1], [2])	2Cov([1], [3])	2Cov([2], [3])
A. Baseline version						
Three-mon	0.36	0.38	0.00	0.26	0.00	0.00
One-yr	0.31	0.27	0.02	0.23	0.06	0.11
Two-yr	0.29	0.22	0.04	0.21	0.09	0.15
Three-yr	0.28	0.19	0.06	0.19	0.11	0.17
Four-yr	0.27	0.17	0.07	0.18	0.12	0.19
Five-yr	0.26	0.16	0.08	0.18	0.14	0.19
Ten-yr	0.21	0.10	0.16	0.14	0.18	0.21
B. Expanded version						
Three-mon	0.37	0.38	0.00	0.25	0.00	0.00
One-yr	0.31	0.23	0.02	0.24	0.05	0.14
Two-yr	0.29	0.15	0.07	0.23	0.07	0.18
Three-yr	0.28	0.11	0.11	0.21	0.10	0.19
Four-yr	0.27	0.08	0.14	0.20	0.12	0.19
Five-yr	0.27	0.07	0.15	0.19	0.14	0.18
Ten-yr	0.26	0.04	0.19	0.16	0.20	0.15

Table 8. Estimated persistence of various components of nominal yields

The table reports model-implied population correlations between the quarter-t and quarter $t+j$ values of expected inflation (one quarter ahead), the one-quarter real rate, and the term premium on a ten-year nominal bond. It also reports these correlations for the model's "non-macro" factor, which contributes to both the one-quarter real rate and to term premia. The model describes the joint dynamics of yields, realized and expected inflation, and measures of economic activity. Relative to the baseline version, the expanded version has an additional state variable and is estimated using observations of two additional macro variables. The sample period is 1968Q4 through 2012Q4.

Lead	Expected inflation	Real rate	Ten-year term premium	Non-macro factor
A. Baseline version				
1	0.96	0.84	0.88	0.92
4	0.86	0.69	0.68	0.84
8	0.77	0.55	0.56	0.70
12	0.69	0.44	0.47	0.59
16	0.62	0.36	0.40	0.49
20	0.56	0.30	0.34	0.41
24	0.51	0.25	0.29	0.34
B. Expanded version				
1	0.97	0.84	0.88	0.92
4	0.90	0.46	0.68	0.72
8	0.83	0.19	0.48	0.52
12	0.77	0.10	0.36	0.38
16	0.73	0.08	0.28	0.27
20	0.69	0.08	0.23	0.20
24	0.65	0.07	0.19	0.14

Table 9. A macro/non-macro decomposition of sample variances of yield shocks

The table reports model-implied decompositions of sample variances of quarterly shocks to nominal Treasury yields. The model describes the joint dynamics of yields, realized and expected inflation, and measures of economic activity. A "non-macro" factor affects only yields, while all other factors affect all observables and are denoted "macro" factors. The model implies the non-macro factor is uncorrelated with the macro factor at all lags. Maximum likelihood estimation does not impose this restriction in sample. The sample period is 1968Q4 through 2012Q4. The values in brackets are 95th percentile bounds, based on the population properties of the model.

	Macro factors	Non-macro factor	2Cov(macro, non-macro)
Three-mon	0.60	0.20	0.19
	[0.42 0.91]	[0.09 0.58]	–
One-yr	0.54	0.24	0.23
	[0.35 0.88]	[0.12 0.65]	–
Two-yr	0.46	0.28	0.26
	[0.28 0.86]	[0.14 0.72]	–
Three-yr	0.40	0.34	0.26
	[0.21 0.83]	[0.17 0.79]	–
Four-yr	0.34	0.40	0.26
	[0.16 0.81]	[0.19 0.84]	–
Five-yr	0.32	0.43	0.25
	[0.15 0.79]	[0.21 0.85]	–
Ten-yr	0.30	0.49	0.21
	[0.14 0.81]	[0.19 0.86]	–

Table 10. Correlations of daily changes in nominal and TIPs yields

The table reports, by calendar year, contemporaneous correlations between daily changes in nominal and TIP Treasury bond yields. The yields are for five-year and ten-year zero-coupon bonds.

