Equity Risk and Treasury Bond Pricing[1]

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ABSTRACT

We investigate whether changes in equity risk can be tied to changes in the slope of the Treasury term structure over the intriguing 1997 to 2007 period; while controlling for Treasury-market state variables and contemporaneous bond-market variables suggested by the literature. Risk is measured by the implied volatility from equity-index options and 10-year T-Note futures options. We find a partial negative relation between monthly changes in equity risk and monthly changes in both the term-structure's second principal component and the '10-year minus 6-month' term yield spread. Further, the lagged level of equity risk contains reliable volatility information about the unexplained portion of the 'change in term-structure slope' variables. It is important to jointly examine both the change in equity risk and the change in T-note risk when trying to distinguish the partial risk relations from the simple risk relations. Further, in contrast with the sizable negative correlation between stock and T-note futures returns over our sample, we find an insignificant positive partial relation between stock and T-note futures returns when controlling for the concurrent changes in the risk. Our findings indicate that changes in equity risk can be important for understanding movements in the Treasury term structure and the risk premia of longer-term Treasuries.

JEL Classification: G12, G14

Keywords: Equity Risk, Treasury Bond Prices, Bond Risk Premia, Stochastic Volatility

1. Introduction

We study whether changes in equity risk can be tied to changes in the slope of the Treasury term structure over the intriguing 1997 to 2007 period. To evaluate the change in the term-structure's slope, we examine both the change in the second principal component derived from the term structure and the change in a '10-year minus 6-month' term yield spread. To measure equity and longer-term Treasury risk, we use the implied volatility from equity-index options and 10-year T-Note futures options, respectively. We also present additional evidence to assist in the interpretation of our primary findings.

Our motivation can be considered to have three related components. First, it is well known that movements in the term-structure's first two principal components account for almost all the variation in Treasury yields. However, while a principal components analysis provides a useful statistical description of the yield curve, the principal components offer little insight into the underlying economic forces that drive movements in the term structure; see Diebold, Piazzesi, and Rudebusch (2005). The second principal component has been shown to be closed tied to the slope of the term structure. Our analysis evaluates whether changes in equity risk can be important for understanding movements in the term-structure's second principal component.[1]

Second, recent work such as Cochrane and Piazzesi (2005) and Campbell, Sunderam, and Viceira (2009) (CSV) are interested in the risk premia of longer-term Treasuries. CSV consider the pricing of nominal Treasury bonds and the comovements between bond and equity prices. They pose the question of whether Treasury bonds can be beneficial to investors as a hedge against other risks. They consider the term yield spread (which is a measure of the term-structure's slope) as one measure of the Treasury term risk premia. For example, if longer-term Treasuries can serve as a hedge against equity risk under certain market conditions, then this suggests that increases in equity risk may make longer-term Treasuries more attractive with a resulting increase in their price and a decrease in the forward-looking Treasury term risk premium. Our empirical investigation bears on these issues raised in CSV.

[1] We derive the first three principal components from zero-coupon Treasury yields at the 6-month, 1-year, 2-year, 3-year, 5-year, 7-year, and 10-year horizon; and then we empirically examine the second principal component.

Third, recent empirical evidence indicates that the 1997 to 2007 period is intriguing in regard to understanding stock and bond market interactions because of its: (1) overall negative stock-bond correlation in an environment of low and stable inflation, (2) episodes of unusually high and sustained negative stock-bond correlations, and (3) sizable variability in equity risk. Further, recent empirical results have indicated that subsequent stock-bond correlations tend to be low when the expected equity volatility is high, especially since about 1997 (Connolly, Stivers, and Sun (2005) and (2007), and Baele, Bekaert, and Inghelbrecht (2009)). Baele, Bekaert, and Inghelbrecht (2009) find that fundamental factors particularly fail to generate the extremely negative stock-bond correlations since 1998. And, Campbell, Sunderam, and Viceira (2009) point out that bond and stock returns are sometimes negatively correlated, notably in the late 1990's and 2000's, which implies that bonds might be useful at times to hedge shocks to aggregate wealth.[2] Collectively, these studies suggest that equity risk may have a role in understanding Treasury pricing, which is the focus of our empirical investigation.

In our empirical work, we strive to capture the partial relation between changes in equity risk and changes in the term-structure's slope. We control for: (1) the lagged forward rates as state variables for the Treasury market (Cochrane and Piazzesi (2005)); (2) the concurrent change in the short-rate yields, due to the importance of movements in the short rate in term structure modeling; (3) the concurrent shock in 10-year T-note risk, to better capture the partial relation to equity risk; (4) the concurrent stock return, because of the sizable negative relation between changes in equity risk and the concurrent stock return; (5) shocks in inflation announcements, due to the importance of inflationary shocks to fixed income values, and (6) changes in FOMC Fed Funds targets, due to their influence on Treasury yields (Piazzesi (2005)).

Over our 1997 to 2007 sample period, we find that the monthly changes in equity risk have a partial negative relation with the monthly change in both the term-structure's second principal

[2]There are also data reasons and structural-shift reasons for focusing on the 1997 to 2007 period. First, the CBOE started publishing its implied Volatility Index (VIX) in 1993 and we were able to obtain the Treasury-note implied volatility only back to 1993. Second, the Federal Open Market Committee (FOMC) changed their policy in 1994 and began announcing their Fed Funds target following every meeting. Third, there appears to have been a structural shift in the stock-bond correlation in about 1997. We further justify our choice of sample period in Section 2 and Appendix A.

component and the ‘10-year minus 6-month’ term yield spread. These partial relations are sizable and highly statistically reliable, evident in both one-half subperiods separately, evident using a variety of different methodologies, and evident over different horizons. Further, we find that the lagged equity implied volatility is reliably informative about the subsequent volatility of the unexplained component of our ‘change in the term-structure slope’ variables; and that the equity implied volatility contains more reliable information than the comparable T-note implied volatility.

Next, we also find that the monthly changes in T-note risk have a partial positive relation with the monthly change in both the term-structure’s second principal component and the ‘10-year minus 6-month’ term yield spread. In some cases, it is important to jointly examine both the change in equity risk and the change in T-note risk when trying to distinguish the partial risk relations from the simple risk relations.

Our findings suggest that changes in equity risk may influence the risk premia of longer-term Treasuries, in the sense of Campbell, Sunderam, and Viceira (2009). A risk premia interpretation would seem to require: (1) a positive relation between changes in equity risk and the excess returns of longer-term Treasuries, which would suggest that longer-term Treasuries could serve as a hedge against changes in equity risk; and/or (2) that changes in equity risk would be negatively related to the subsequent stock-bond return correlation, which suggest an increased diversification benefit to longer-term Treasury holdings during times of increased equity risk. We investigate these two issues using futures returns for 10-year T-notes and the S&P 500 and find evidence consistent with the two above conjectures.

Further, in contrast with the simple negative return correlation between stock and T-note futures returns over our sample, we find an insignificant positive partial relation between stock and T-note futures returns after controlling for the concurrent changes in the risk. This suggests that the negative stock-bond return correlation over 1997 to 2007 is primarily reflecting the positive relation between changes in equity risk and bond values, rather than some other potential explanation.

Our collective findings indicate that changes in equity risk can be important for understanding movements in the Treasury term structure, changes in the Treasury term risk premia, and comovements between stock and bond returns, at least under market conditions that existed over 1997 to 2007. The remainder of this paper is organized as follows. In Section 2, we briefly discuss additional related literature. Section 3 explains our sample selection and presents our data. Section 4 presents our main empirical results. In Section 5, we present related evidence to assist in interpretion. Section 6 concludes.

2. Additional Related Literature

Our work is also motivated by several different, but related, parts of the literature on pricing equity and bonds. The focus on aggregate equity volatility follows directly from Chen (2003) and Ang, Hodrick, Xing, and Zhang (2006) (among others). Premised on the logic that aggregate equity volatility risk may be a priced factor (Chen, 2003), Ang, et. al. demonstrate empirically that stocks with a high beta with respect to innovations in aggregate volatility (changes in the VIX implied volatility measure) have lower expected returns.[3] In related work using quarterly data from 1990 to 2005, Bollerslev, Tauchen, and Zhou (2009) find that aggregate volatility risk explains about 15 percent of the variation in quarterly excess stock market returns.[4] They conclude that time-variation in both volatility risk and risk aversion influence the dynamics of equity market returns, but do not address whether the bond market might be affected, too. Accordingly, one of our aims in this paper is to investigate whether the insights about the role of aggregate volatility in equity asset pricing are also relevant to understanding bond market dynamics, especially during periods when the equity risk is high relative to Treasury bond risk and when the equity risk has substantial time-series variability.

Cochrane and Piazzesi (2005) show that a single return-forecasting factor based on a set of forward rates describes temporal movement in all expected excess bond returns. Their results

[3] The VIX refers to the Volatility Index from the Chicago Board Options Exchange, which is a standardized implied volatility from equity-index options.

[4] Their measure of aggregate volatility risk is based on the difference between VIX and realized volatility built from high-frequency returns, and it dominates a list of predictor variables including the P/E ratio, the dividend yield, the default spread, and the consumption-wealth ratio (CAY).

spring from empirical analysis of one-year horizon real risk premia in the nominal term structure, net of inflation and the level of interest rates. In contrast, our focus is on the monthly horizon and interactions of bond pricing with equity risk. In our work, we take into account the information in the forward rates at the beginning of holding period, in the spirit of state variables to describe the Treasury market conditions. To foreshadow our results, we find that the lagged forward interest rates are important explanatory terms for both of our term-structure slope variables.

Bekaert, Engstrom, and Grenadier (2005) show that stochastic risk aversion may be important in understanding joint stock-bond pricing, but their model generates a correlation that is somewhat larger than the data. Baele, Bekaert, and Inghelbrecht (2009) examine the determinants of stock and bond return comovements. They focus on fundamentals over longer horizons and find that "even the best fitting economic factor model fits the dynamics of stock-bond return correlations poorly". They find that the difference between VIX and the fitted volatility from return shocks has information about stock-bond correlations.

In our introduction, we argued that our 1997 to 2007 sample period is intriguing because it exhibited both a negative stock-bond return correlation, and modest and stable inflation. Consider that from the long-term fundamentals perspective of Campbell and Ammer (1993) and Fama and French (1989), only the variation in expected inflation acts to generate a negative stock-bond correlation while variation in real interest rates and common movements in long-term expected returns act to generate a positive stock-bond correlation. Thus, this traditional fundamentals perspective seem inadequate to explain the recent negative stock-bond return correlations.

The literature on return comovement also addresses some of the questions we study here, particularly the stock-bond return correlation. For example, Fleming, Kirby, and Ostdiek (1998) propose that cross-market hedging may be important in understanding the linkages between the financial markets of different asset classes. In their analysis, demand for bonds is affected by information events that alter expected stock returns. Expected short-term interest rates and expected inflation may be unchanged, but bond markets can be importantly affected. They take this influence into account when estimating the volatility linkage between stocks, bonds, and bills and find stronger linkages than previously thought.[5] Through the cross-market rebalancing avenue of Kodres and Pritsker (2002), investors respond to shocks in one market by optimally readjusting their positions in other markets. This action transmits the shocks, so that a shock in one asset market, which may appear to be largely asset specific, may have a material influence on other financial assets.

Researchers studying markets under stress have developed some additional perspectives on joint stock-bond price formation. In this line of research, cross-market pricing effects may be considered a flight-to-quality (FTQ) or flight-to-liquidity (FTL) effect in some settings. Several recent papers have tried to distinguish between pricing influences attributed to FTQ versus FTL; see, e.g., Vayanos (2004) and Beber, Brandt and Kavajecz (2008). The distinction in Vayanos (2004) considers FTQ as a flight from more volatile assets and FTL as a flight to more liquid assets. Further, Goyenko and Ukhov (2009) find that illiquidity conditions in the stock market affect the Treasury bond market, with positive shocks to stock illiquidity decreasing bond illiquidity. In our study, distinguishing between FTQ and FTL effects is not a fundamental goal.

3. Sample Selection and Data Description

3.1. Selection of Sample Period

As discussed in our introduction, we feel that the 1997 to 2007 period is intriguing for understanding joint stock-bond pricing because of the observed negative stock-bond return correlation combined with the low and stable inflation. Further, there are data availability issues and structural-change issues which contribute to our sample choice. Since our introduction already summarizes the reasons for our sample selection, we provide the full details for our sample justification in Appendix A in order to maintain brevity in our main text.

Another potential advantage of our modest, recent sample is that financial market structure and the menu of financial instruments and hedging strategies has changed dramatically since the

[5] In a similar vein, Underwood (2008) examines order flow in a high frequency analysis of the stock and bond spot market. He finds evidence that cross-market hedging is an important source of linkages across the two markets during periods of elevated equity volatility.

1960's and 70's. As compared to a study that evaluates a sample period over many decades, our work can better be considered to hold market structure constant, in terms of the availability of implied volatility and futures contracts.

3.2. Data and Variable Construction

Our work uses the following times series over the 1997 - 2007 sample period: (1) daily yields of the Treasury Constant Maturity series from the 6-month through the 10-year debt maturity; (2) daily futures returns on the S&P 500 futures contracts and 10-year T-Note futures contracts; and (3) equity-index implied volatility from option contracts, specifically the CBOE's Volatility Index or VIX; and (4) 10-year Treasury implied volatility from options on 10-year T-Note futures contracts. For brevity in the main text, we report additional data details in Appendix A.

In parts of our work, we use the daily returns of futures contracts to measure the realized stock and T-Note returns, rather than spot returns. Futures contracts on the S&P 500 and Treasury notes are very widely traded and the corresponding returns are derived from prices on a single contract, rather than an aggregation of different price quotes as for spot portfolio returns. Thus, the futures returns avoid potential microstructure-related measurement concerns. Ahn, Boudoukh, Richardson, and Whitelaw (2002) elaborate on this point and find that daily stock futures returns do not display the positive autocorrelation that is evident in daily spot portfolio returns. Further, the realized return on futures contracts are naturally interpreted as excess returns. Appendix A.2 provides details on the futures return data.

We use the CBOE's VIX as our primary measure of equity risk. Within the Black-Scholes framework, VIX is a direct forecast of the future level of stock volatility. Further, given the well-known bias in the Black-Scholes-type implied volatility of equity index options, VIX may also be related to stochastic volatility (the volatility-of-volatility) or even, perhaps, time-variation in risk aversion.[6] Our empirical work reports on the original CBOE's VIX, now known as VXO,

[6] It is well known that the Black-Scholes implied volatility is biased high as a measure of expected future volatility for stock indices. Papers such as Coval and Shumway (2001) and Bakshi and Kapadia (2003) suggest that this bias may be because index options include a stochastic volatility premium. Bollerslev, Tauchen, and Zhou (2009) suggests the bias between implied volatility and realized volatility may be related to the degree of risk aversion. Also, recall that time-varying risk aversion is important in the framework of Campbell, Sunderam,

due to its familiarity and well-known theoretical basis. However, we have repeated our empirical work with the current VIX in place of the original VXO and find essentially the same results. Henceforth, our exposition uses the term 'VIX' to refer to the VXO.

For the risk or expected volatility of the 10-year Treasury notes, we use the implied volatility from options on the 10-year T-Note futures contracts. We use the implied volatility series from Bloomberg, which is constructed from the two near-term options contracts. In our empirical work, we refer to this series as the 10-year Treasury Implied Volatility or TIV. Details on the TIV constructions are in Appendix A.3.

