Do stylized facts of equity-based volatility indices apply to fixed-income volatility indices? Evidence from the US Treasury market

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Abstract

In this paper, we examine whether widely documented properties of equity-based volatility indices apply to US Treasury bond volatility indices (TBVIXs). We calculate TBVIXs in a model-free way using the market prices of five-, ten- and 30-year Treasury futures options over a sample of more than 20 years. The empirical findings of this study reveal that movements in TBVIXs are positively correlated with both changes in Treasury yield rates and changes in non-fixed income volatility indices (i.e., commodity, equity and foreign exchange volatility indices). Our analysis also shows that statistically significant bidirectional Granger causality is at work between TBVIXs and the S&P 500 volatility index (VIX). Finally, we find that TBVIXs fall following scheduled macroeconomic news announcements, whereas perception of uncertainty in the Treasury market tends to rise during stock market crashes. This study's findings have implications for volatility risk management using the recently listed futures on the implied volatility of government security prices by the Chicago Board of Options Exchange (CBOE) Futures Exchange.

Keywords: implied volatility; volatility index; Treasury; implied volatility spillovers; news announcements

JEL classification: G11, G12, G14

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1. Introduction

Since the 2003 launch of the S&P 500 volatility index (VIX) by the Chicago Board of Options Exchange (CBOE), the number of exchanges worldwide that calculate volatility indices based on stock market indices has significantly increased (see Siriopoulos and Fassas, 2009 for a comprehensive review). Thus, there exists a vast literature analyzing the properties of volatility indices in international equity markets. Several interesting stylized facts can be drawn from the research. First, there is a negative contemporaneous relationship between changes in volatility indices and the underlying stock indices' returns (see e.g., Giot, 2005; González and Novales, 2009; Whaley, 2009). Second, there is a significant contemporaneous and dynamic relationship among international equity-based volatility indices (see e.g., Äijö, 2008b; Konstantinidi *et al.*, 2008; Siriopoulos and Fassas, 2012). Third, volatility indices tend to fall (rise) following scheduled news announcements on macroeconomic fundamentals (unexpected events) (see e.g., Jiang *et al.*, 2012; Nikkinen and Sahlström, 2004a; Vähämaa and Äijö, 2011).

Extending the existing literature, we investigate whether stylized facts of equity-based volatility indices apply to fixed-income volatility indices. To address our research question, we calculate three Treasury bond volatility indices (TBVIXs) with a fixed 30-day maturity using the market prices of US Treasury futures options for three different government security maturities (i.e., five, ten and 30 years). Thus, TBVIXs capture short-term market uncertainty about the development of medium- and long-term government security prices. The Treasury derivatives that we employ to calculate TBVIXs are very liquid instruments: according to the CME Group, the average trading volume in 2013 for Treasury futures and options traded at the Chicago Board of Trade (CBOT) was 3.1 million contracts per day. We construct TBVIXs based on the concept of the model-free implied variance developed by Britten-Jones and Neuberger (2000), which relies exclusively on the market prices of European options. Because Treasury futures options are American-style, one of this study's contributions is that it describes the process of calculating volatility indices using American option prices.

Although the properties of volatility indices in international equity markets are well documented in numerous papers, this question has received little attention in the fixed-income literature. To our knowledge, Markellos and Psychoyios (2013) is the only related study. However, that study differs from ours in at least three aspects. First, Markellos and Psychoyios (2013) create a set of interest rate volatility indices based on the prices of CBOE options on the spot yield of US Treasury securities. However, these options are less liquid than the Treasury futures options that we employ (Hull, 2009). Moreover, Markellos and Psychoyios (2013) use the CBOE's implementation of the model-free implied variance, which according to Jiang and Tian (2007) may lead to several types of approximation errors. Thus, we address the implementation issues of the model-free implied variance highlighted by Jiang and Tian (2007) for the calculation of TBVIXs. Second, Markellos and Psychoyios (2013) examine the relationship between changes in the interest rate volatility indices and VIX, whereas we consider a wider set of CBOE volatility indices, including foreign exchange and commodity-based volatility indices. Thus, this study analyzes the interaction of short-term investors' uncertainty in the Treasury market with uncertainty in the commodity, equity and foreign exchange markets. Third, Markellos and Psychoyios (2013) investigate the impact of scheduled macroeconomic news announcements on the volatility indices, whereas we also analyze whether unexpected market or world events affect Treasury bonds' implied volatility.