Year	Changes in Five-year yields	Changes in Ten-year yields
1999	0.28	0.32
2000	0.46	0.51
2001	0.73	0.73
2002	0.82	0.84
2003	0.88	0.88
2004	0.86	0.85
2005	0.79	0.84
2006	0.80	0.86
2007	0.91	0.92
2008	0.69	0.75
2009	0.66	0.77
2010	0.78	0.81
2011	0.63	0.76
2012	0.56	0.75

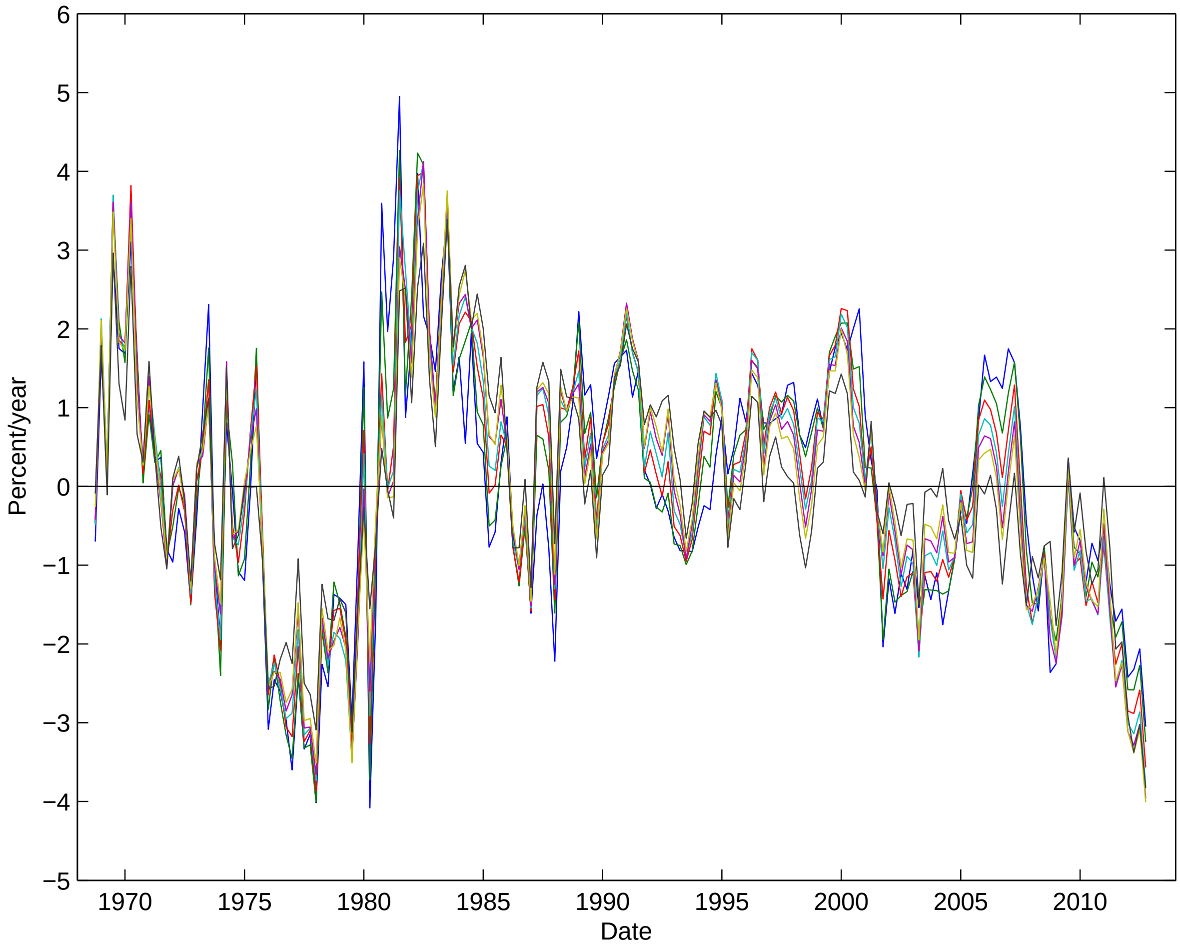

Figure 1. Residuals of OLS regressions of nominal yields on contemporaneous observations of economic activity and inflation expectations.