In Table 1, we present the means, standard deviations, and pairwise correlations for the key data series featured in this paper. We report separately for the full 1997 - 2007 sample, and for one-half subperiods over 1997 - 2002.06 and 2002.07 - 2007.

Next, to examine whether shocks in inflation announcements are important in our setting, we also collect Consumer Price Index (CPI) and Producer Price Index (PPI) data. We collect both the actual monthly announcement value and the consensus monthly estimate from Bloomberg. We then calculate an inflation news shock, defined as the difference between the actual news release and the consensus estimate.

From the Federal Reserve, we obtain the time-series of the FOMC targeted Federal Funds rate over our sample period. We later use the change in the Fed Funds target rate as an additional explanatory term towards understanding changes in the term-structure's slope. See Piazzesi (2005) for recent evidence that the Fed Funds target rate influences Treasury yields, especially at the shorter horizons.

Finally, one complication for a study about the partial relation between equity implied-volatility changes and T-bond pricing is the strong negative contemporaneous relation between stock returns and the implied volatility from equity-index options.[7] Over our primary 1997 to 2007 period, the simple correlation between the 22-trading-day change in VIX and the corresponding 22-trading-day stock futures return is sizable at -0.76, with one-half subperiod correlations

and Viceira (2009), with risk aversion being modeling as a linear transformation of the aggregate dividend yield.

[7]See, for example, Pan (2002) and Dennis, Mayhew, and Stivers (2006).

of -0.71 and -0.82 for the 1997 to 2002.06 and 2002.07 to 2007 subperiods, respectively. Our subsequent empirical takes this correlation into consideration.

3.3. The Second Principal Component Derived from the Term Structure

When modeling the cross-section of Treasury yields, the term structure can be nearly fully described by two or three orthogonal principal components. The first three principal components typically are closely related to empirical proxies for the level, slope, and curvature of the term structure, respectively; see Diebold, Piazzesi, and Rudebusch (2005) (DBR hereafter) and Andersen and Benzoni (2009). DBR note that the first two principal components account for almost all (99 percent) of the variation in yields. This '99 percent explanatory' result for the first two principal components is also evident over our sample period, when we estimate the first three principal components from 6-month, 1-year, 2-year, 3-year, 5-year, 7-year, and 10-year Treasury zero-coupon yields. See Appendix B for details on the principal components evaluation in our data.

In our primary empirical investigation, we use the change in the 'second principal component' value as a measure of the change in the term-structure's shape that is closely related to the change in the term-structure's slope. As compared to a direct measure of the slope that uses just the yield difference between one long-term and one short-term Treasury, the second principal component is derived from information in the entire term structure and it is constructed to be orthogonal to the first principal component. Thus, we feel an evaluation of the second principal component is interesting as an alternate measure that is closely tied to the term-structure's slope (as compared to the our primary 'term yield spread' measure that is equal to the difference in yields between the 10-year and 6-month Treasury).

To provide intuition and a check on the tie between the second principal component and the slope of the term structure, we investigate the relation between the estimated 'second principal component' value and a 'term yield spread' variable (defined as the difference between the 10-year and 6-month Treasury zero-coupon yield). For our 1997-2007 sample, the 'second principal component' value is highly correlated with this 'term yield spread' variable with a +0.72 correlation coefficient. Further, and more directly related to our investigation, the monthly changes in the 'second principal component' value and the monthly changes in this 'term yield spread' variable are even more highly correlated with a +0.86 correlation coefficient. Thus, as expected, the second principal component is closely tied to the term yield spread in our sample.

3.4. Implied Volatility and Subsequent Realized Volatility

Our main empirical work in Section 4 relies upon the implied-volatility series being good proxies for the forward-looking risk, or expected volatility, of the respective underlying return series. Accordingly, we investigate: (1) whether each implied-volatility series contains substantial and reliable information about the subsequent realized volatility for the respective daily future returns; and (2) whether each implied-volatility series captures essentially all of the predictability for the subsequent realized volatility of the respective underlying return series, when adding in other likely explanatory terms. For brevity in our main text, we report details in Appendix C.

We find that: (1) the TIV does contain substantial and reliable information about the subsequent month's volatility of daily 10-year T-Note futures returns (the R-squared value is 45.5%, for a regression where the dependent variables is the realized sample standard deviation of daily 10-year T-note futures returns over trading days t to $t+21$ and the sole explanatory term is TIV_{t-1}); (2) when including other likely explanatory terms, the TIV captures most of the volatility predictability; and (3) the VIX contains substantial and reliable information about the subsequent month's volatility of daily 10-year T-Note futures returns, both by itself and when controlling for the lagged forward rates. These findings both support our use of TIV as a forward-looking measure of the T-Note risk and support the premise of a common comovement in the volatility of stocks and longer-term Treasuries.

As expected, we also find that: (1) the VIX contains substantial and reliable information about the subsequent month's volatility of daily S&P 500 futures returns (the R-squared value is 52.1%, for a regression where the dependent variables is the realized sample standard deviation of daily S&P 500 futures returns over trading days t to $t + 21$ and the sole explanatory term is VIX_{t-1}); (2) when including other likely explanatory terms, the VIX captures most of the volatility predictability; and (3) the level of volatility predictability in Table C.1 by TIV for the T-Note futures returns and in Table C.2 by VIX for the S&P 500 futures returns are of comparable magnitude. Our findings support our joint use of VIX and TIV in our main empirical work, as comparable forward-looking measures of equity and 10-year T-Note risk.

3.5. Forward-looking Information in the Lagged Forward Rates

We also use the Treasury Constant Maturity (TCM) series at the 1-year, 2-year, 3-year, 5-year, 7-year, and 10-year horizon to calculate six forward interest rates. To control for the predictability documented in Cochrane and Piazzesi (2005), we use the forward rates at the beginning of the holding period as explanatory 'state variables' for the subsequent monthly changes in our term-structure slope variables. Appendix D provides details on our forward rate data. The predictability from the lagged forward rates allows us to interpret the partial relations among the contemporaneous variables as relations to the shock in the variables, where by 'shock' we refer to the deviation from a conditional expected value using lagged information.

Specifically, to obtain a conditional expected value for the change in the term-structure's second principal component, we estimate the following regression over our 1997 to 2007 sample period.

$$\Delta PC2_{t-1,t+21} = \lambda_0 + \sum_{j=1}^{6} \lambda_j FwdRt_{j,t-1} + \varepsilon_t \tag{1}$$

where $\Delta PC2_{t,t+21}$ is defined as the difference between the second principal component value from the day $t+21$ term structure and that from the day $t-1$ term structure; $FwdRt_{j,t-1}$ are the six forward rates at the end of day $t-1$ as explained in Appendix D; and the seven λs are coefficients to be estimated.

We then retain the fitted value from equation (1), denoted as $E(\Delta PC2_{t,t+21})$, as our measure of the conditional expected change in the second principal component. We do not re-estimate equation (1) for each one-half sample period because of concerns for over fitting the data with six highly correlated explanatory terms. Instead, we use the fitted value from the full-sample regression for use in each one-half subperiod analysis. We use the $E(\Delta PC2_{t,t+21})$ as an additional explanatory term in our subsequent regression models for the shock in $\Delta PC2_{t,t+21}$, to control for the conditional expect change.[8] Using the same approach, we also estimate the expected change in the term yield spread by estimating an alternate version of (1) with $\Delta(Yld10yr - Yld6m)_{t,t+21}$ as the dependent variable; where $\Delta(Yld10yr - Yld6m)_{t,t+21}$ is defined as the difference between the term yield spread on day $t + 21$ and day $t - 1$, with the term yield spread equal to the difference between the 10-year and 6-month Treasury yield.

Over our sample period, the lagged forward rates contain substantial and reliable information for these two term-structure variables. Specifically, we find that: (1) for the case with the subsequent monthly change in the second principal component as the dependent variable, the R-squared is 13.1% and the p-value is less than 0.1% for a joint-significance test of the six lagged forward rates; and (2) for the case with the subsequent monthly change in the term yield spread as the dependent variable, the R-squared is 21.7% and the p-value is less than 0.1% for a joint-significance test of the six lagged forward rates.

4. Main Results: The Term-Structure's Slope and IV Changes

In this section, we provide our primary analysis of the relation between monthly risk changes and: (1) the monthly change in the term-structure's second principal component, and (2) the monthly change in the '10-year minus 6-month' term yield spread.[9] Supported by the evidence in Appendix C, we use the VIX and TIV as observable measures of expected, forward-looking

[8]We acknowledge there are alternate empirical approaches. For example, we could have simply added the six lagged forward rates as additional explanatory terms in our subsequent models. However, this would add five more explanatory terms in each model, which complicates the interpretation and potentially allows for over fitting the data. With a maximum likelihood estimation for our models that allow for time-varying volatility, we prefer the parsimony of fewer estimated coefficients. As another alternative, instead of adding the expected component as an explanatory term, we could have used the residual from equation (1) as the dependent variable. In practice, we have estimated our models with these alternate approaches and find essentially the same results for our coefficients of interest on the IV-change terms. Additionally, we acknowledge that we could have used other lagged variables as additional state variables, such as the expected T-Note return volatility or expected stock volatility. However, in our sample, the expected volatilities add little to no incremental forward-looking information beyond the information contained in the lagged forward interest rates. For parsimony, we maintain a consistent approach and use the lagged forward rates as state variables to capture the state of the Treasury debt market, prior to the realization of the dependent variables.

[9]We use the 6-month Treasury Constant Maturity (TCM) yield as a proxy for the risk-free rate, because shorter-term TCM debt is subject to greater distortions presumably due to the institutional features of the market. Common term structure models have a difficult time pricing the 3-month maturity T-bill, which either implies segmentation/noise at the very short horizon or inadequate term structure models.

risk; and the monthly change-in-VIX and change-in-TIV as observable risk changes.

We are particularly interested in the partial risk relations. So, where appropriate, our primary specifications also control for: (1) the lagged forward interest rates at the beginning of the holding period, as state variables to capture the Treasury-market's state prior to the subsequent risk change (Cochrane and Piazzesi (2005)), (2) the concurrent change in short-term Treasury yields, given the prominence of movements in the short-rate in understanding movements in term structure and bond returns; and (3) the concurrent stock return, to better capture the partial relation between equity risk and our Treasury pricing terms. We also later consider the influence of inflationary news shocks and the influence of changes in the FOMC's targeted Fed Funds rate.

For our empirical investigation, we focus on changes at the monthly horizon, using rolling 22-trading-day periods. This approach is a compromise between reducing noise from high-frequency changes while still providing a sizable number of observations. Using rolling 22-trading-day observations should also better measure the dynamics, rather than relying only on calendar-month observations. Additionally, a 22-trading-day horizon is roughly one calendar month, which matches the horizon of the CBOE's VIX and follows from the numerous finance studies that focus on the one-month horizon. During later robustness checks, we consider other horizons.

For all of our empirical work in this section, we report on three estimation periods in our tables: (1) the full 1997 - 2007 sample period; (2) the first-half of our sample period over January 1997 through June 2002; and (3) the second-half of our sample period over July 2002 through December 2007.

4.1. Main Results for the Term Structure's Second Principal Component

For the monthly changes in the term-structure's second principal component, we estimate and report on the following two-equation system:

$$\Delta PC2_{t-1,t+21} = \alpha_0 + \alpha_1 \, \Delta VIX_{t-1,t+21} + \alpha_2 \, \Delta TIV_{t-1,t+21} +$$

$$\alpha_3 \, r^S_{t,t+21} + \alpha_4 \, \Delta Yld6m_{t-1,t+21} + \alpha_5 E(\Delta PC2_{t,t+21}) + \varepsilon_t \quad (2)$$

$$v_t = \lambda_0 + \lambda_1 TIV_{t-1} + \lambda_2 VIX_{t-1} \quad (3)$$

where, for equation (2), $\Delta PC2_{t-1,t+21}$ is the difference between the second principal component value from the Treasury term structure on day $t+21$ and day $t-1$; $\Delta VIX_{t-1,t+21}$ ($\Delta TIV_{t-1,t+21}$) is the concurrent VIX change (TIV change), defined as the closing VIX (TIV) on day $t+21$ minus the closing VIX (TIV) on day $t-1$; $r^S_{t,t+21}$ is the monthly return for the S&P 500 futures contract overs trading-days t to $t+21$; $\Delta Yld6m_{t-1,t+21}$ is the change in the 6-month T-bill yield over days $t+21$ and $t-1$; $E(\Delta PC2_{t,t+21})$ is the expected, or fitted, change in the second principal component based on the information in the six lagged forward rates at $t-1$ per Section 3.5; ε_t is the residual; and the αs are coefficients to be estimated. For equation (3), v_t is the conditional variance of the residual ε_t in equation (2), which may vary with the lagged TIV and lagged VIX; TIV_{t-1} is the closing Treasury implied volatility from day $t-1$ and VIX_{t-1} is the closing VIX on day t-1; and the λs are coefficients to be estimated.

For the estimations that allow for time-varying volatility in this section and Section 4.2, we estimate the conditional mean and variance equation simultaneously, using maximum likelihood assuming a conditional normal density. We report t-statistics for each estimated coefficient, using standard errors that are robust to departures from conditional normality and autocorrelation in the residuals. The number of lags for the autocorrelation structure is set to 22 since we use 22-trading-day overlapping variables.

For comparison and to enable us to report a conventional R-squared value, we also report separate results when estimating variations of equation (2) by standard Ordinary Least Squares (OLS) with autocorrelation and heteroskedastic consistent standard errors. In later robustness checks, we evaluate comparable models using non-overlapping variables.

Given our interest in movements in risk, we feel it is important and logically consistent to allow for time-varying volatility in our main estimation results. We allow the conditional variance of the residual from equation (2) to vary with both the lagged TIV and lagged VIX. Neither of these implied volatilities is directly an expected volatility of the residual for the dependent variable. Rather, for the TIV, it seems plausible that the volatility of the change in the term-structure's slope (as measured by the second principal component) would be related to the volatility of the T-note futures return. For the stock implied volatility, we know the VIX contains substantial information for the subsequent volatility of both the stock returns (see Appendix C) and the subsequent variability of VIX.[10] Thus, if the VIX-change or the stock return is important for understanding the change in the term-structure's slope, then it seems plausible that the lagged VIX might contain information about the volatility of the residual in equation (2).

Table 2 reports the estimation results. Models 1 through 3 in the table report on the simple relation of $\Delta PC2$ to ΔVIX, ΔTIV, and the stock-futures return, respectively. For model-1, we find a reliable and sizable negative simple relation between the ΔVIX term and the $\Delta PC2$ term for all three estimation periods. For model-2, we find a positive simple relation to ΔTIV, but the coefficient is only statistically significant for the full sample. Finally, for the stock-futures return in model-3, the simple relation is marginally positive.

Next, model-4 jointly includes both IV changes and the stock-futures return as explanatory terms. For model-4, we find the following: (1) the relation to the ΔVIX term remain reliably negative, with the coefficient's value increasing appreciably in magnitude for the partial relation, as compared to the simple relation reported in the model-1; (2) the relation to the ΔTIV term remains positive, with the coefficient's value increasing and becoming more statistically reliable for the partial relation, as compared to the simple relation reported in model-2; and (3) the relation to the stock-futures return is now statistically insignificant, with the estimated coefficient actually changing signs for the partial relation as compared to the simple relation reported in row three. Thus, jointly controlling for both ΔVIX and ΔTIV serves to: (1) sharpen the risk relations (compare the α_1 and α_2 coefficients for model-4 to the simple α_1 and α_2 coefficients for model-1 and model-2) and (2) change the apparent relation to the stock-futures returns (compare the insignificant negative α_3 estimate in model-4 to the marginally positive α_3 estimate in model-3).