The results of this study provide novel insights into the use of volatility derivatives for managing volatility risk in the Treasury market. Indeed, these insights have become reality: in November 2014, the CBOE Futures Exchange listed futures on the CBOE's 10-year Treasury note volatility index. First, therefore, the positive relationship between changes in TBVIXs and Treasury yield rates, together with the negative yield-price relationship of government securities, suggests benefits to investors with a long position in futures and/or options on the implied volatility of Treasury securities. Second, the positive contemporaneous correlation among the commodity, equity, foreign exchange and Treasury bond volatility indices can reduce the benefits of portfolio diversification with volatility products. Third, we find evidence that VIX changes can be applied to improve forecasts of the changes in TBVIXs (and vice versa), thereby providing valuable information for volatility risk management purposes in the equity and Treasury markets. Fourth, the significant fall of TBVIXs following the employment announcement, whose date of release is known a priori, can be exploited by going short on derivatives on the implied volatility of Treasury securities.

The remainder of this paper is structured as follows. Section Two reviews the literature that documents some of the stylized facts of equity-based volatility indices.

Section Three presents the data set. Section Four describes the calculation of the TBVIXs, which is compared to the CBOE's calculation of the ten-year Treasury note volatility index, and examines the statistical properties of the volatility indices. Sections Five, Six and Seven investigate whether the above-mentioned stylized facts of equity-based volatility indices apply to TBVIXs and discuss their implications for portfolio management. Section Eight offers the main conclusions of the study.

2. Literature review

Three salient features of volatility indices based on stock market indices are now well documented in the literature. Those features are the negative contemporaneous relationship between changes in volatility indices and the returns of the underlying stock indices; the relationship between international equity-based implied volatility indices; and the fall (rise) of volatility indices following scheduled news announcements (unexpected events). Next, we review some of the studies that address these three aspects.

2.1. The relationship between volatility indices and market returns

Academic papers contain consistent empirical evidence of a negative contemporaneous association between changes in implied volatility indices and the underlying stock indices' returns. The negative return-volatility relationship is usually explained in the literature by two different arguments. The first argument relies on the leverage effect suggested by Black (1976a), according to which a fall (rise) in equity prices increases (decreases) a firm's leverage, which in turn leads to higher (lower) equity risk and volatility. The second argument is based on the increase in the general perception of risk due to the arrival of news in the market. Such an increase may lead to selling decisions (i.e., negative returns in the equity market), which simultaneously pulls the demand for put options by hedgers, thereby increasing their price and thus implied volatility.

In the US market, Whaley (2000), Simon (2003), Giot (2005) and Whaley (2009), among others, document the negative correlation for three CBOE volatility indices: VXN, VXO and VIX. With respect to European volatility indices – Siriopoulos and Fassas (2008) for VFTSE (UK); González and Novales (2009) for VDAX-NEW (Germany), VSMI (Switzerland) and VIBEX (Spain); and Siriopoulos and Fassas

(2012) for GRIV (Greece) – the findings are also consistent. Ting (2007), Frijns *et al.* (2010) and Kumar (2012) extend the empirical evidence to Korea, Australia and India, respectively. Moreover, most studies show that the relationship between returns and implied volatility is also asymmetric: a rise (fall) in implied volatility (the equity market) has a stronger opposite effect on equity market returns (implied volatility) than does a decrease (increase) in implied volatility (equity market).[1]

2.2. The relationship among international equity-based implied volatility indices

Some studies provide evidence of the contemporaneous and dynamic correlation among the volatility indices of international equity markets. Thus, Nikkinen and Sahlström (2004b) document a positive contemporaneous relationship among changes in the volatility indices for the US, the UK, Germany and Finland, whereas implied volatility changes in the US and German equity markets lead changes in the other markets. Äijö (2008b) investigates the linkages among the volatility term structures estimated from the VDAX-NEW, VSMI and the Dow Jones EURO STOXX 50 volatility index (VSTOXX) calculated from options expiring in two, six, nine and 18 months. The study reveals not only a strong contemporaneous correlation among the three implied volatility term structures but also that lags in the implied volatility term structure of the German stock market index DAX are useful for explaining the implied volatility term structures of the Swiss and Eurozone stock market indices (SMI and Dow Jones EURO STOXX 50, respectively).

Konstantinidi *et al.* (2008) perform a vector autoregressive (VAR) analysis based on a set of four US (VIX, VXO, VXN and VXD) and three European (VDAX-NEW, VCAC and VSTOXX) volatility indices. They find that the one-day lagged differences in some of the US volatility indices are statistically significant for explaining changes in the European ones, whereas only the French VCAC is statistically significant for explaining movements in the US volatility indices. More recently, Siriopoulos and Fassas (2012) show a leading volatility spillover effect from the German and US equity markets to the developing Greek market.