The data are quarterly. The measures of economic activity are log real per capital GDP less a lagged 16-quarter average of the same variable, CFNAI, and survey-based expected current GDP growth. The inflation variables are realized inflation from $t-2$ to $t-1$, survey-based expected current inflation, and survey-based expected inflation from $t+2$ to $t+3$. The bonds have maturities of three months, one through five years, and ten years.

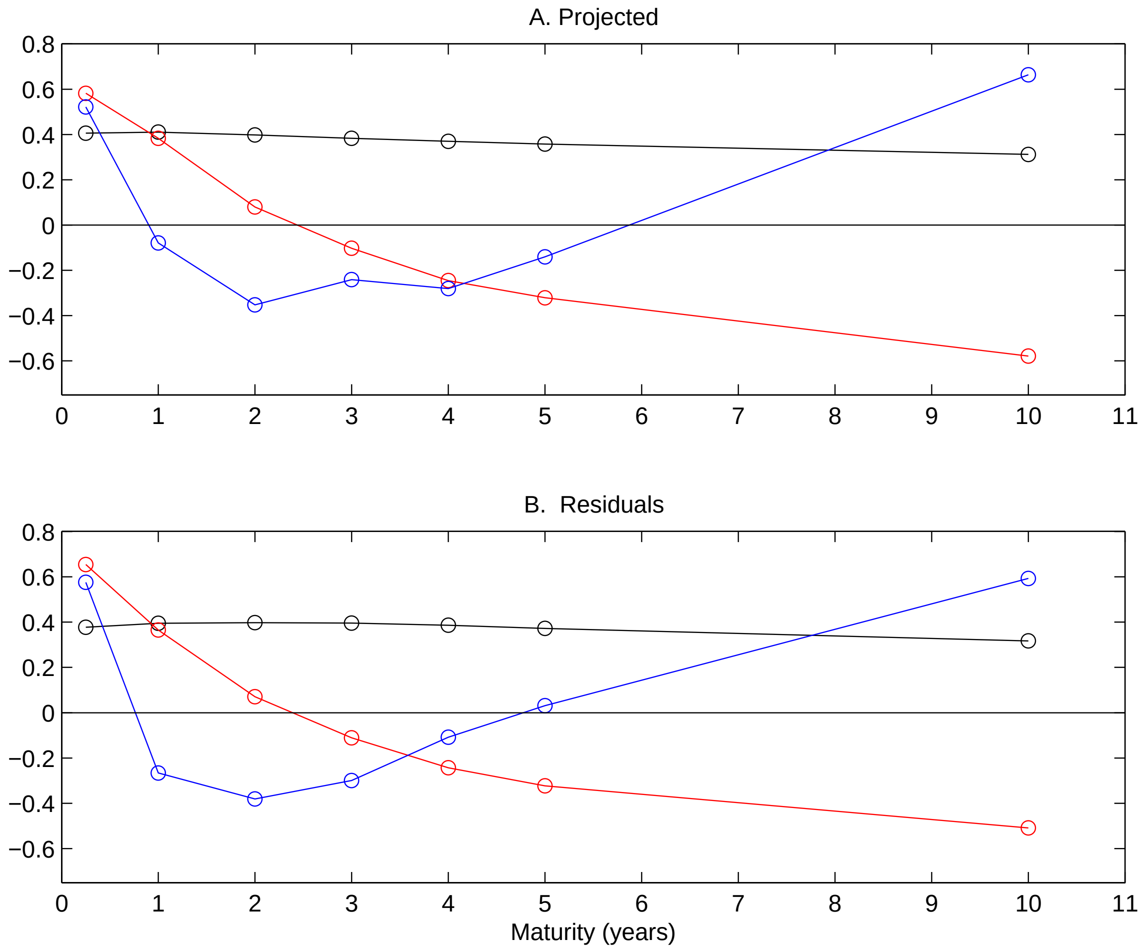

Figure 2. Principal components of fitted nominal yields and yield residuals.