Next, we discuss models-5 and -6 which include the full set of explanatory terms. For all three estimation periods and for both estimation methods, we find that the estimated α_1 coefficients on

[10]In our sample for a regression with the absolute monthly change in VIX as the dependent variable and the lagged VIX level as the explanatory variable, we find that the lagged VIX is positively and reliably related to the subsequent absolute VIX-change with a 0.01% p-value and an R-squared of 21%. We have also added the lagged squared residual as an additional explanatory variable for the conditional variance equation, but it turns out not to be an important explanatory term.

the ΔVIX term is always reliably negative. This indicates that the second principal component tends to decrease as the VIX increases, while controlling for the other variables. Further, we find that the estimated α_2 on the ΔTIV term is reliably positive, again for all three estimation periods and both estimation methods. Also, note that the OLS and TVV model yield very similar results for the estimated coefficients from equation (2).

For the other explanatory terms, neither the change in the 6-month yield (the α_4 term) nor the concurrent stock-futures return (the α_3 term) are reliably related to the $\Delta PC2$ term. The expected value of $\Delta PC2$ from the lagged forward rates (the α_5 term) is reliably positively related.

For the conditional variance equation, the estimated λ_2 on the lagged VIX is positive and statistically significant for all three periods, which indicates there is volatility information in the lagged VIX. However, the estimated λ_1 on the lagged TIV is not statistically significant. In alternate model variations (that are not in the table), we have omitted the lagged VIX term and then we find that the lagged TIV term becomes reliably and positively related to the subsequent volatility. Thus, our results indicate that the volatility information in VIX dominates the volatility information in TIV for the $\Delta PC2$ residual. In our view, this seems intriguing and supports the importance of equity risk in understanding changes in the slope of the term structure; why else would a stock-market risk measure dominate a T-note risk measure in terms of the $\Delta PC2$ volatility?

To conclude, our results here indicate that equity risk is important for understanding both the realized shock for the change in the term-structure's second principal component (the α_1 term) and the volatility of the unexplained change in the second principal component (the λ_2 term). We stress that these are partial relations, after controlling for both lagged state variables (through the α_5 term) and other likely concurrent terms. Under the interpretation that the second principal component represents the slope in the term structure and that the slope is a measure of the longer-term Treasury risk premia, our results suggest a tie between Treasury term risk premia and equity risk. Jointly controlling for both the VIX-change and TIV-change serves to sharpen the risk relations to $\Delta PC2$ and reverse the apparent relation of the stock-futures return to $\Delta PC2$.

4.2. Main Results for Changes in the Term-Yield Spread

We next present our main results for the partial relation between the monthly changes in risk and the monthly change in the '10-year minus 6-month' term yield spread. We estimate and report on the following two-equation system:

$$\Delta(Yld10yr - Yld6m)_{t-1,t+21} = \alpha_0 + \alpha_1\,\Delta VIX_{t-1,t+21} + \alpha_2\,\Delta TIV_{t-1,t+21} +$$

$$\alpha_3\, r^S_{t,t+21} + \alpha_5 E(\Delta(Yld10yr - Yld6m)_{t,t+21}) + \varepsilon_t \tag{4}$$

$$v_t = \lambda_0 + \lambda_1 TIV_{t-1} + \lambda_2 VIX_{t-1} \tag{5}$$

where, for equation (4), $\Delta(Yld10yr - Yld6m)_{t-1,t+21}$ is the difference between the term yield spread on day $t+21$ and day $t-1$, where the term yield spread is the difference in the Treasury 10-year and 6-month yield; $E(\Delta(Yld10yr - Yld6m)_{t,t+21})$ is the expected, or fitted, change in the term yield spread based on the information in the six lagged forward rates at $t-1$ per Section 3.5; and the other terms are as defined for equations (2). For equation (5), v_t is the conditional variance of ε_t in equation (4), and the other terms are as defined for equation (3). For equation (4), we does not include the α_3 term on the change in 6-month yield, since this yield difference is used when calculating the dependent variable. Estimation details are the same as explained for equations (2) and (3).

Table 3 reports on the estimation results. We again begin by considered the simple relation between $\Delta(Yld10yr - Yld6m)$ and each IV change and the stock-futures return. For model-1 with ΔVIX as the sole explanatory term, we find that the estimated α_1 coefficients on the ΔVIX term are negative for all three sample periods, but the point estimates are only statistically significant for the second-half subperiod and only at the 10% level. Next, model-2 reports on the simple relation between the term yield spread and the concurrent TIV change. We find that the estimated α_2 coefficients on $\Delta TIV_{t-1,t+21}$ are positive and statistically significant for all three sample periods. Model-3 indicates there is no simple relation between the term yield spread and the concurrent stock futures return.

Next, model-4 includes both IV changes and the stock-futures returns as joint explanatory terms. When comparing the model-4 results to the simple relations in the model-1 through model-3, we find several interesting results. First, the magnitude of the estimated α_1 coefficients on the ΔVIX term increase appreciably for the model-4 case aas compared to the simple relation in model-1, and the α_1s are now negative and statistically significant for all three sample periods. Thus, in contrast to the simple relation, the partial relation indicates that the change in equity risk is negatively and reliably related to the change in the term yield spread. Second, the estimated α_2 coefficients on the $\Delta TIV_{t-1,t+21}$ all increase marginally in magnitude (become more positive) as compared to the simple relation. Jointly controlling for both ΔVIX and ΔTIV again serve to sharpen the risk relations (the α_1 and α_2 coefficients).

We next discuss models-5 and 6, with the full set of explanatory terms. First, note that the OLS estimations have sizable R-squared values in the 28% to 30% range. For the full sample and both one-half subperiods, we find that the estimated α_1 coefficients on the ΔVIX are negative and statistically significant. The estimated α_2 coefficients on the ΔTIV term are positive and statistically significant for all three periods with a 1% p-value or better. When comparing the partial α_1 relation in model-5 to the simple single-variable relation in model-1, note that the partial-relation α_1 coefficients on the VIX-change term are more than twice as large (in magnitude) than the simple-relation α_1 coefficients.

For model-6 that allows from time-varying volatility (TVV), note that the OLS and TVV model yield very similar results for the estimated coefficients from equation (4). Further, we find that the estimated λ_2 on the lagged VIX is positive and statistically significant for all three periods, which indicates the lagged VIX contains useful information about the volatility of the residual from equation (4). The estimated λ_1 coefficients on the lagged TIV are not statistically significant for any of the estimation periods. This VIX volatility results supports the importance of the equity risk.

To conclude, our results indicate that the monthly changes in the term yield spread have: (1) a negative partial relation with changes in equity risk, and (2) a positive partial relation with changes in T-Note risk. Since the term yield spread has a natural interpretation as the expected risk premium in the 10-year T-Note, these finding suggest that the expected risk premium: (1) intuitively increases with T-Note risk; and (2) decreases with equity risk, which suggests a notable cross-asset pricing influence. The Table 3 results reinforce our earlier findings in Table 2. Again, jointly controlling for the VIX and TIV changes serves to sharpen the risk relations.

4.3. Robustness Checks and Additional Investigation

4.3.1. Inflation News Shocks

Inflation news shocks should directly impact the value of fixed income investments, and as such might be important in understanding the Treasury pricing terms that we evaluate in Tables 2 and 3. However, we have argued that inflation is relatively modest and stable over our sample period, so inflation seems unlikely to have an important influence on our primary results. We directly examine this issue by adding the news shocks from the monthly CPI and PPI announcements as additional explanatory variables in our primary models.

Specifically, over each rolling 22-trading-day period, we calculate the sum of the news shocks for the CPI and PPI announcements that occur over the 22-trading-day period. We then take the resulting inflation news shock and add it as an additional explanatory variable in equations (2) and (4). For a given CPI or PPI announcement, the news shock is defined as the difference between the actual announcement and the median expectation obtained from Bloomberg.

To summarize the results over our 1997 to 2007 period, we find that the estimated coefficient on the additional inflation news-shock term is positive for both the change in the term-structure's second principal component and the change in the term yield spread. A positive coefficient on the inflation shock seem plausible, which suggest an increasing term-structure slope with positive inflation shocks. However, none of the estimated coefficients on the inflation news-shock term are statistically significant (t-statistic values are 0.64 for the change in the second principal component and 0.19 for the change in the term yield spread, using autocorrelation and heteroskedastic standard errors).

More importantly for our purposes, for our models in Tables 2 and 3, the addition of the inflation news-shock term has essentially no impact on the value or the statistical reliability of the estimated coefficients on the IV-change terms (the α_1 and α_2 coefficients). Thus, for parsimony, we do not include the inflation news-shock term in our primary tabular results.

4.3.2. Changes in the FOMC's Targeted Fed Funds Rate

As discussed in Piazzesi (2005), actions of the Federal Open Market Committee (FOMC) can be considered as a two-way avenue in that their actions are both: (1) influenced by existing financial market conditions, and (2) influential in the subsequent behavior of financial markets. When modeling the influence of FOMC actions, specifically the targeted Fed Funds rate; Piazzesi is able to improve beyond existing term-structure models, especially at the short end of the yield curve.

In terms of our empirical investigation, FOMC actions might be responsive to some of the factors that drive changes in the term-structure's slope and the changes in VIX and TIV. Conversely, FOMC actions might directly influence further changes in these variables. Accordingly, we next extend our investigation to evaluate whether 'changes in the FOMC targeted Fed Funds rate' are important in our setting, especially regarding the apparent partial relation of the ΔVIX term.

From the Federal Reserve, we obtain the history of changes in the FOMC targeted Fed Funds rate. We then add the 'change in the Fed Funds rate' variable as an additional explanatory variable to our main models, as given by equations (2) and (4). Table 4 provides the detailed specification and estimation results.

To summarize the results in Table 4, we find that the estimated α_6 coefficient on the additional 'change in the Fed Funds rate' variable is sizably negative. This result is reliably evident when either considering the Fed Fund variable by itself (model-1 in the table) or when including the full complement of other explanatory terms (model-2 and model-3 in the table). Since the 'change in Fed Funds' would be expected to influence the short-rate more substantially than the long-rate, the negative estimate for the coefficient is intuitive (for example, if the Fed Funds rate increases and the shorter-rate Treasury yields tend to increase more than the longer-term Treasury yields, then this would translates to a decrease in the term-structure's slope).

While the 'change in Fed Funds' variable is reliably negatively related to changes in the term-structure's slope, the inclusion of the Fed Funds term has only a marginal influence on the estimated α_1 coefficients on the ΔVIX term. In all cases, the estimated α_1 coefficients remain reliably negative with p-values of less than 1% (model-2 and model-3 in Table 4). The magnitude of the α_1 coefficients in Table 4 are about 16 to 28% smaller than comparable α_1 coefficients in Tables 2 and 3. This suggests that the Fed Funds changes and the ΔVIX term capture some of the same information. We conclude that the importance of the ΔVIX term survives the inclusion of the 'changes in Fed Funds' term.

4.3.3. Comparable Results Using Non-overlapping Observations

Recall that our primary results feature overlapping observations by calculating rolling 22-trading-day observations from single trading-day observations. The standard errors are adjusted to reflect the resulting serial correlation in the residuals.

We also perform comparable estimations to those in Tables 2 and 3, but with non-overlapping variables. With a 22-trading-day horizon for our key variables of interest, one can construct 22 different non-overlapping data sets since one can select 22 different starting days for the first day of the 22-trading-day periods. We estimate our models for each of the 22 different possibilities for non-overlapping data so we end up with 22 different point estimates for each coefficient. To summarize, our principal findings are also reliably evident for our analysis using non-overlapping data. Details are in Appendix E.

4.3.4. Results from Sorting on the VIX Change

Our primary regressions in Tables 2 and 3 test for a linear relation between the IV changes and the 'change in the term-structure slope' variables. Another approach is to perform sorts on the monthly change in VIX and then evaluate the subset characteristics of VIX-change percentile groupings of the observations. Such an investigation will serve as a robustness check and should help evaluate whether the relations are asymmetric (for example, the change terms might respond much stronger to VIX increases than to VIX decreases).

We perform such an exercise as follows. First, using a linear regression, we obtain a fitted value for the 'change in the second principal component' term and the 'change in the '10-year mins 6-month' term yield spread' term, given the lagged forward rates and the concurrent ΔTIV term. We then retain the residuals from each regression and sort the residuals into VIX-change quintile groupings.

Figure 2, Panels A and B, reports the results. For both Treasury pricing terms, the figure indicates that the observations that correspond to the high VIX-change quintiles are appreciably different than those that correspond to the low VIX-change quintile. Using a dummy variable method to evaluate the low and high VIX-change quintiles, we find the following: (1) for the shock in the change in the second principal component (Panel A), the mean shock for both the high VIX-change quintile and low VIX-change quintile are reliably different than the mid VIX-change quintiles with 1% and 5% p-values respectively, and (2) for the shock in the change in the term yield spread (Panel B), the mean shock for the high VIX-change quintile is reliably lower than the mean shock for the low VIX-change quintile with a 1% p-value.

We conclude that our primary results are also reliably evident when evaluating VIX-change quintile groupings. Further, the VIX-change relations are largely symmetric in the sense that: (1) the mean shocks for the highest VIX-change quintiles are appreciably different than those for the lowest VIX-change quintile and with opposite signs, and (2) the three mid-range VIX-change quintiles all have mean shocks near zero.

4.3.5. 10-Trading-Day Horizons Results

Our primary results examine a 22-trading-day horizon, or roughly one month. While we argue that there are good reasons for this choice, readers might naturally wonder whether the key results in Tables 2 and 3 are also evident over shorter horizons. In addition to exploring the pervasiveness of our key results, such an investigation is also attractive because a shorter horizon provides more observations that do not share overlapping trading days.

Table 5 reports results from analyzing a 10-trading-day horizon, in place of the 22-trading-day horizon. We estimate identical models to those detailed in Tables 2 and 3, except that we replace all the variables that are calculated over a 22-trading-day period with comparable variables that are calculated over a 10-trading-day period.

We find that our primary findings are also evident at the 10-trading-day horizon. The estimated α_1 coefficients on the ΔVIX term are reliably negative for both the changes in the term-structure's second principal component and the changes in the term yield spread. The estimated α_2 coefficients on the ΔTIV term are reliably positive for both the changes in the term-structure's second principal component and the changes in the term yield spread. Thus, the Table 5 results reinforce our primary findings in Tables 2 and 3.

4.4. Discussion of Results

Our primary results over 1997 to 2007 indicate a negative, reliable, and substantial relation between changes in equity risk and changes in both: (1) the second principal component derived from the term structure, and (2) the '10-year minus 6-month' term yield spread. Further, we note that the lagged VIX contains reliable volatility information for the residuals for both the 'change in the second principal component' and the 'change in the term yield spread'. Under the interpretation that our two measures of the term-structures slope are forward-looking measures of the Treasury term risk premia, then our results suggest a tie between changes in equity risk and changes in the risk premia of longer term Treasuries.

Our empirical investigation also indicates a positive partial relation between change in T-Note implied volatility and the changes in the second principal component and term yield spread. The relations between the risk-changes terms and the slope terms becomes sharper when jointly controlling for both the VIX-change and TIV-change terms.