Finally, Kumar (2012) analyzes volatility transmission among three developed equity markets from three different geographic regions (the US, the UK and Japan) and

[1] The asymmetric relationship has been investigated in the literature treating either the stock index returns (see e.g., González and Novales, 2009; Whaley, 2000) or the relative changes in the volatility index (see e.g., Giot, 2005; Siriopoulos and Fassas, 2012) as the dependent variable.

an emerging market (India). The results based on a VAR model show that past changes in VIX are statistically significant for explaining changes in other volatility indices – VFTSE for the UK, VXJ for Japan and India VIX for India - , and that past changes in VFTSE (VXJ) are statistically significant for explaining changes in VXJ (VIX).

Thus, prior studies provide evidence of implied volatility transmission among European equity markets; among US, European and Asian equity markets; and from developed to developing and emerging equity markets.

2.3. The impact of scheduled news announcements and unexpected events on volatility indices

Several papers document the fall (rise) of volatility indices following scheduled news releases on macroeconomic fundamentals (unexpected events). Put differently, scheduled news announcements lead to resolution of equity market uncertainty, whereas unexpected events contribute to create market uncertainty.[2]

Graham *et al.* (2003) and Nikkinen and Sahlström (2004a) show that the release of the US employment report and Federal Open Market Committee (FOMC) meeting days exert the strongest effect on the volatility index VXO. Carr and Wu (2006), Chen and Clements (2007), Vähämaa and Äijö (2011) and Krieger *et al.* (2012) confirm the significant impact of FOMC meetings on VIX. In a multinational setting, Nikkinen and Sahlström (2004c) find that the US employment report and the FOMC meeting days significantly affect both the German and Finnish volatility indices, whereas domestic news announcements have no effect on these indices. Äijö (2008a) extends the empirical evidence on the significant impact of US macroeconomic news announcements on the implied volatility of the UK stock market index FTSE-100.

In turn, Simon (2003) and Whaley (2009) relate historical jumps in the Nasdaq 100 volatility index (VXN) and VIX, respectively, to important unexpected market and world events. Actually, this is the reason why VIX has been called the “investor fear gauge” (Whaley, 2000). Based on a comprehensive list of unscheduled releases related to finance, political risk and human health, Jiang *et al.* (2012) further confirm the increase in implied volatility for some European volatility indices.

[2] The rationale for this finding is provided in the work by Ederington and Lee (1996).

3. Data

We collect daily closing prices of American-style options on five- and ten-year Treasury notes and 30-year Treasury bond futures, and of the underlying Treasury futures contracts themselves traded at the CBOT. We also collect data on trading volume and open interest for each option contract. The data supplier for futures options is the CME Group, whereas data for the Treasury futures contracts have been obtained from Bloomberg.[3]

The expiry months for futures options are the first three consecutive contract months - two serial and one quarterly expiration - plus the next four (two) months in the March quarterly cycle for options on five- and ten-year Treasury notes (30-year Treasury bond) futures. Unexercised options expire at 8:00 pm ET on the last trading day (i.e., after the market closes trading). Therefore, we measure the remaining days to maturity as the number of calendar days between the trade date and the expiration date.

The sample spans the period May 1990 (January 1986) to February 2012 for the five-year Treasury note (ten-year Treasury note and 30-year Treasury bond) futures and options.[4] To obtain our final data sample, several commonly used data filters are applied. First, to minimize pricing anomalies and avoid liquidity concerns, we discard options with less than a week remaining to maturity as well as options that expire in more than 26 weeks (Whaley, 1986). Second, we only select options that have trading volume (open interest) above zero (100) contracts and have closing prices larger than 3/64 USD.[5] Third, no-arbitrage restrictions are applied. Fourth, we discard a very small subset of options with implied volatilities above 100%, these correspond to deep out-of-the-money (OTM) options (see e.g., Jiang and Tian, 2007; Neumann and Skiadopoulos, 2013). To recover the implied volatility of Treasury futures option prices, we employ the Barone-Adesi and Whaley (1987) analytic approximation for pricing American options.

To calculate the model-free implied variance, daily BBA USD Libor rates are also collected from Bloomberg as a proxy for the risk-free interest rate. Because Libor

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[3] The author thanks the Xfi Centre for Finance and Investment (University of Exeter) for purchasing the data on futures options while I was visiting the University.

[4] To obtain a longer historical time series, we use data from the open outcry trading session. Both futures and options cease trading at 3:00 pm ET, and thus, the chance of non-simultaneity in the prices occurring is minimized.