The regressions are described in the notes to Figure 1. This figure displays the first three principal components of the sample covariance matrix of fitted yields (Panel A) and the same for the sample covariance matrix of yield residuals (Panel B).

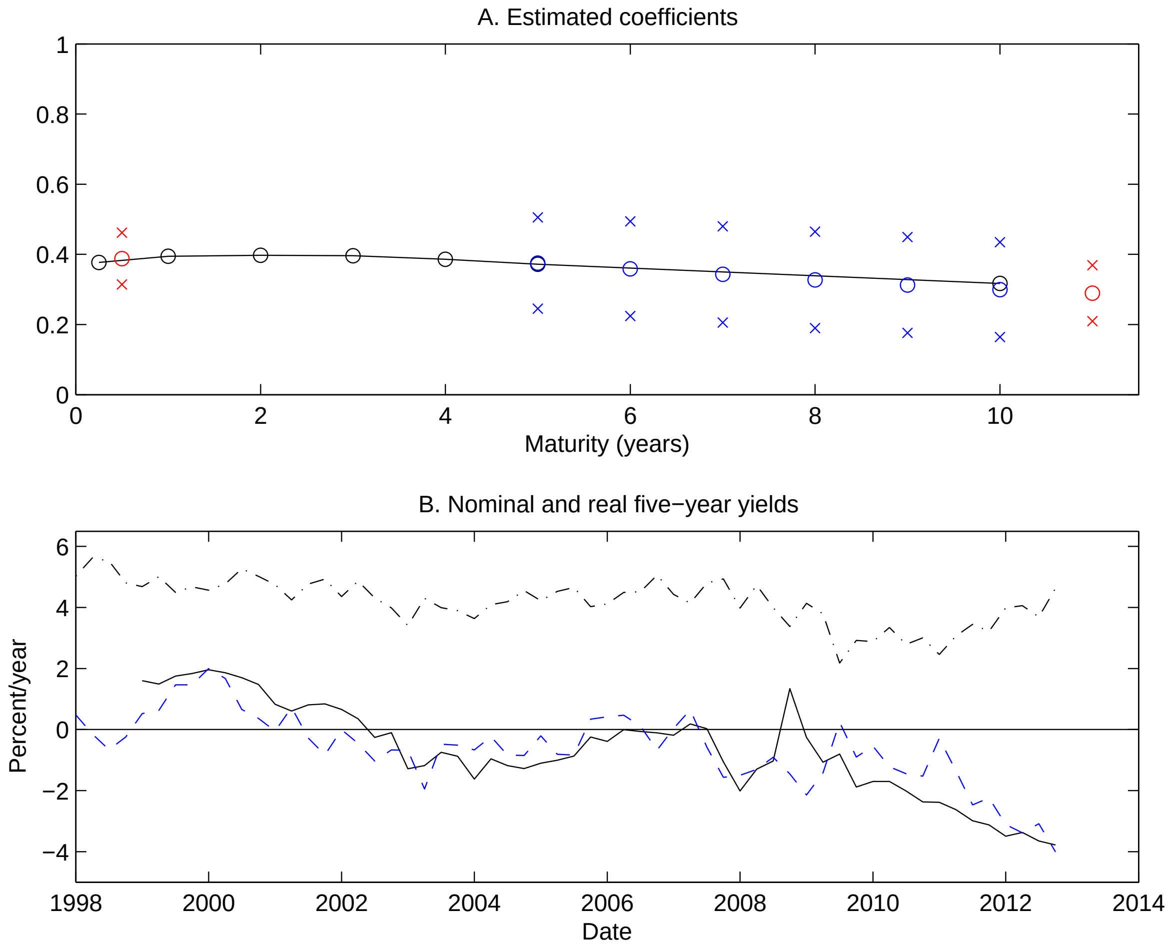

Figure 3. Nominal yield residuals and other yields

The black line and circles in Panel A are the first principal component of nominal yield residuals described in the notes to Figure 2. The blue circles are estimated coefficients of regressions of TIPS yields on the principal component. The x's are plus/minus two standard errors. The red circles and x's are corresponding coefficient estimates for the six-month Eurodollar deposit rate and Moody's Aaa long-term bond yield. The black dashed-dotted line in Panel B is the fitted component of the five-year nominal yield from the regression described in the notes to Figure 1. The blue dashed line is the residual. The black line is the five-year TIPS yield adjusted to have the same mean as the blue dashed line.