The interpretation of our primary results in Tables 2 through 3 remains an open question. One possibility is that increases in equity risk can influence investors to bid up the prices of longer-term Treasuries, both because T-Notes are safer and because T-Notes may serve as a hedge against equity risk, with the result that the forward-looking T-Note risk-premium decreases. A second possibility is that the equity risk is serving as a proxy for some other economic condition or economic variable; and, if we could better identify and control for this unidentified economic variable, then the partial relation between the change in the equity risk and the change in the term-structure slope variables would diminish or disappear.

We acknowledge that our study cannot definitively distinguish between these two possibilities. Rather, our approach is to control for the key bond-pricing factors suggested by Cochrane and Piazzesi (2005) and the term structure literature, and then examine the partial relation of equity-risk changes with changes in the term-structure's slope. Next, we perform additional empirical work that may assist on the interpretation of our main results.

5. T-Note and Stock Futures Returns and IV Changes

Our primary results in Tables 2 through 5 indicates that changes in equity risk have a negative partial relation to the change in the term-structure's second principal component and the change in the term yield spread. Under a risk-premium interpretation for our main findings, the negative partial relation to the VIX change implies that investors are willing to hold T-Notes with a lower forward-looking risk premium as equity risk increases (while controlling for the market-state and other Treasury-related variables). In this section, we provide supplementary empirical evidence to assist in the interpretation of our main results in Section 4.

Why might T-Note values be revised upward with increasing equity risk? Possibilities include: (1) because T-bonds are relatively safer, (2) because T-bonds may provide a hedge against increasing equity risk, and/or (3) because subsequent stock-bond return correlations might be lower when equity risk is high and increasing. Under this third possibility, a decreasing and negative stock-bond correlation during times of increasing and high equity risk implies that T-Notes could provide increased diversification benefits in times of increasing equity risk; which could translate to a decrease in the required risk premium. We investigate the second and third possibility above in Sections 5.1 and 5.2, respectively, using futures returns for 10-year T-notes and the S&P 500.

Finally, in Section 5.3, we investigate the relation between stock-futures returns and the IV changes. Then, we consider the implications of the results for our study.

5.1. The Concurrent Relation between T-Note Futures Returns and IV Changes

Here, we examine the T-Note futures return as a tradeable financial security whose return can be interpreted as an excess return. The results should bear on the question of whether T-bonds can serve as a hedge against changes in equity risk.

We report on the following two-equation system:

$$r^{TN}_{t,t+21} = \alpha_0 + \alpha_1 \, \Delta VIX_{t-1,t+21} + \alpha_2 \, \Delta TIV_{t-1,t+21} +$$

$$\alpha_3 \, r^{S}_{t,t+21} + \alpha_4 \, \Delta Yld6m_{t-1,t+21} + \alpha_5 E(r^{TN}_{t,t+21}) + \varepsilon_t \tag{6}$$

$$v_t = \lambda_0 + \lambda_1 TIV_{t-1} + \lambda_2 VIX_{t-1} \tag{7}$$

where, for equation (6), $r^{TN}_{t,t+21}$ is the return for the 10-year T-note futures over trading days t to $t+21$; $E(r^{TN}_{t,t+21})$ is the expected, or fitted, T-note futures return based on the information in the six lagged forward rates at $t-1$; and the other terms are as defined for equation (2).[11] For equation (7), v_t is the conditional variance of ε_t in equation (6), and the other terms are as defined for equation (3). Estimation details are the same as explained for equations (2) and (3).

Table 6 reports the results. We begin by discussing the results for the simple relations, as depicted in model-1 through -3 in the table. Model-1 reports on the case with ΔVIX as the sole explanatory term. We find that the ΔVIX term is positively and highly reliably related to the concurrent T-Note future return, with estimated α_1 coefficients that have p-values of better than 0.1% for the full period and both one-half subperiods.

Next, model-2 reports on the simple relation between the T-Note futures return and the concurrent TIV change. We find that the estimated α_2 coefficients on ΔTIV are negative, as one would anticipate if asset values decrease as their risk increases. However, for model-2, the estimated α_2 coefficients are not statistically significant for any of the three periods.

Model-3 reports on the simple relation between the T-Note futures return and the concurrent stock futures return. The estimated α_3 coefficients on the stock-futures return are negative and

[11] For the monthly futures return for the 10-year T-note, we use the lagged forward rates to form a conditional expected return in the same way as we do for the term-structure slope variables in Section 3.5. For the monthly future return, the lagged forward rates are again jointly statistically significant as explanatory variables with a 0.1% p-value and an R-squared value of 12.0% for the regression.

statistically significant for all three sample periods, as expected since the simple stock-bond correlation is sizably negative over our sample period.

Next, model-4 evaluates the case with both IV-changes and the stock-futures return as joint explanatory terms. When comparing the results for model-4 to the simple relations in model-1 through model-3, we note several interesting results. First, the estimated α_1 coefficients on the ΔVIX term remain sizable and highly reliably positive. In fact, for all three periods, the estimated α_1's actually increase modestly as compared to the simple relation in model-1. Second, for model-4, the partial relation with the stock-futures is insignificantly positive, as compared to the reliable and sizable negative relation for the simple case in model-3. Finally, the estimated α_2 coefficients on the ΔTIV term all increase appreciably in magnitude (become more negative) and are now statistically significant for the overall period and the second-half subperiod.

Next, we discuss the OLS model with the full set of explanatory terms (model-5). First, we note that the R-squared values are sizable in the 38% to 44% range. For the full sample and both one-half subperiods, we find that the estimated α_1 coefficients on the ΔVIX remain positive and statistically significant. The estimated α_2 coefficients on the ΔTIV term are negative and statistically significant for all three periods, and the α_2 estimates for the full model are appreciably larger in magnitude than for model-2 and model-4.

For the full sample estimation that allows for time-varying volatility (TVV), we find that both the estimated λ_1 and λ_2 are positive and marginally statistically significant. Jointly, the lagged TIV and lagged VIX contains reliable information about the volatility of the residual from equation (6). Again, the OLS and TVV model yield similar results for the estimated coefficients for equation (6).

Next note that the stock-futures return is not a reliable explanatory variable with the estimated α_3 being positive but statistically insignificant for all three estimation periods (in contrast to the strong simple negative relation depicted in model-3 of the table). Thus, the partial relation between ΔVIX and the T-Note futures return is more reliable and pervasive than the partial relation between the stock-futures return and the T-Note futures return.

The results for the other explanatory variables are also interesting. First, consistent with results in Cochrane and Piazzesi (2005), the lagged forward rates jointly provide reliable information, as indicated by the large t-statistics on the α_5 coefficient. Second, as one would expect, the contemporaneous change in the short-rate yield is very substantially negatively related to the T-Note futures return (see the estimated α_4 coefficients).

To conclude, our results here indicate that the 10-year T-Note futures returns have: (1) a positive partial relation with changes in equity risk, and (2) a negative partial relation with changes in T-Note risk, and (3) no reliable partial relation to the stock-futures returns (in contrast to the sizable negative simple stock-bond return relation). Thus, our results suggest that the dominant relation appears to be the movement between 10-year T-Note futures prices and equity implied volatility (rather than 10-year T-Note futures and stock prices). The partial positive relation with the change in equity risk suggests that T-bonds can serve as a hedge against increases in equity risk, which supports a risk premia interpretation for our main findings in Section 4. Finally, the partial negative relation with ΔTIV only becomes reliably evident when controlling for the change in equity risk and other variables.

5.2. The Stock-Bond Return Correlation and the Lagged IV Changes

If increases in Treasury-debt prices during periods of heightened equity risk was only because of the safety of government fixed income securities, then it would seem that investors would favor short-term debt, and one would not observe the second-principal-component results in Table 2 and the term-yield-spread results in Table 3. However, if longer-term Treasuries have enhance diversification benefits during times of high and increasing euqity risk, then investors might particularly value longer-term Treasuries during periods of heightened equity risk. Thus, an intertemporal empirical question is whether changes in VIX have a negative partial relation with the subsequent stock-bond return correlation.

We examine the relation between a month's VIX-change and the subsequent month's stock-bond return correlation by estimating the following model:

$$Corr(St, Bond)_{t+23,t+44} = \psi_0 + \psi_1 \Delta VIX_{t-1,t+21} + \psi_2 \Delta TIV_{t-1,t+21} +$$

$$+\psi_3 VIX_{t-1} + \psi_4 TIV_{t-1} + \varepsilon_t \tag{8}$$

where $Corr(St, Bond)_{t+23,t+44}$ is the Fisher transformation of the sample correlation of the daily stock and T-note futures returns over trading days $t+23$ to $t+44$; VIX_{t-1} (TIV_{t-1}) is the lagged VIX (TIV) at the close of trading day $t-1$; the other explanatory terms are as defined in Table 2; and the ψs are coefficients to be estimated. Note that, with this timing, one trading day is skipped between the dependent variable and the lagged explanatory implied-volatility variables. Following from results in Connolly, Stivers, and Sun (2005), (2007), and Baele, Bekaert, and Inghelbrecht (2009), here we also include the lagged VIX and TIV level (the IV level prior to the monthly IV changes) as state variables to capture the 'risk state' of the market prior to the IV changes.

Our primary interest is whether the VIX-change will be negatively related to the subsequent stock-bond return correlation. Consider that, in regard to the subsequent stock-bond correlation, it may be that the monthly VIX change is largely noise and that the lagged VIX level (the ψ_3 term) largely captures the explanatory relation between VIX and the subsequent stock-bond correlation.

Table 7 reports the estimation results. We find that the estimated ψ_1 coefficients on the ΔVIX term are negative and statistically significant for the overall 1997-2007 period and both one-half subperiods. The estimated ψ_3 coefficient on the earlier VIX level (the level before the VIX change) is also sizably and reliably negative, as expected from the literature. In contrast, the estimated coefficient on the ΔTIV term is not statistically significant for any of the periods. These results are consistent with the notion that T-Note values may be revised upward with increasing equity risk, both because T-bonds are safer and because stock-bond correlations decrease with increasing equity risk under certain market conditions. In our view, this evidence is consistent with a risk premia interpretation for our main results in Tables 2 through 5.

5.3. Stock-Futures Returns and IV Changes

Our results in Tables 2 through 6 document simple and partial contemporaneous relations to the IV changes. With contemporaneous relations, the estimated coefficients can only strictly be considered as documenting statistical comovement, with the economic causality remaining an open question. Accordingly, we are also interested in evaluating the partial relations between the stock futures return and the IV changes to see if the results may help interpret our results in Tables 2 through 6.

We estimate two variations of the following two-equation system:

$$r^{S}_{t,t+21} = \alpha_0 + \alpha_1\,\Delta VIX_{t-1,t+21} + \alpha_2\,\Delta TIV_{t-1,t+21} +$$

$$\alpha_3\,r^{TN}_{t,t+21} + \alpha_4\,\Delta Yld6m_{t-1,t+21} + \alpha_5 E(r^{S}_{t,t+21}) + \varepsilon_t \tag{9}$$

$$v_t = \lambda_0 + \lambda_1 VIX_{t-1} \tag{10}$$

where $r^{S}_{t,t+21}$ is the monthly return for the S&P 500 futures contracts overs trading days t to $t+21$; $E(r^{S}_{t,t+21})$ is the expected, or fitted, S&P 500 futures return based on the information in the six lagged forward rates at $t-1$; VIX_{t-1} is the closing VIX implied volatility from day $t-1$; and the other terms are as defined for equations (6) and (7). Estimation details are the same as explained for equations (2) and (3).

We first estimate a variation of the model that omits the ΔVIX explanatory term. When considering the ΔTIV relation for this restricted case, there would seem to be a couple of possibilities. First, we know that there is a positive correlation between ΔTIV and ΔVIX and that there is a strong negative relation between ΔVIX and the stock return. Thus, the ΔTIV might largely be serving as a proxy for the ΔVIX, which would suggest that the α_2 would be negative. Alternately, an increase in ΔTIV could reflect an increase in the T-Note risk relative to the stock market, and stocks could then become relatively more attractive with a possible price appreciation when T-Note risk increases. If so, this would suggest that the estimated α_2 would be positive.

Table 8, Panel A, reports the results for the restricted model without the ΔVIX term. We find that the estimated α_2 is reliably negative. Also, note that the estimated α_3 on the concurrent T-Note futures return is negative, which is suggested by the observed negative stock-bond correlation over our sample period.

Next, Table 8, Panel B, reports the results for the unrestricted model. With the inclusion of the ΔVIX term, we find that the estimated coefficients on the ΔTIV and T-Note futures returns are no longer statistically significant. For the α_3 coefficient on the T-Note future return, the point estimate even changes sign when comparing the Panel B results to the Panel A results. These results suggests that the reliability of the α_2 and α_3 coefficients in Panel A are driven by the relation of ΔVIX to the ΔTIV and the T-Note futures return.

To sum up, when jointly considering the results in Tables 2 through 6 for the T-Note variables and Table 8 for the stock-futures return, it would seem that the change in equity risk is important in understanding the T-Note market and the correlation between the stock and bond market. In contrast, the change in T-Note risk is not related to the stock-futures return, when also controlling for the change in equity risk. These observations seem to support the notion of changes in equity risk as a first-order effect, when considering cross-asset pricing influences.

6. Conclusions

We investigate whether changes in equity risk can be tied to changes in the slope of the Treasury term structure over the intriguing 1997 to 2007 period. In our view, this sample period is interesting because it experienced both a negative stock-bond return correlation and a modest and stable inflationary environment, along with both high levels and high variability in equity risk.

In our empirical work, we strive to evaluate the partial relation between equity risk and the term-structure variables, so we control for: (1) the lagged forward rates as state variables for the Treasury market; (2) the concurrent change in the short-rate yields, due to the importance of movements in the short rate in term structure modeling; (3) the concurrent shock in 10-year T-note risk, to better capture the partial relation to equity risk; (4) the concurrent stock return, because of the sizable negative relation between changes in equity risk and the concurrent stock return; (5) shocks in inflation announcements, due to the importance of inflationary shocks to fixed income values, and (6) changes in FOMC Fed Funds targets, due to their influence on Treasury yields.

Our findings include the following. First and foremost, we find that changes in equity risk (T-note risk) have a negative partial relation (positive partial relation) to changes in the term-structure's slope over our sample period. Our evidence clearly supports these conclusions for our overall period and both one-half subperiods separately, for our two different measures of the term structure's slope, and for a variety of modeling approaches. Thus, our findings suggest that changes in equity risk can have a role in understanding changes in the shape of the Treasury term structure. Further, under the interpretation that the slope of the term structure is a measure of the forward-looking risk premia of longer-term Treasuries, our findings suggest that changes in equity risk may have a role in understanding Treasury term risk premia.

Second, we find that the lagged VIX level is reliably informative about the subsequent volatility of the unexplained component of both our 'change in term-structure slope' variables. Further, the lagged VIX contains more reliable volatility information about these term-structure variables than the comparable T-note implied volatility. These volatility findings also supports the contention that equity risk can be important for understanding movements in the term structure.

Third, our results in Section 5 suggest that longer-term Treasuries can serve as a hedge against variations in equity risk under certain market conditions. These findings support a risk premia interpretation of our main results in Section 4; where the value of longer-term Treasuries may be revised upward with increasing equity risk because of this hedging/diversification attribute, with a resulting decline in the forward-looking risk premia in longer-term Treasuries.