[5] Options are quoted with a precision of 1/64, with only the exception of the five-year Treasury note futures options whose tick size is one-half of 1/64 since March 2008. Thus, the minimum closing price filter that we apply for the five-year futures options since that date is 1.5/64 instead of 3/64.

rate maturities must coincide with those of options, we either linearly interpolate between the two rates whose terms to maturity are closest (above and below) to the option maturity or simply extrapolate when the option maturity is shorter (longer) than the shortest (longest) available Libor rate term.

Finally, we use an additional set of data to investigate the properties of TBVIXs, namely, five-, ten- and 30-year government yield rates obtained from the US Treasury department; closing prices of four CBOE volatility indices provided by the exchange (the US dollar/euro exchange rate volatility index (EVZ), the gold ETF volatility index (GVZ), the crude oil ETF volatility index (OVX) and VIX); and the dates and release times for six scheduled news announcement items related to the state of the economy retrieved from Bloomberg. Table 1 provides a summary of the announcements.

Table 1. Summary of scheduled news announcements. Entries report the source of the report, the frequency of release and the time at which each announcement was usually released during the period from January 2, 1998, to February 29, 2012.

	Source of report	Frequency	Time of release
CPI (Consumer price index)	Bureau of Labor Statistics	Monthly	8:30 am ET
GDP (Gross domestic product)	Bureau of Economic Analysis	Monthly[a]	8:30 am ET
NFP (Non-farm payrolls)	Bureau of Labor Statistics	Monthly	8:30 am ET
PPI (Producer price index)	Bureau of Labor Statistics	Monthly	8:30 am ET
CCI (Consumer confidence index)	Conference Board	Monthly	10:00 am ET
FOMC (Federal Open Market Committee monetary policy decision)	Federal Reserve	The FOMC holds eight meetings per year	2:15 pm ET

[a] GDP is a quarterly statistic; however, the advance, preliminary and final estimates for the quarter are released in successive months.

4. Calculating the Treasury bond volatility indices

4.1. Construction methodology

We calculate the Treasury bond volatility indices based on the model-free implied variance derived by Britten-Jones and Neuberger (2000):

$$\frac{1}{T}E^{Q}\left[\int_{0}^{T}\left(\frac{dS_t}{S_t}\right)^2\right]=\frac{2}{T}\int_{0}^{\infty}\frac{\exp(rT)C(T,X)-\max(S_0\exp(rT)-X,0)}{X^2}dX\ , \tag{1}$$

where Q denotes the risk-neutral probability measure, $\int_0^T (dS_t/S_t)^2$ is the integrated return variance of the asset over the period [0,*T*], r is the annualized risk-free interest rate, T denotes the time until expiration of the option expressed in annual terms by dividing the remaining (calendar) days to maturity by 365, $C(T,X)$ is the price of a European-style call option with time to maturity T and strike X, S_0 is the current asset price, and $\max(S_0 \exp(rT) - X, 0)$ is the intrinsic value of an option with time to maturity T and strike X.[6]

Next, we discuss some practical implementation issues of the model-free implied variance. First, partitioning the integral in Equation (1) into two segments at $X = S_0 \exp(rT)$ and using the put-call parity, we have:

$$\frac{1}{T} E^Q\left[\int_0^T \left(\frac{dS_t}{S_t}\right)^2\right] = \frac{2}{T}\left[\int_0^{S_0 \exp(rT)} \frac{\exp(rT)P(T,X)}{X^2} dX + \int_{S_0 \exp(rT)}^{\infty} \frac{\exp(rT)C(T,X)}{X^2} dX\right], \quad (2)$$

where $P(T,X)$ is the price of a European-style put option with time to maturity T and strike X. Next, the numerical integration of Equation (2) using the trapezoidal rule yields the following (see e.g., Jiang and Tian, 2007):

$$\frac{1}{T} E^Q\left[\int_0^T \left(\frac{dS_t}{S_t}\right)^2\right] \approx \frac{2\exp(rT)}{T}\left\{\sum_{F_0 \geq X_i} \frac{\Delta X_i}{2}\left[\frac{P(T,X_i)}{X_i^2} + \frac{P(T,X_{i-1})}{X_{i-1}^2}\right] + \sum_{F_0 < X_i} \frac{\Delta X_i}{2}\left[\frac{C(T,X_i)}{X_i^2} + \frac{C(T,X_{i-1})}{X_{i-1}^2}\right]\right\}, \quad (3)$$

where $\Delta X_i = X_i - X_{i-1}$ and F_0 is the current futures price with maturity coinciding with that of the options.[7] We obtain futures prices for each required maturity by interpolating linearly across the adjacent maturities. Note that for the estimation of the model-free implied variance, in-the-money (ITM) options are excluded from the sample because

[6] In reality, the authors derive the formula by assuming zero interest rates. In the presence of nonzero deterministic interest rates, the option and underlying asset prices are viewed as forward prices.