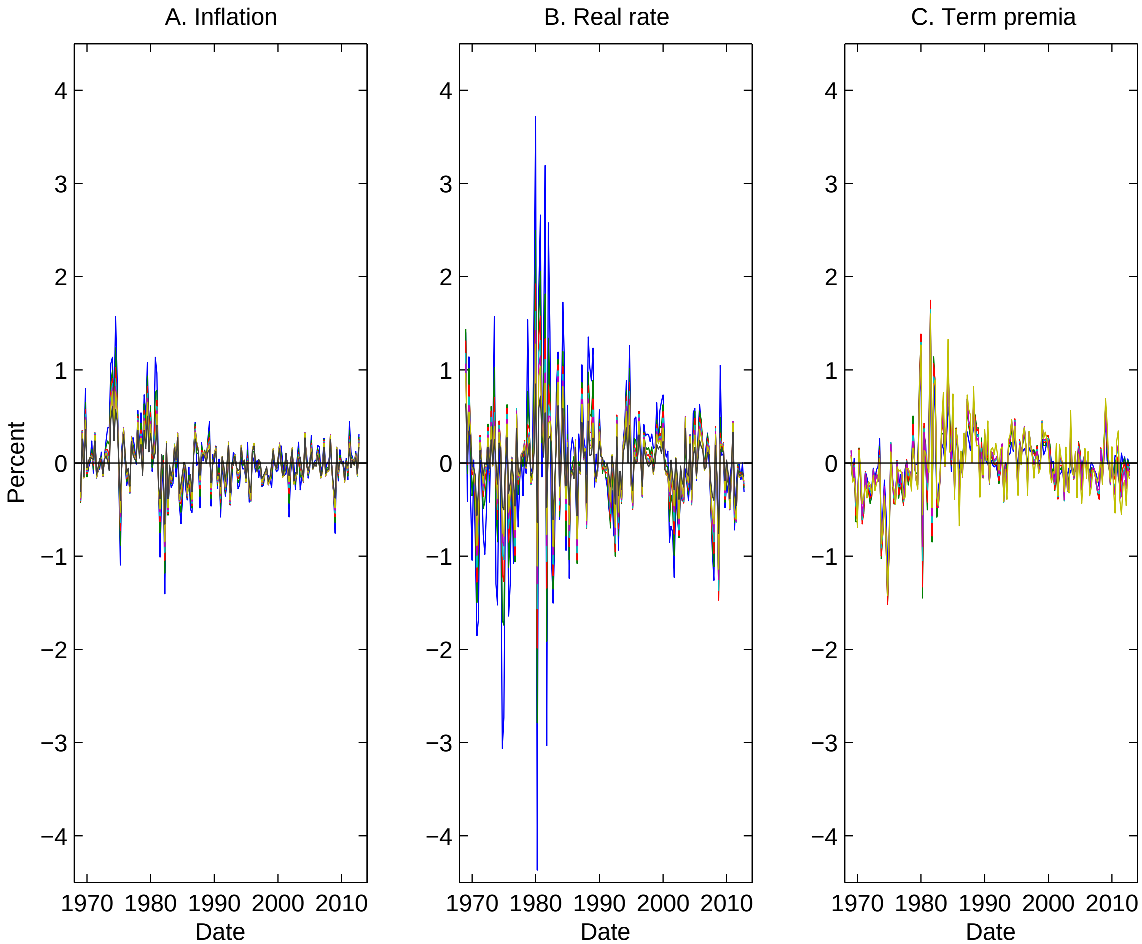

Figure 4. Shocks to the components of nominal yields

Quarterly shocks to nominal yields are the sum of shocks to average expected inflation during the life of the bond, average expected real rates during the life of the bond, and term premia. The figure plots fitted shocks for maturities from three months to ten years. The shocks are inferred from an estimated dynamic model of yields, inflation, and economic activity.