Fourth, we find that the well-known negative relation between stock and T-note returns over 1997 to 2007 is not evident in a partial relation sense, when jointly controlling for the relation between Treasury pricing and changes in risk. In contrast, the positive relation between T-note futures return and changes in equity risk remains robust to our battery of other control variables. This finding suggests that the negative stock-bond return correlation over our sample period is a noisier representation of the positive relation between Treasury prices and equity-risk changes.

Fifth, jointly examining both changes in equity risk (the VIX) and changes in longer-term Treasury risk (the TIV) serve to better reveal the partial relations between the risk changes and our Treasury pricing terms. Jointly controlling for both risk changes is necessary to find a reliable partial relation between: (1) the VIX-change and the change in the '10-year minus 6-month' yield spread (Table 3 for our overall period and the first-half subperiod); the TIV-change and the change in the second principal component (Table 2, for both one-half subperiods); and (3) the TIV-change and the 10-year T-note futures return (Table 6, for our overall period and both one-half subperiods).

An open question is whether the change in the equity risk can be interpreted as driving the change in the term-structure's slope, or whether the link between these changes reflects a common movement to some omitted factor. In other words, do our findings indicate causality or just statistical association? Under the assumption that our empirical model adequately captures the other influences on T-bond pricing, our results suggest that equity risk may directly influence the term-structure's slope. Further, our collective findings indicates that changes in equity risk have important cross-market information for the Treasury market, but that changes in longer-term Treasury risk does not have partial information for stock returns (Table 8). This asymmetry is interesting and suggests an importance for equity risk.

However, we cannot rule out the possibility that changes in equity risk might not be important in a better specified empirical framework. Thus, at a minimum, our results document: (1) a reliable comovement between changes in equity risk and changes in the term-structure's slope, while controlling for other important bond-pricing factors, and (2) that longer-term Treasuries can serve as a hedge against changes in equity risk under certain market conditions.

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Table 1: Summary Data Statistics

This table reports summary statistics for the data. Panel A reports the means and standard deviations for the following variables: (1) the daily stock futures returns, (2) the daily 10-yr Treasury note futures returns, (3) the implied volatility of the S&P 100 from the CBOE, denoted as VIX, (4) the 22-trading-day change in VIX, (5) the implied volatility of 10-year T-note futures from Bloomberg, denoted as TIV, (6) the 22-trading-day change in TIV, (7) the 10-year Treasury note yield from the constant maturity series, (8) the 22-trading-day change in the 10-year Treasury note yield, (9) the 6-month Treasury Bill yield from the constant maturity series, (10) the 22-trading-day change in the 6-month T-bill yield, (11) the term-yield spread, defined as the difference between the 10-year and 6-month Treasury yield, (12) the 22-trading-day change in the term-yield spread, and (13) the monthly 12-month inflation rate, where a month's inflation is the percentage change in the CPI-U for that month as compared to the CPI-U one year earlier. The means and standard deviations are in percentage units. Panel B reports the correlation between 22-trading-day VIX changes and concurrent variables.

Panel A: Means and Standard Deviations

	1997-2007		1997-2002.06		2002.07-2007	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
1. Stock Futures Return	0.0068	1.167	-0.0058	1.322	0.019	0.986
2. T-Futures Returns	0.015	0.364	0.015	0.363	0.015	0.365
3. VIX Level	21.94	7.90	25.67	4.90	18.17	8.54
4. Monthly Δ VIX	0.02	4.92	0.11	5.47	-0.24	4.10
5. TIV Level	6.19	1.56	6.25	1.19	6.11	1.82
6. Monthly Δ TIV	0.01	1.05	0.01	1.07	-0.002	1.02
7. 10-yr T-Note Yield	5.00	0.80	5.61	0.62	4.38	0.39
8. Monthly Δ T-Note Yield	-0.02	0.27	-0.03	0.27	-0.010	0.27
9. 6-month T-bill Yield	3.87	1.72	4.72	1.33	3.00	1.64
10. Monthly Δ T-bill Yield	-0.02	0.24	-0.06	0.28	0.026	0.20
11. Term-yield Spread	1.13	1.25	0.89	1.04	1.37	1.38
12. Monthly Δ Yield Spread	-0.004	0.27	0.03	0.29	-0.036	0.25
13. Inflation Level	2.57	0.83	2.35	0.79	2.80	0.82

Table 1: (Continued)

Panel B reports on pairwise correlations for the following key variables featured in this study: (1) the change in VIX over a 22-trading-day period, $\Delta VIX_{t-1,t+21}$; (2) the change in the implied volatility from options on 10-year T-Notes, $\Delta TIV_{t-1,t+21}$; (3) the return on the 10-year T-Note futures contracts over a 22-trading-day period, $r^{TN}_{t,t+21}$; (4) the return on the S&P 500 futures contracts over a 22-trading-day period, $r^{S}_{t,t+21}$; (5) the change in the second principal component from the Treasury term structure over a 22-trading-day period, $\Delta PC2_{t-1,t+21}$; and (6) the change in the Treasury term yield spread over a 22-trading-day period, $\Delta(Yld10yr - Yld6m)_{t-1,t+21}$, defined as the difference between the 10-year T-Note yield and the 6-month T-Bill yield.

Panel B: Pairwise Correlations

	1. $\Delta VIX_{t-1,t+21}$	2. $\Delta TIV_{t-1,t+21}$	3. $r^{TN}_{t,t+21}$
Full Sample: 1997 - 2007			
1. $\Delta VIX_{t-1,t+21}$	1.0		
2. $\Delta TIV_{t-1,t+21}$	0.260	1.0	
3. $r^{TN}_{t,t+21}$	0.288	-0.082	1.0
4. $r^{S}_{t,t+21}$	-0.757	-0.226	-0.213
5. $\Delta PC2_{t-1,t+21}$	-0.214	0.183	-0.852
6. $\Delta(Yld10yr - Yld6m)_{t-1,t+21}$	-0.120	0.255	-0.529
First-half Sample: 1997 - 2002.06			
1. $\Delta VIX_{t-1,t+21}$	1.0		
2. $\Delta TIV_{t-1,t+21}$	0.269	1.0	
3. $r^{TN}_{t,t+21}$	0.318	-0.032	1.0
4. $r^{S}_{t,t+21}$	-0.707	-0.253	-0.225
5. $\Delta PC2_{t-1,t+21}$	-0.202	0.176	-0.810
6. $\Delta(Yld10yr - Yld6m)_{t-1,t+21}$	-0.081	0.256	-0.422
Second-half Sample: 2002.07 - 2007			
1. $\Delta VIX_{t-1,t+21}$	1.0		
2. $\Delta TIV_{t-1,t+21}$	0.252	1.0	
3. $r^{TN}_{t,t+21}$	0.226	-0.140	1.0
4. $r^{S}_{t,t+21}$	-0.825	-0.195	-0.162
5. $\Delta PC2_{t-1,t+21}$	-0.220	0.196	-0.892
6. $\Delta(Yld10yr - Yld6m)_{t-1,t+21}$	-0.169	0.262	-0.654

Table 2: Monthly Changes in the Term-Structure's Second Principal Component and IV Changes

This table reports how monthly changes in implied volatility for both the equity index (VIX) and T-Note (TIV) are related to monthly changes in the value of the second principal component of the Treasury term structure. We report on two estimations featuring the following model:

$$\Delta PC2_{t-1,t+21} = \alpha_0 + \alpha_1\, \Delta VIX_{t-1,t+21} + \alpha_2\, \Delta TIV_{t-1,t+21} +$$

$$\alpha_3\, r^S_{t,t+21} + \alpha_4\, \Delta Yld6m_{t-1,t+21} + \alpha_5 E(\Delta PC2_{t-1,t+21}) + \varepsilon_t$$

where $\Delta PC2_{t-1,t+21}$ is the difference between the second principal component value from the Treasury term structure on day $t+21$ and day $t-1$; $\Delta VIX_{t-1,t+21}$ ($\Delta TIV_{t-1,t+21}$) is the concurrent VIX change (TIV change), defined as the closing VIX (TIV) on day $t+21$ minus the closing VIX (TIV) on day $t-1$; $r^S_{t,t+21}$ is the monthly return for the S&P 500 futures contract overs trading-days t to $t+21$; $\Delta Yld6m_{t-1,t+21}$ is the change in the 6-month T-bill yield over days $t+21$ and $t-1$; $E(\Delta PC2_{t,t+21})$ is the expected, or fitted, change in the second principal component based on the information in the six lagged forward rates at $t-1$ per Section 3.5; ε_t is the residual; and the αs are coefficients to be estimated. Models 1 through 5 below report on variations of the above equation estimated by standard OLS. Model 6 below allows for time-varying volatility (TVV) where the conditional variance of ε_t may vary with TIV_{t-1} and VIX_{t-1}, estimated in a maximum likelihood system that assumes conditional normality; see equations (2) and (3) in Section 4.1. For the conditional variance equation in Model 6, λ_1 is the coefficient on TIV_{t-1} and λ_2 is the coefficient on VIX_{t-1}. For both estimations, t-statistics are in parenthesis that are calculated with heteroskedastic and autocorrelation consistent standard errors. [1], [2], [3], and [4] indicate 0.1%, 1%, 5%, and 10% p-values.

Model	α_1x100	α_2x100	α_3x100	α_4	α_5	λ_1x100	λ_2x100	R^2
			Panel A: Full Sample, 1997 - 2007					
1. OLS	-1.31							4.6%
	(-3.78)[1]							
2. OLS		5.28						3.4%
		(2.19)[3]						
3. OLS			0.69					1.2%
			(1.69)[4]					
4. OLS	-2.21	7.28	-0.68					11.2%
	(-4.20)[1]	(3.21)[2]	(-1.22)					
5. OLS	-1.82	6.65	-0.69	0.134	0.911			21.9%
	(-3.57)[1]	(3.27)[2]	(-1.18)	(1.56)	(4.56)[1]			
6. TVV	-1.74	6.55	-0.79	0.166	0.911	0.095	0.303	n/a
	(-3.36)[1]	(3.42)[1]	(-1.39)	(2.15)[3]	(4.59)[1]	(0.24)	(3.26)[2]	

Table 2: (continued)

Model	α_1x100	α_2x100	α_3x100	α_4	α_5	λ_1x100	λ_2x100	R^2
				Panel B: First-half Sample, 1997 - 2002.06				
1. OLS	-1.09							4.1%
	(-2.38)^{3}							
2. OLS		4.86						3.1%
		(1.58)						
3. OLS			0.38					0.5%
			(0.71)					
4. OLS	-1.89	6.64	-0.64					10.5%
	(-3.00)^{2}	(2.31)^{3}	(-0.98)					
5. OLS	-1.82	6.65	-0.69	0.134	0.911			21.9%
	(-3.57)^{1}	(3.27)^{2}	(-1.18)	(1.56)	(4.56)^{1}			
6. TVV	-1.74	6.55	-0.79	0.166	0.911	0.095	0.303	n/a
	(-3.36)^{1}	(3.42)^{1}	(-1.39)	(2.15)^{3}	(4.59)^{1}	(0.24)	(3.26)^{2}	

				Panel C: Second-half Sample, 2002.07 - 2007				
1. OLS	-1.65							4.8%
	(-3.14)^{2}							
2. OLS		5.88						3.8%
		(1.57)						
3. OLS			1.26					2.2%
			(1.81)^{4}					
4. OLS	-2.84	8.09	-0.92					11.9%
	(-2.91)^{2}	(2.29)^{3}	(-0.81)					
5. OLS	-2.57	7.32	-1.60	0.425	1.90			30.9%
	(-2.69)^{2}	(2.62)^{2}	(-1.32)	(3.39)^{1}	(4.88)^{1}			
6. TVV	-2.30	6.42	-1.66	0.444	1.95	-0.137	0.559	n/a
	(-2.52)^{3}	(2.74)^{2}	(-1.65)^{4}	(4.04)^{1}	(6.78)^{1}	(-0.31)	(2.80)^{2}	

Table 3: Monthly Change in the Term-Yield Spread and IV Changes

This table reports on the partial relation between the monthly change in the term-yield spread and the concurrent changes in the implied volatility for both the equity index (VIX) and the T-Note (TIV). We report on two estimations featuring the following model:

$$\Delta(Yld10yr - Yld6m)_{t-1,t+21} = \alpha_0 + \alpha_1\,\Delta VIX_{t-1,t+21} + \alpha_2\,\Delta TIV_{t-1,t+21} +$$

$$\alpha_3\, r^S_{t,t+21} + \alpha_5 E(\Delta(Yld10yr - Yld6m)_{t-1,t+21}) + \varepsilon_t$$

where $\Delta(Yld10yr - Yld6m)_{t-1,t+21}$ is the difference between the term yield spread on day $t+21$ and day $t-1$, where the term yield spread is the difference in the Treasury 10-year and 6-month yield; $E(\Delta(Yld10yr - Yld6m)_{t-1,t+21})$ is the expected, or fitted, change in the yield spread based on the information in the six lagged forward rates at $t-1$ per Section 3.5; and the other terms are as defined for Table 2. Models 1 through 5 below report on variations of the above equation estimated by standard OLS. Model 6 below allows for time-varying volatility (TVV) where the conditional variance of ε_t may vary with TIV_{t-1} and VIX_{t-1}, estimated in a maximum likelihood system that assumes conditional normality; see equations (4) and (5) in Section 4.1. For the conditional variance equation in Model 6, λ_1 is the coefficient on TIV_{t-1} and λ_2 is the coefficient on VIX_{t-1}. For both estimations, t-statistics are in parenthesis that are calculated with heteroskedastic and autocorrelation consistent standard errors. [1], [2], [3], and [4] indicate 0.1%, 1%, 5%, and 10% p-values.