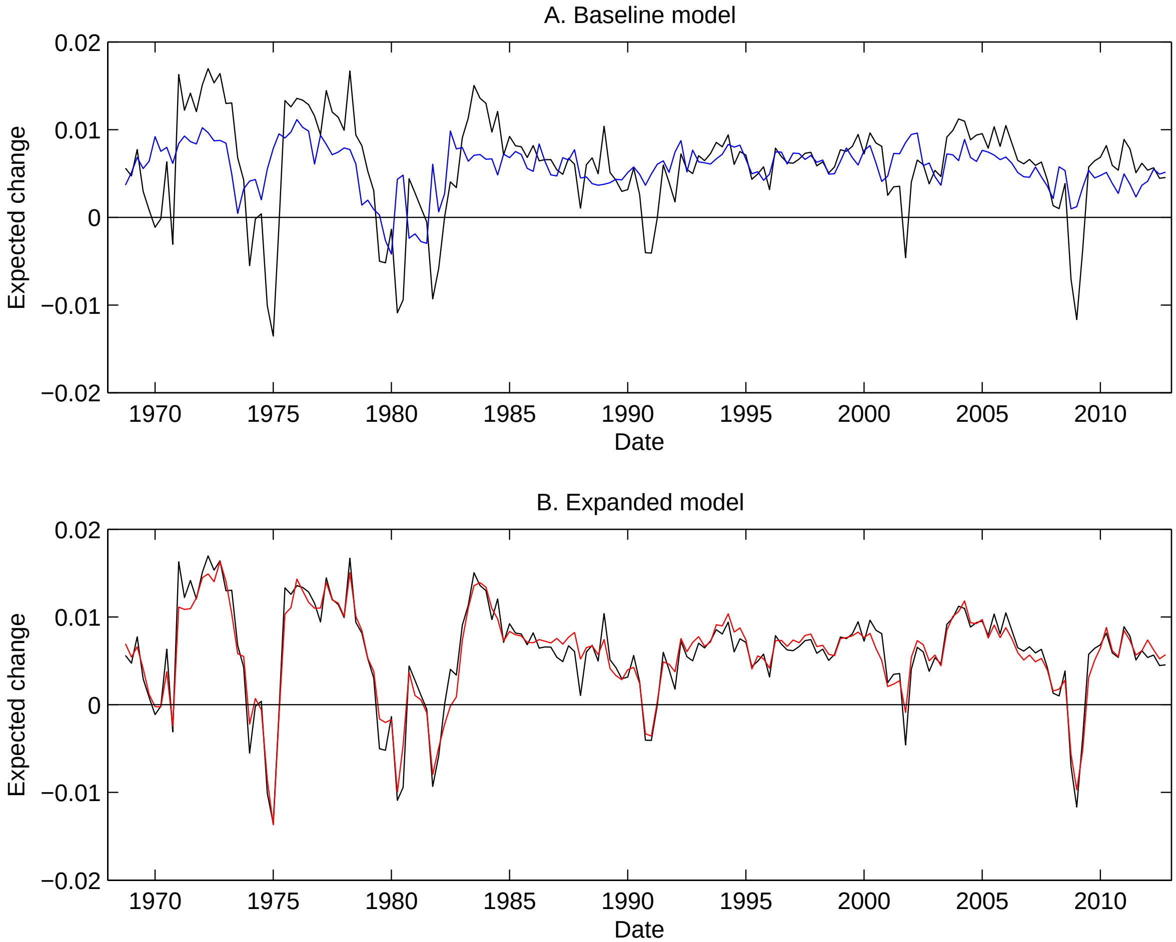

Figure 5. Survey expectations of contemporaneous GDP growth

The black line in each panel is a survey-based measure of expected GDP growth from quarter $t-1$ to quarter t. Two dynamic models are estimated in which variables including the survey measure are observed with idiosyncratic transitory shocks. The blue and red lines in Panels A and B respectively are fitted estimates of the survey measure stripped of the shocks.