Model	α_1x100	α_2x100	α_3x100	α_5	λ_1x100	λ_2x100	R^2
			Panel A: Full Sample, 1997 - 2007				
1. OLS	-0.66						1.4%
	(-1.51)						
2. OLS		6.57					6.5%
		(3.88)[1]					
3. OLS			0.14				0.1%
			(0.32)				
4. OLS	-1.64	7.79	-0.76				11.0%
	(-3.19)[2]	(4.83)[1]	(-1.51)				
5. OLS	-1.39	5.92	-0.75	0.906			28.1%
	(-2.91)[2]	(4.28)[1]	(-1.45)	(5.84)[1]			
6. TVV	-1.33	5.49	-0.86	0.863	-0.209	0.317	n/a
	(-2.71)[2]	(3.90)[1]	(-1.68)[4]	(6.40)[1]	(-1.04)	(4.90)[1]	

Table 3: (continued)

Model	α_1x100	α_2x100	α_3x100	α_5	λ_1x100	λ_2x100	R^2
			Panel B: First-half Sample, 1997 - 2002.06				
1. OLS	-0.42						0.7%
	(-0.71)						
2. OLS		6.82					6.6%
		$(2.83)^2$					
3. OLS			-0.17				0.1%
			(-0.31)				
4. OLS	-1.37	7.72	-0.76				10.0%
	$(-2.09)^3$	$(3.32)^1$	(-0.76)				
5. OLS	-1.00	5.54	-0.45	0.966			30.4%
	$(-1.73)^4$	$(2.90)^2$	(-0.71)	$(4.49)^1$			
6. TVV	-0.79	3.86	-0.47	0.755	0.511	0.525	n/a
	(-1.53)	$(1.85)^4$	(-0.78)	$(3.19)^2$	(0.80)	$(3.32)^1$	

Model	α_1x100	α_2x100	α_3x100	α_5	λ_1x100	λ_2x100	R^2
			Panel C: Second-half Sample, 2002.07 - 2007				
1. OLS	-1.03						2.8%
	$(-1.83)^4$						
2. OLS		6.37					6.9%
		$(2.56)^3$					
3. OLS			0.77				1.3%
			(1.25)				
4. OLS	-2.01	7.95	-0.66				13.1%
	$(-2.54)^3$	$(3.43)^2$	(-0.81)				
5. OLS	-2.22	6.38	-1.31	0.951			30.1%
	$(-2.93)^2$	$(3.23)^2$	(-1.52)	$(5.54)^1$			
6. TVV	-2.00	5.72	-1.30	0.928	-0.275	0.394	n/a
	$(-2.53)^3$	$(2.90)^2$	(-1.22)	$(5.66)^1$	(-1.37)	$(3.54)^1$	

Table 4: Changes in the Term-Structure's Slope, IV Changes, and FOMC Fed Funds Changes

This table reports on an extension of the models in Table 2 and 3, with the 'change in the FOMC Fed Funds target rate' as an additional explanatory variable. For Panel A with the 'change in the term-structure's second principal component' as the dependent variable, we report on variations of the following model:

$$\Delta PC2_{t-1,t+21} = \alpha_0 + \alpha_1\,\Delta VIX_{t-1,t+21} + \alpha_2\,\Delta TIV_{t-1,t+21} + \alpha_3\,r^S_{t,t+21} +$$

$$\alpha_4\,\Delta Yld6m_{t-1,t+21} + \alpha_5 E(\Delta PC2_{t-1,t+21}) + \alpha_6\,\Delta FF_{t-1,t+21} + \varepsilon_t$$

where $\Delta FF_{t-1,t+21}$ is the sum of changes in the FOMC's targeted Fed Funds rate over trading days $t-1$ to $t+21$; and the other terms are as defined for Table 2. Models 1 and 2 below are estimated by standard OLS. Model 3 below allows for time-varying volatility (TVV) where the conditional variance of ε_t may vary with TIV_{t-1} and VIX_{t-1}, as for equation (3) in Section 4.1. For the conditional variance equation in Model 3, λ_1 is the coefficient on TIV_{t-1} and λ_2 is the coefficient on VIX_{t-1}. Panel B reports on a similar model as in Table 3 with the 'change in the term yield spread' as the dependent variable, but with the addition of the $\Delta FF_{t-1,t+21}$ explanatory variable, as above. The sample period is 1997 to 2007.

Model	α_1x100	α_2x100	α_3x100	α_4	α_5	α_6	λ_1x100	λ_2x100	R^2
			Panel A: Dependent Variable is $\Delta PC2_{t-1,t+9}$; See the Table 2 Model						
1. OLS						-0.426			9.3%
						(-5.29)[1]			
2. OLS	-1.31	6.61	-0.55	0.430	0.735	-0.563			31.5%
	(-2.87)[2]	(3.53)[1]	(-1.03)	(4.90)[1]	(4.03)[1]	(-6.40)[1]			
3. TVV	-1.34	6.60	-0.66	0.443	0.774	-0.549	0.007	0.250	
	(-2.80)[2]	(3.58)[1]	(-1.20)	(5.31)[1]	(4.23)[1]	(-6.40)[1]	(0.02)	(3.00)[2]	
			Panel B: Dependent Variable is $\Delta(Yld10yr - Yld6m)_{t-1,t+9}$; See the Table 3 Model						
1. OLS						-0.700			31.4%
						(-10.15)[1]			
2. OLS	-1.03	5.39	-0.46		0.524	-0.523			42.2%
	(-2.76)[2]	(3.97)[1]	(-1.09)		(4.42)[1]	(-7.94)[1]			
3. TVV	-1.11	5.41	-0.59		0.559	-0.478	-0.135	0.198	
	(-2.94)[2]	(4.47)[1]	(-1.46)		(4.92)[1]	(-6.94)[1]	(-0.57)	(3.73)[1]	

Table 5: 10-Trading-Day Changes in the Term-Structure's Slope and IV Changes

This table reports on the same models as in Table 2 through 3, but for 10-trading-day changes for all of the relevant 'change terms' (instead of 22 trading days). Panel A reports on the 10-trading-day change in the term structure's second principal component the dependent variable, using a modification of the model in Table 2. Panel B reports on the 10-trading-day change in the term yield spread as the dependent variable, using a modification of the model in Table 3. The primary coefficient of interest is α_1 on the $\Delta VIX_{t-1,t+9}$ term and α_2 on the $\Delta TIV_{t-1,t+9}$ term. The sample period is 1997 to 2007.

Model	α_1x100	α_2x100	α_3x100	α_4	α_5	λ_1x100	λ_2x100	R^2
		Panel A: Dependent Variable is $\Delta PC2_{t-1,t+9}$; See the Table 2 Model						
1. OLS	-1.08	5.38	-0.13	0.146	0.941			14.8%
	(-2.98)^{2}	(4.74)^{1}	(-0.31)	(1.68)^{4}	(5.24)^{1}			
2. TVV	-1.08	4.51	-0.32	0.184	0.915	0.424	0.087	
	(-2.83)^{2}	(3.70)^{1}	(-0.77)	(2.04)^{3}	(5.13)^{1}	(3.32)^{1}	(3.21)^{2}	
		Panel B: Dependent Variable is $\Delta(Yld10yr - Yld6m)_{t-1,t+9}$; See the Table 3 Model						
1. OLS	-0.68	4.30	-0.20		0.927			16.3%
	(-1.94)^{4}	(4.73)^{1}	(-0.58)		(6.24)^{1}			
2. TVV	-0.69	3.46	-0.31		0.857	0.156	0.106	
	(-2.14)^{3}	(4.42)^{1}	(-1.01)		(7.18)^{1}	(1.59)	(3.95)^{1}	

Table 6: Monthly 10-yr T-note Futures Return and IV Changes

This table reports on the partial relation between the monthly return on the 10-yr T-Note futures contract and the concurrent changes in the implied volatility for both the equity index (VIX) and the T-Note (TIV). We report on six estimations featuring the following model:

$$r^{TN}_{t,t+21} = \alpha_0 + \alpha_1\,\Delta VIX_{t-1,t+21} + \alpha_2\,\Delta TIV_{t-1,t+21} +$$

$$\alpha_3\,r^{S}_{t,t+21} + \alpha_4\,\Delta Yld6m_{t-1,t+21} + \alpha_5 E(r^{TN}_{t,t+21}) + \varepsilon_t$$

where $r^{TN}_{t,t+21}$ is the return for the 10-year T-note futures over trading days t to $t+21$; $E(r^{TN}_{t,t+21})$ is the expected, or fitted, T-note futures return based on the information in the six lagged forward rates at $t-1$; and the other terms are as defined for Table 2. Models 1 through 5 below report on variations of the above equation estimated by standard OLS. Model 6 below allows for time-varying volatility (TVV) where the conditional variance of ε_t may vary with TIV_{t-1} and VIX_{t-1}, estimated in a maximum likelihood system that assumes conditional normality; see equations (6) and (7) in Section 5.1. For the conditional variance equation in Model 2, λ_1 is the coefficient on TIV_{t-1} and λ_2 is the coefficient on VIX_{t-1}. For both estimations, t-statistics are in parenthesis that are calculated with heteroskedastic and autocorrelation consistent standard errors. [1], [2], [3], and [4] indicate 0.1%, 1%, 5%, and 10% p-values.

Model	α_1x100	α_2x100	α_3x100	α_4	α_5	λ_1	λ_2	R^2
			Panel A: Full Sample, 1997 - 2007					
1. OLS	10.08							8.3%
	(5.92)[1]							
2. OLS		-13.57						0.7%
		(-0.86)						
3. OLS			-7.72					4.5%
			(-3.25)[2]					
4. OLS	11.61	-27.76	0.004					10.9%
	(3.99)[1]	(-1.96)[3]	(0.01)					
5. OLS	9.63	-38.74	1.84	-3.17	0.689			38.8%
	(3.83)[1]	(-3.37)[1]	(0.67)	(-7.64)[1]	(4.20)[1]			
6. TVV	8.99	-35.26	1.87	-3.28	0.636	0.198	0.042	n/a
	(3.75)[1]	(-3.04)[2]	(0.70)	(-8.53)[1]	(3.82)[1]	(1.88)[4]	(1.90)[4]	

Table 6: (Continued)

Model	α_1x100	α_2x100	α_3x100	α_4	α_5	λ_1	λ_2	R^2
			Panel B: One-half Sample, 1997 - 2002.06					
1. OLS	9.75							10.1%
	$(4.45)^1$							
2. OLS		-4.98						0.1%
		(-0.24)						
3. OLS			-6.97					5.1%
			$(-2.27)^3$					
4. OLS	10.42	-19.98	-0.55					11.6%
	$(3.12)^2$	(-1.10)	(-0.15)					
5. OLS	8.35	-33.36	0.97	-2.98	0.549			39.8%
	$(2.82)^2$	$(-2.19)^3$	(0.32)	$(-6.16)^1$	$(2.99)^2$			
6. TVV	6.24	-26.22	1.94	-3.21	0.548	0.083	0.174	n/a
	$(2.70)^2$	$(-1.72)^4$	(0.84)	$(-6.93)^1$	$(3.21)^2$	(1.25)	$(6.08)^1$	

Model	α_1x100	α_2x100	α_3x100	α_4	α_5	λ_1	λ_2	R^2
			Panel C: Second-half Sample, 2002.07 - 2007					
1. OLS	9.69							5.1%
	$(3.44)^1$							
2. OLS		-24.09						2.0%
		(-1.09)						
3. OLS			-7.79					2.6%
			$(-1.92)^4$					
4. OLS	15.01	-36.37	4.12					9.5%
	$(2.46)^3$	$(-1.77)^4$	(0.55)					
5. OLS	12.01	-44.38	4.04	-3.76	1.17			43.6%
	$(2.66)^2$	$(-2.71)^2$	(0.73)	$(-6.31)^1$	$(4.08)^1$			
6. TVV	10.35	-41.72	3.12	-3.68	1.07	0.193	0.045	n/a
	$(2.45)^3$	$(-2.91)^2$	(0.60)	$(-7.03)^1$	$(3.57)^1$	(1.18)	(0.73)	

Table 7: Subsequent Stock-bond Correlations and the Lagged Monthly VIX Change

This table examines the partial relation between the lagged monthly equity-risk change and the subsequent month's stock-bond correlation. We estimate the following model:

$$Corr(St, Bond)_{t+23,t+44} = \psi_0 + \psi_1 \Delta VIX_{t-1,t+21} + \psi_2 \Delta TIV_{t-1,t+21} +$$

$$+\psi_3 VIX_{t-1} + \psi_4 TIV_{t-1} + \varepsilon_t$$

where $Corr(St, Bond)_{t+23,t+44}$ is the Fisher transformation of the sample correlation of the daily stock and T-note futures returns over trading days $t+23$ to $t+44$; VIX_{t-1} (TIV_{t-1}) is the lagged VIX (TIV) at the close of trading day $t-1$; the other explanatory terms are as defined in Table 2; and the ψs are coefficients to be estimated. Note that, with this timing, one trading day is skipped between the dependent variable and the lagged explanatory implied-volatility variables. The sample period is 1997 through 2007. T-statistics are in parenthesis, calculated with heteroskedastic and autocorrelation consistent standard errors. [1], [2], [3], and [4] indicate 0.1%, 1%, 5%, and 10% p-values.

ψ_1 (x100)	ψ_2 (x100)	ψ_3 (x100)	ψ_4 (x100)	R^2
Panel A: Full Sample, 1997 - 2007				
-1.35	-2.82	-1.27	-5.85	11.6%
(-2.25)[3]	(-1.07)	(-2.58)[2]	(-2.39)[3]	
Panel B: First-half Sample, 1997 - 2002.06				
-1.60	-3.46	-1.96	-9.00	9.0%
(-1.83)[4]	(-0.93)	(-1.76)[4]	(-1.70)[4]	
Panel C: Second-half Sample, 2002.07 - 2007				
-3.17	3.23	-3.91	3.38	38.4%
(-4.62)[1]	(1.16)	(-7.94)[1]	(1.24)	

Table 8: Monthly S&P 500 Futures Return and IV Changes

This table reports on the partial relation between the monthly return on the S&P 500 futures contract and the concurrent changes in the implied volatility for both the equity index (VIX) and the T-Note (TIV). We report on two variations of the following model with two different estimation methods:

$$r^S_{t,t+21} = \alpha_0 + \alpha_1\, \Delta VIX_{t-1,t+21} + \alpha_2\, \Delta TIV_{t-1,t+21} +$$
$$\alpha_3\, r^{TN}_{t,t+21} + \alpha_4\, \Delta Yld6m_{t-1,t+21} + \alpha_5 E(r^S_{t,t+21}) + \varepsilon_t$$

where $r^S_{t,t+21}$ is the monthly return for the S&P 500 futures contracts overs days t to $t+21$; $\Delta VIX_{t-1,t+21}$ ($\Delta TIV_{t-1,t+21}$) is the concurrent VIX (TIV) change, defined as the closing VIX (TIV) on day $t+21$ minus the closing VIX (TIV) on day $t-1$; $r^{TN}_{t,t+21}$ is the concurrent 10-year T-Note futures return over days t to $t+21$; $\Delta Yld6m_{t-1,t+21}$ is the concurrent change in the 6-month T-bill yield; $E(r^S_{t,t+21})$ is the expected, or fitted, S&P 500 futures return based on the information in the six lagged forward rates at $t-1$; ε_t is the residual; and the αs are coefficients to be estimated. Model 1 below reports on the above equation estimated by standard OLS. Model 2 below allows for time-varying volatility (TVV) where the conditional variance of ε_t depends on VIX_{t-1}, estimated in a maximum likelihood system that assumes conditional normality; see equations (9) and (10) in Section 5.3. For the conditional variance equation in Model 2, λ_1 is the coefficient on VIX_{t-1}. For both models, t-statistics are in parenthesis that are calculated with heteroskedastic and autocorrelation consistent standard errors. [1], [2], [3], and [4] indicate 0.1%, 1%, 5%, and 10% p-values. The sample period is 1997 to 2007.

Model	α_1x100	α_2x100	α_3x100	α_4	α_5	λ_1	R^2
Panel A: Model Variation 1 with α_1 restricted to zero							
1. OLS		-99.31	-49.53	1.03	0.763		12.9%
		(-4.35)[1]	(-2.15)[3]	(0.64)	(2.26)[3]		
2. TVV		-80.23	-30.08	1.02	0.769	1.35	n/a
		(-4.58)[1]	(-1.86)[4]	(0.77)	(2.49)[3]	(7.72)[1]	
Panel B: Unrestricted Model Variation							
1. OLS	-71.65	-3.85	13.37	1.43	0.386		58.3%
	(-18.23)[1]	(-0.24)	(0.96)	(1.52)	(1.55)		
2. TVV	-73.03	-2.44	10.59	0.44	0.422	0.727	n/a
	(-23.05)[1]	(-0.19)	(1.03)	(0.50)	(1.74)[4]	(5.64)[1]	

Figure 1: Time-series of Implied Volatility

Figure 1 displays the time-series for the stock and 10-year T-Note implied volatility. The VIX is the CBOE's stock Volatility Index (VIX). This is the original VIX series, now referred to as VXO by the CBOE. The TIV is the implied volatility from options on 10-year T-Note futures from Bloomberg. The sample period is 1997 to 2007.