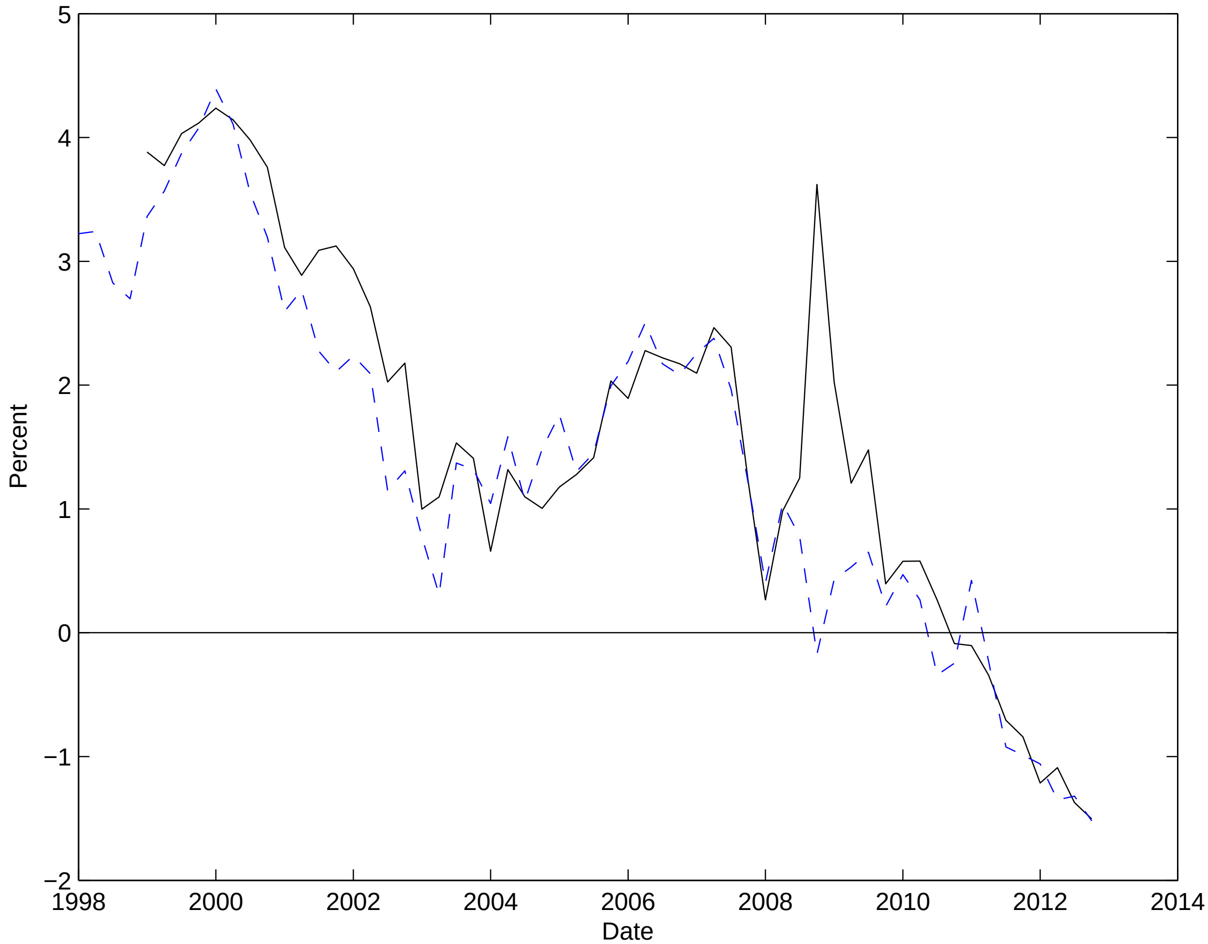

Figure 6. The five-year TIPs yield and the five-year nominal yield less expected inflation

The black line is the five-year TIPS yield. The blue dashed line is the five-year nominal yield less model-implied average expected inflation over the next five years.