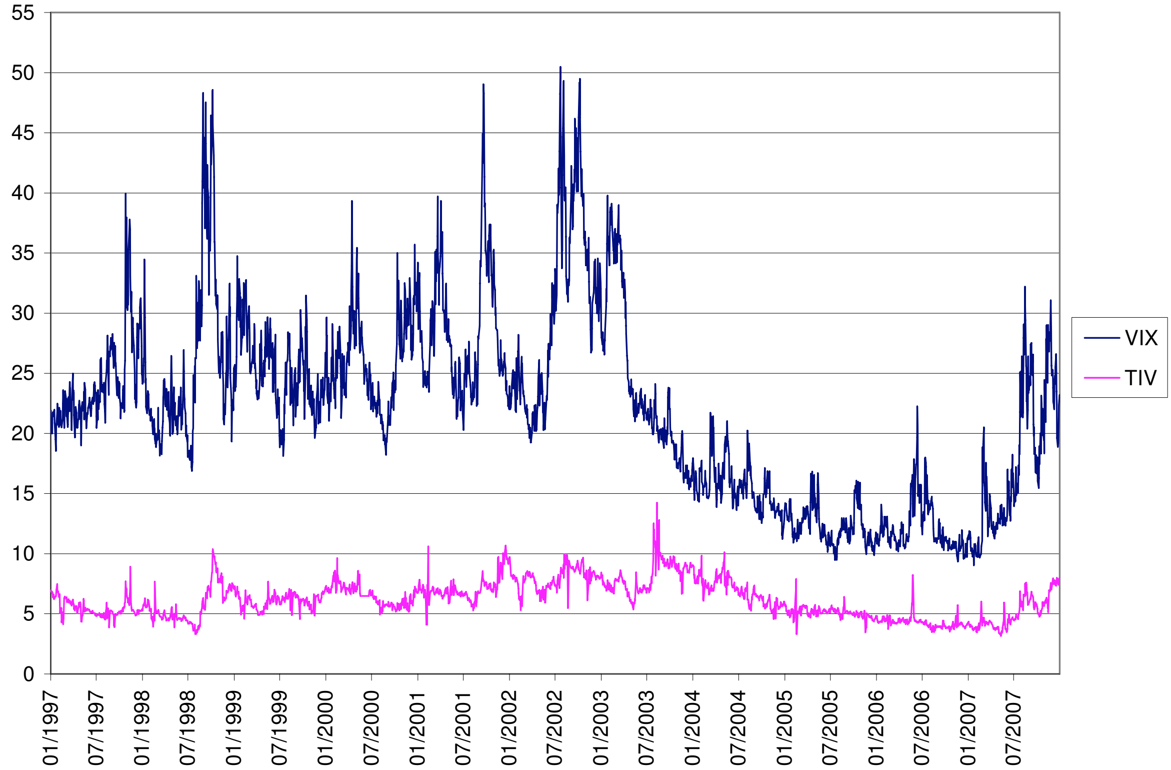
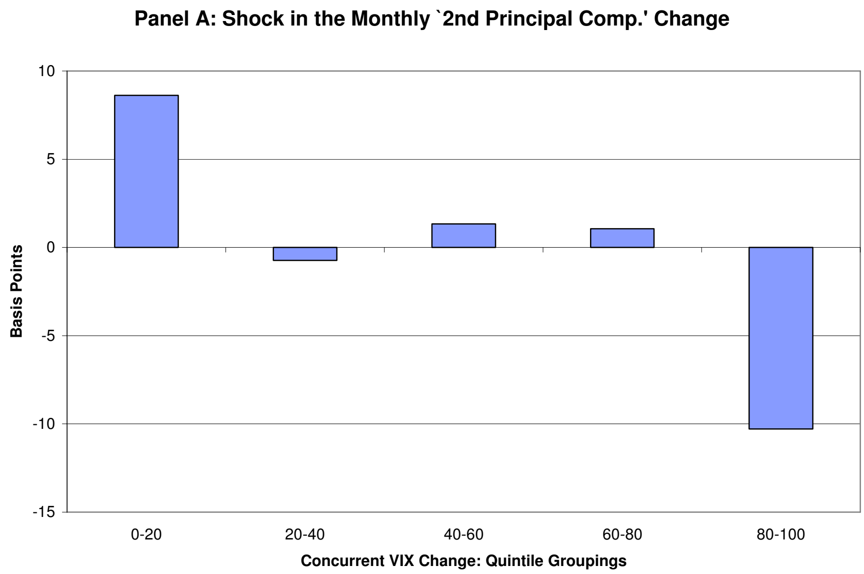
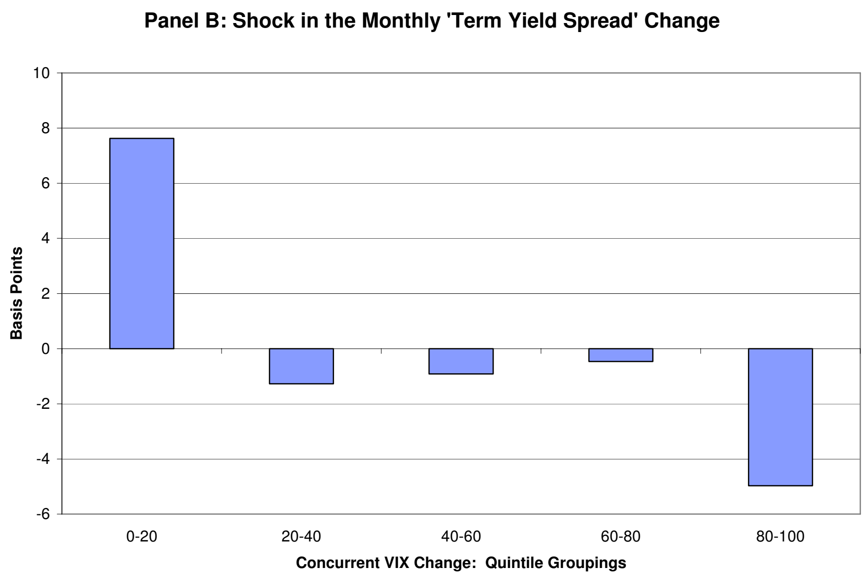


Figure 2: Monthly Changes in the Term-Structure's Slope and Changes in VIX

Figure 2 shows how the following vary with the concurrent change in VIX: (1) the shock in the monthly change of the term-structure's second principal component (Panel A); and (2) the shock in the monthly change in the '10-year minus 6-month' term yield spread (Panel B). The vertical values report the average shock for the different quintile ΔVIX groupings on the horizontal axis. The units on the vertical axis are 'basis points', indicating 1/100 of a percentage point. The shock refers to the difference from the expected value, given the lagged forward rates and the concurrent change in the implied volatility for the T-Note futures. The sample period is 1997 through 2007.





Appendix A: More Data Description and Sample Selection Discussion

A.1. Additional Sample Selection Discussion. In this appendix, we discuss the reasons for our sample selection and provide additional quantitative descriptions of our sample period, as compared to earlier periods.

We begin by discussing the attractive inflation characteristics of our sample. Before proceeding, consider the complications introduced by high time-variation in inflation. First, changes in inflation lead to variability in the real future cash flows of bonds and stocks and can influence discount rates for both bonds and stocks. In contrast, with stable inflation, the real future cash flows of Treasury bonds may be essentially regarded as fixed and known. Second, in the framework of Campbell and Ammer (1993), changes in inflation expectations are the only fundamental factor which induce a negative correlation between stock and bond returns. Thus, sample periods with low and stable inflation are quite attractive for a study, like ours, that attempts to isolate the partial relation between equity risk and dimensions of longer-term Treasury pricing.

Over our 1997 - 2007 sample period, the average of the months' annualized inflation rate is 2.66% with a monthly standard deviation of 0.72%.[12] For perspective, the comparable average/standard deviation of the monthly inflation is 7.86%/3.31% for the 1971-1980 decade and 4.74%/2.29% for the 1981 to 1990 decade. Thus, both the level and variability of inflation is quite modest for our sample as compared to the 1970's and 1980's. Accordingly, we believe the impact of inflation on bond prices and return dynamics over our sample should be modest. Our later empirical results support this premise.

Next, there are data issues that factor into our sample selection. The CBOE first started computing VIX in 1993, with backfill to 1986. Additionally, the implied volatility from the 10-year T-note futures options is available from Bloomberg back to June 1993. Additionally, in 1994 the FOMC began a new policy where they announced the target Fed Funds rate following every meeting, see Piazzesi (2005). Piazzesi (2005) shows that the FOMC target for the Fed Funds rate influences Treasury yields, especially at the shorter horizons. Given this data availability and the shift in the FOMC policy, another choice would have been to begin our analysis in 1993 or 1994.

However, as compared to our 1997-2007 period, the 1993 through 1996 period was substantially different in terms of the observed stock-bond correlation and the relative risk characteristics for equities and longer-term Treasuries. The apparent shift in the stock-bond correlations is noted in several studies, including Connolly, Stivers, and Sun (2005) and (2007), Baele, Bekaert, and Inghelbrecht (2009), and Campbell, Sunderam, and Viceira (2009).

Consider the following comparisons. For the 1993 to 1996 period, the correlation between the monthly stock and T-note futures returns was 0.504, the average VIX was 13.9, the standard deviation of the monthly VIX-change was 2.21, and the average ratio of VIX over TIV was 1.80. By comparison, over the first-half of our main sample from January 1997 through June 2002, the correlation between the monthly stock and T-note futures returns was -0.225 (thus, the correlation's value decreased over 0.7 from the

[12] A month's inflation rate is defined as the percentage change in that month's CPI-U index relative to the CPI-U index value from 12 months earlier.

value over 1993-96, with a change in the sign), the average VIX was 25.6 (nearly twice that of 1993-96), the standard deviation of the monthly VIX-change was 5.47 (over twice that of 1993-96), and the average ratio of VIX over TIV was 4.20 (over twice that of 1993-96). Over the second-half of our main sample from July 2002 through December 2007, the numbers are also substantially different than 93-96, although the differences are somewhat more modest than those observed in the first-half period. For our second-half period, the correlation between the monthly stock and T-note futures returns was -0.162, the average VIX was 18.2, the standard deviation of the monthly VIX-change was 4.10, and the average ratio of VIX over TIV was 2.96.

To summarize, as compared to our sample period over 1997 to 2007, the 1993 to 1996 period is substantially different in terms of the observed stock-bond correlation, the level and variability in equity risk, and the ratio of equity risk to long-term T-note risk. Thus, in our view, it did not make sense to mix the 1993-96 regime with the 1997 to 2007 regime in our analysis, given our interest in a negative stock-bond correlation with relatively high levels and high variability of equity risk.

A.2. Stock and 10-year T-Note Futures Return Data. Our analysis features the returns on futures contracts, rather than spot returns. For computing returns, we use the continuous futures series computed by Datastream for the S&P 500 futures contracts and the 10-year T-Note futures contracts. The continuous series uses the price of the nearest to maturity contract until the month in which the contract expires. Then, the series switches at that point to the next nearest to maturity contract.[13]

The principal S&P500 contract is traded on the Chicago Mercantile Exchange (CME) both in an open outcry and electronic market. Pit trading takes place between 8:30 a.m. and 3:15 p.m. The E-mini S&P500 contract, introduced in September 1997, trades on the CME's Globex electronic trading system, with the E-mini contract being one-fifth the size of the full contract.

The T-Note futures contracts trades on the Chicago Board of Trade (CBOT), both in an open outcry and electronic market. Open outcry trading begins at 7:20 a.m. and closes at 2:00 p.m. Thus, there are some differences between the stock and bond futures trading times.[14]

Our empirical work focuses on the 10-year T-Note futures contract for several reasons. First, for our principal analysis, we desire a futures contract where the underlying asset is a longer-term bond, whose maturity should roughly correspond to the bond holdings in a portfolio that is allocated across stock, bonds, and the money market. Second, we desire a very widely-traded contract where prices should rapidly respond to changing conditions. In our sample, the 10-yr T-Note futures contract has the largest trading volume.

Much of our empirical work features rolling monthly statistics, calculated from rolling 22-trading-day periods. For our monthly correlations and return standard deviations, we calculate the sample statistics under the assumption that the expected daily return is zero. Alternately, we could use the sample mean

[13]The switch of the series as one rolls into the maturity month will result in an artificial return on that day. Accordingly, when computing returns, we discard those four days a year.

[14]Making comparisons across the markets using close-to-close returns entails some timing mismatch because the S&P 500 market closes later than the Treasury bond market. Fleming, Kirby, and Ostdiek (1998) assess the impact of this mismatch by using stock futures prices from 2 PM (CST). Their results when using the stock futures returns from 2 PM were not qualitatively different from those obtained using close-to-close returns.

for the 22 observations as the month's expected return for the purposes of calculating the correlation or standard deviation. However, since we estimate statistics from only 22 observations, our method prevents a large return realization from implying a large expected return for that given 22-trading-day period. In practice for our setting, both methods generate similar results.

In our regression model in Table 7, we use the Fisher transformation for the sample correlation, where the Fisher transformation is given by:

$$\rho_{Fisher} = \frac{1}{2} \log \frac{1+\rho}{1-\rho} \tag{11}$$

where ρ_{Fisher} is the Fisher transformation of the sample correlation, log is the natural log, and ρ is the sample 22-trading-day correlation, as described above. This transformation converts the raw correlations, which are bounded between -1 and 1, into a continuous variable that is closer to normally distributed. In our sample, this transformation reduces the skewness from positive and significant to statistically insignificant and reduces the negative excess kurtosis by about half.

A.3. The Implied Volatility Series. To measure the implied volatility of the U.S. stock market, we rely on the original VIX measure produced by the Chicago Board Options Exchange (CBOE), now denoted as VXO by the CBOE. This daily series measures the implied volatility of a hypothetical at-the-money option on the S&P 100 stock index with 30 calendar days until expiration (about 22 trading days). The CBOE constructs this VIX as a weighted average of the implied volatilities extracted from eight different options. Specifically, these are call and put options written at the two strike prices closest to the money plus the two options (both puts and calls) nearest to expiration, excluding options that are within one week of expiration. The implied volatilities account for dividend payments and the possibility of early exercise.

To measure the implied volatility of the 10-year Treasury notes, we use the implied volatility from options on 10-year T-note futures contracts from Bloomberg. We use the rolling implied volatility of the Bloomberg TY1 series. We denote this series as TIV in our main text. This series uses the implied volatility of closest to at-the-money strikes for both puts and calls, using the near month expiry, unless there are less than 20 business days until expiration, then the second nearest expiry is used.

Appendix B: Principal Components Estimation and Results

In this appendix, we describe our principal components evaluation, using the term structure of 6-month, 1-year, 2-year, 3-year, 5-year, 7-year, and 10-year Treasury zero-coupon bond yields over our 1997-2007 sample period. We calculate the first three principal components, constructed to be orthogonal to each other. Recall that these first three principal components have been shown to be closely tied to the level, slope, and curvature of the term structure's shape.

The estimated principal components nearly fully describe the variation for each of the seven yields. After estimating the time-series of the first three principal components, we retain the first two principal components and use them as explanatory variables in seven different regressions with the zero-coupon yield for each horizon as the dependent variable. For each of the seven time-series regressions, the two principal components explain over 99% of the yield variation, with a minimum R-squared value of 99.46% for the 10-year horizon yield. For these seven regressions, the estimated coefficient on the second principal component is highly statistically significant for each yield horizon (p-values all less than 0.01%), and the estimate coefficient increases monotonically with the yield horizon (as one would expect with the interpretation that the second principal component is closely tied to the slope of the term structure).

Appendix C: The Implied-Volatility Series and the Subsequent Return Volatilities

Our main empirical work in Section 4 relies upon the implied-volatility series being good proxies for the forward-looking risk, or expected volatility, of the respective underlying return series. In this appendix, we investigate the information content in the TIV and VIX for the subsequent realized monthly volatility of the 10-year T-note and S&P 500 futures returns, respectively.

We begin by investigating how the subsequent 22-trading-day volatility of the daily 10-year T-Note futures returns is related to the lagged TIV, the lagged VIX, and the lagged realized T-Note futures volatility. We estimate five variations of the following volatility model:

$$\sigma^{TN}_{t,t+21} = \beta_0 + \beta_1 TIV_{t-1} + \beta_2 \sigma^{TN}_{t-1,t-22} + \beta_3 VIX_{t-1} + \sum_{j=1}^{6} \lambda_j FwdRt_{j,t-1} + \varepsilon_t \tag{12}$$

where $\sigma^{TN}_{t,t+21}$ is the sample standard deviation of the daily 10-yr T-Note futures returns over trading days t to $t+21$; TIV_{t-1} is the implied volatility from 10-yr T-Note futures options on day $t-1$; $\sigma^{TN}_{t-1,t-22}$ is the lagged sample standard deviation of the daily 10-year T-Note futures returns over trading days $t-1$ to $t-22$; VIX_{t-1} is the implied volatility from S&P 100 index options on day $t-1$; $FwdRt_{j,t-1}$ are the six forward rates from day $t-1$; and the βs and λs are coefficients to be estimated. We report separately on our primary 1997 - 2007 period and on inclusive one-half subperiods.

Table B.1 reports the results from estimating equation (12). The first model variation includes only the TIV explanatory term. We find that the lagged TIV contains substantial and highly reliable information about the subsequent realized volatility for the T-Note futures. For the full sample and both one-half subperiods, the estimated β_1 coefficients on the TIV term are positive with p-values of less than 0.1%. The R-squared values also seem sizable at 45.5%, 24.1%, and 65.1% for the full period, first-half period, and second-half period, respectively.

Next, the second model variation in Table B.1 includes only the VIX explanatory term We find that the VIX, by itself, also contains sizable and substantial information about the subsequent T-Note futures volatility. The p-values on the estimated β_2 coefficients on the VIX term are all less than 0.1%. Note, however, that the R-squared values for the model with VIX as the only explanatory term are appreciably less than the model with TIV as the only explanatory term.

Next, Andersen and Benzoni (2009) note that affine term structure models imply that the instantaneous yield volatility should be spanned by the cross-section of yields.[15] If so, then the lagged VIX should provide no explanatory power for the volatility when also controlling for the cross-section of yields. Accordingly, in the third model variation in Table B.1, we examine whether VIX contains information about the subsequent T-Note futures return volatility beyond the information in the cross-section of forward rates. We find that the VIX contains reliable incremental information about the subsequent T-Note volatility, while controlling for the lagged forward rates.[16] This indicates a role for expected stock risk in understanding yield volatility, consistent with the premise our our primary empirical investigation in the next section. This finding also contributes towards the question raised in Andersen and Benzoni, in terms of what factors may be important for understanding yield volatility beyond the cross-section of yields.

For the fourth model variation in Table B.1, we examine whether the recent historical volatility of the T-Note futures contains incremental information beyond that in TIV. For the overall period and the first-half period, we find that the lagged monthly realized volatility (the $\sigma^{TN}_{t-1,t-22}$ term with the β_2 coefficient) does not contain reliable incremental information. For the second-half subperiod, the lagged volatility does contain information beyond the TIV, but the increase in the R-squared value is very modest.

Finally, for the fifth model variation in Table B.1, we examine whether the lagged VIX and lagged forward rates contain incremental volatility information beyond the TIV. For the full period and the first-half subperiod, we find that the VIX and the lagged forward rates do contain modest incremental information beyond TIV for the subsequent T-Note future volatility. For the second-half period, the estimated coefficients on the lagged VIX and lagged forward rates are not statistically significant.

Overall, the results in Table B.1 indicate that: (1) the TIV does contain substantial and reliable information about the subsequent month's volatility of daily 10-year T-Note futures returns; (2) when including other likely explanatory terms, the TIV captures most of the volatility predictability; and (3) the VIX contains substantial and reliable information about the subsequent month's volatility of daily 10-year T-Note futures returns, both by itself and when controlling for the lagged forward rates. These findings both support our use of TIV as a forward-looking measure of the T-Note risk and support the premise of a common comovement in the volatility of stocks and longer-term Treasuries.

Next, we document the strong relation between VIX and the subsequent realized stock-futures volatility over our sample period. We estimate four variations of the following regression:

$$\sigma^{S}_{t,t+21} = \beta_0 + \beta_1 VIX_{t-1} + \beta_2 \sigma^{S}_{t-1,t-22} + \beta_3 TIV_{t-1} + \varepsilon_t \qquad (13)$$

where $\sigma^{S}_{t,t+21}$ is the sample standard deviation of the daily S&P 500 futures returns over trading days t to $t+21$; $\sigma^{S}_{t-1,t-22}$ is the lagged standard deviation of the daily S&P 500 futures returns over trading days $t-1$ to $t-22$; VIX_{t-1} is the implied volatility from S&P 100 index options on day $t-1$; TIV_{t-1}

[15] Also, Viceira (2009) finds that the short rate is positively related to bond return volatility. Recall that that our first forward rate is really the one-year interest rate, so the forward-rate explanatory terms in equation (12) are also suggested by Viceira's findings.

[16] We also estimate a version of equation (12) where the dependent variable is the yield volatility of the 10-year zero-coupon Treasury yield in the sense of Andersen and Benzoni (2009), rather than the volatility of daily T-note futures returns. We find that the explanatory power of the lagged VIX for the subsequent yield volatility is comparable to that in Table B.1 for the futures return volatility.

is the implied volatility from 10-yr T-Note futures options on day $t-1$; and the βs are coefficients to be estimated.

Table B.2 reports the results. For the first model variation that includes the lagged VIX as the sole explanatory term, we find that the lagged VIX contains substantial and highly reliable information about the subsequent volatility of the S&P 500 futures returns. The estimated β_1 coefficients on the VIX term all have p-values of less than 0.1% and the R-squared values are sizable at 52.1%, 14.5%, and 68.4% for the full sample, first-half sample, and second-half sample, respectively.

Next, the second model variation in Table B.2 includes only the TIV explanatory term We find that the TIV, by itself, contains reliable information about the subsequent stock-index futures volatility for our full sample period and the second-half subperiod.

For the third model variation in Table B.2, we examine whether the recent historical volatility of the stock-index futures contains incremental information beyond that in VIX. None of the estimated β_2 coefficients on the $\sigma^S_{t-1,t-22}$ term are statistically significant at a 5% level.

Finally, for the fourth model variation in Table B.2, we examine whether the lagged TIV appears to contain incremental information beyond the VIX for the subsequent stock-index futures volatility. Interestingly, the estimated β_3 coefficients are negative and statistically significant for the overall period and the second-half subperiod (rather than being positive and statistically significant as for the second model variation).[17] Note for this fourth model variation, however, that the R-squared values do not increase appreciably with the addition of the TIV explanatory term.

We conclude that the lagged VIX is a good proxy for the forward-looking expected stock volatility, which supports its use in our main empirical work.

[17]It is well known that VIX tends to be biased high for equity-index volatility. We conjecture that the VIX value may be biased relatively more highly during times when both VIX and TIV are relatively high.

Table C.1: Realized T-Note Futures Volatility and the Lagged Implied Volatility

This table reports how the realized monthly volatility of daily 10-year Treasury note futures returns vary with the lagged implied volatility from 10-year T-note futures options and stock-index options. We report on five variations of the following regression:

$$\sigma^{TN}_{t,t+21} = \beta_0 + \beta_1 TIV_{t-1} + \beta_2 \sigma^{TN}_{t-1,t-22} +$$

$$\beta_3 VIX_{t-1} + \sum_{j=1}^{6} \lambda_j FwdRt_{j,t-1} + \varepsilon_t$$

where $\sigma^{TN}_{t,t+21}$ is the standard deviation of the daily 10-yr T-Note futures returns over trading days t to $t+21$; TIV_{t-1} is the implied volatility from 10-yr T-Note futures options on day $t-1$; $\sigma^{TN}_{t-1,t-22}$ is the lagged standard deviation of the daily 10-year T-Note futures returns over trading days $t-1$ to $t-22$; VIX_{t-1} is the implied volatility from S&P 100 index options on day $t-1$; $FwdRt_{j,t-1}$ are the six forward rates at the end of day $t-1$; and the βs and λs are coefficients to be estimated. We report on the 1997 to 2007 period and one-half subperiods. T-statistics are in parenthesis, calculated with heteroskedastic and autocorrelation consistent standard errors. An F-statistic is in brackets which jointly tests the coefficients on the six forward rates, (λ_1 to λ_6). ^{1}, ^{2}, ^{3}, and ^{4} indicate 0.1%, 1%, 5%, and 10% p-values.

Variation	β_1	β_2	β_3	F-stat (Fwd Rt)	R^2
			Panel A: Full Sample, 1997 - 2007		
1.	0.800 (15.26)^1				45.5%
2.			0.106 (7.84)^1		21.1%
3.			0.073 (3.20)^2	[11.82]^1	47.5%
4.	0.737 (8.87)^1	0.064 (0.79)			45.6%
5.	0.520 (6.59)^1		0.046 (2.21)^3	[2.92]^3	53.8%
			Panel B: First-half Sample, 1997 - 2002.06		
1.	0.736 (5.80)^1				24.1%
2.			0.169 (4.65)^1		21.8%
3.			0.144 (3.39)^1	[3.27]^2	38.9%
4.	0.771 (4.28)^1	-0.031 (-0.27)			24.1%
5.	0.431 (4.00)^1		0.107 (2.56)^3	[1.91]^4	43.8%
			Panel C: Second-half Sample, 2002.07 - 2007		
1.	0.825 (16.41)^1				65.1%
2.			0.125 (7.26)^1		33.1%
3.			0.050 (1.96)^3	[4.64]^1	65.1%
4.	0.597 (7.86)^1	0.254 (2.61)^2			66.5%
5.	0.527 (4.36)^1		0.024 (0.94)	[1.33]	69.9%

Table C.2: Realized Stock Futures Volatility and the Lagged Implied Volatility

This table reports how the realized monthly volatility of daily S&P 500 futures returns vary with the lagged implied volatility from equity-index options and 10-yr T-note futures options. We report on four variations of the following regression:

$$\sigma^S_{t,t+21} = \beta_0 + \beta_1 VIX_{t-1} + \beta_2 \sigma^S_{t-1,t-22} + \beta_3 TIV_{t-1} + \varepsilon_t$$

where $\sigma^S_{,t,t+21}$ is the standard deviation of the daily S&P 500 futures returns over trading days t to $t+21$; $\sigma^S_{t-1,t-22}$ is the lagged standard deviation of the daily S&P 500 futures returns over trading days $t-1$ to $t-22$; VIX_{t-1} is the implied volatility from S&P 100 index options on day $t-1$; TIV_{t-1} is the implied volatility from 10-yr T-note futures options on day $t-1$; and the βs and λs are coefficients to be estimated. We report on the 1997 to 2007 period and one-half subperiods. T-statistics are in parenthesis, calculated with heteroskedastic and autocorrelation consistent standard errors. An F-statistic is in brackets which jointly tests the coefficients on the six forward rates, (λ_1 to λ_6). ^{1}, ^{2}, ^{3}, and ^{4} indicate 0.1%, 1%, 5%, and 10% p-values.

Variation	β_1	β_2	β_3	R^2
		Panel A: Full Sample, 1997 - 2007		
1.	0.714 (13.71)^1			52.1%
2.			1.30 (2.77)^2	6.5%
3.	0.833 (9.08)^1	-0.143 (-1.68)^4		52.7%
4.	0.788 (12.99)^1		-0.751 (-2.71)^2	53.7%
		Panel B: First-half Sample, 1997 - 2002.06		
1.	0.523 (4.16)^1			14.5%
2.			-0.116 (-0.18)	0.1%
3.	0.637 (3.94)^1	-0.114 (-0.97)		15.2%
4.	0.586 (4.33)^1		-0.859 (-1.35)	16.6%
		Panel C: Second-half Sample, 2002.07 - 2007		
1.	0.701 (10.15)^1			68.4%
2.			1.677 (3.23)^2	17.7%
3.	0.787 (6.66)^1	-0.111 (-1.09)		68.8%
4.	0.799 (9.87)^1		-0.719 (-3.48)^1	70.4%

Appendix D: Forward Rate Data

We also use the Treasury Constant Maturity (TCM) series at the 1-year, 2-year, 3-year, 5-year, 7-year, and 10-year horizon to approximate six forward interest rates. Our procedure is as follows. We first back out the yield of zero coupon bonds for each of these six horizons for the TCM maturity series, while treating the bonds as having an annual coupon.[18] We then approximate the following six annualized forward rates from the yield curve of zero-coupon yields in the usual way, where the first subscript indicates the start time for the forward debt and the second subscript indicates the end time: (1) $Fwd_{0,1}$ is the one-year TCM yield for debt commencing now and maturity in one-year, so it is not really a forward rate; (2) $Fwd_{1,2}$ is the forward rate for debt commencing in one year and maturing in two years; (3) $Fwd_{2,3}$ is the forward rate for debt commencing in two years and and maturing in three years; and etc. for (4) $Fwd_{3,5}$; (5) $Fwd_{5,7}$; and (6) $Fwd_{7,10}$. To control for the return predictability documented in Cochrane and Piazzesi (2005), we then use the forward rates at the beginning of the holding period as state variables to provide an expected value for subsequent change in our term-structure slope variables.

Appendix E: Analysis Using Non-overlapping Observations

We also perform estimations comparable to our main results in Tables 2 and 3, but with non-overlapping variables. With a 22-trading-day horizon for our key variables of interest, one can construct 22 different non-overlapping data sets since one can select 22 different starting days for the first day of the 22-trading-day periods. We estimate our models for each of the 22 different possibilities for non-overlapping data so we end up with 22 different point estimates for each coefficient.

We find that the estimations using the non-overlapping observations reinforce the relations depicted in Tables 2 and 3. For the change in the term-structure's second principal component (comparable to the OLS model-5 in Table 2), we find that: (1) all 22 of the estimated α_1 coefficients on the ΔVIX term are negative, the median α_1 is -0.0178, and 19 of the 22 α_1 point estimates are statistically significant; and (2) all 22 estimated α_2 coefficients on the ΔTIV term are positive, the median α_2 is 0.0718, and 18 of the 22 α_2 point estimates are statistically significant. For the change in the term yield spread (comparable to the OLS model-5 in Table 3), we find that: (1) all 22 of the estimated α_1 coefficients on the ΔVIX term are negative, the median α_1 is -0.0138, and 15 of the 22 α_1 point estimates are statistically significant; and (2) 21 of the 22 estimated α_2 coefficients on the ΔTIV term are positive, the median α_2 is 0.0590, and 19 of the 22 α_2 point estimates are statistically significant. We conclude that our primary results are robust to estimations with non-overlapping observations.

[18]For the coupons of the 5-year, 7-year, and 10-year bonds where there is not a corresponding TCM maturity, we discount that particular coupon at the last available zero-coupon yield.