[7] Note that the forward asset price $S_0 \exp(rT)$ is replaced by the price of the underlying futures of options under the assumption of non-stochastic interest rates. This assumption may appear contradictory because the primary factor affecting the volatility of Treasury futures prices is interest rate uncertainty. However, this assumption concerns the short risk-free interest rate and not directly the interest rate underlying medium- and long-term Treasury securities.

they are less liquid than at-the-money (ATM) or OTM options (see e.g., Jones *et al.*, 1998).

The implementation of Equation (3) must overcome two problems. The first problem is derived from the requirement for European option prices, whereas the Treasury futures options are American-style. The second obstacle is the limited availability of strike prices over which option prices are quoted.

To address the first issue, we extract European option prices from Treasury futures option prices using the Barone-Adesi and Whaley (1987) analytic approximation for pricing American options (see e.g., Bedendo and Hodges, 2009). According to Tian (2011), this method provides very accurate estimates for European option prices with the use of OTM options.

With respect to the second obstacle, following Neumann and Skiadopoulos (2013), we interpolate across available implied volatilities as a function of delta using cubic splines or simply extrapolate to fill in a delta grid of 1,000 points ranging from 0.01 to 0.99.[8,9] Thus, we first convert available European option prices to implied volatilities and strikes to deltas using Black's model (Black, 1976b). For the calculation of deltas, we use ATM implied volatilities to avoid altering the ordering of the strikes. We apply some filters based on deltas. To ensure that options are adequately OTM, we exclude those maturities for which there are no call (put) options with deltas below (above) 0.25 (0.75). However, we discard call (put) options with deltas below (above) 0.01 (0.99) because these are considered deep OTM options. In addition, before applying interpolation and extrapolation techniques, we also ensure that we have at least two call and two put options. Then, we interpolate across implied volatilities inside the available delta range and extrapolate using the endpoint implied volatility beyond the available delta range.

Finally, we use Black's model again (Black, 1976b) to translate the delta grid and the derived implied volatilities into strikes and option prices, respectively. We then calculate the model-free implied variance as in Equation (3) from the prices of five- and ten-year Treasury notes and 30-year Treasury bond futures options along the sample. At the final stage, we compute TBVIX with a fixed 30-day maturity as follows:

[8] The advantage of interpolating in the implied volatility-delta space rather than in the option price-strike space is that implied volatilities of far OTM options are grouped more closely together than those of near-the-money options. This allows a better fit near the center of the distribution where options are more frequently traded (see e.g., Bliss and Panigirtzoglou, 2002).

[9] For notional simplicity, we express all deltas in terms of call option deltas, between zero and one.

$$TBVIX = 100 \times \sqrt{\left\{ T_1 MFIV(T_1) \left[\frac{N_{T_2} - 30}{N_{T_2} - N_{T_1}} \right] + T_2 MFIV(T_2) \left[\frac{30 - N_{T_1}}{N_{T_2} - N_{T_1}} \right] \right\} \times \frac{365}{30}}, \qquad (4)$$

where *TBVIX* is the Treasury bond volatility index (expressed in annualized percentage terms) with a fixed maturity of 30 calendar days, T_1 (T_2) is the time to expiration of the near-term (the next-term) options with N_{T_1} (N_{T_2}) calendar days to maturity, $T_1 = N_{T_1}/365$ and $T_2 = N_{T_2}/365$ ($N_{T_2} > 30 > N_{T_1}$), and $MFIV(T_1)$ ($MFIV(T_2)$) denotes the model-free implied variance computed from options with time to maturity T_1 (T_2).[10] When the shortest (longest) term to maturity of *MFIV* is more (less) than 30 days, we simply extrapolate to obtain the value of the Treasury bond volatility index.

Thus, the derived volatility indices measure the risk-neutral expected volatility of five- and ten-year Treasury notes and 30-year Treasury bond futures over the remaining 30 days (i.e., they capture short-term market expectations of volatility of medium- and long-term government security futures prices).

4.2. The CBOE's calculation of the ten-year Treasury note volatility index

The CBOE calculates the ten-year Treasury note volatility index, called VXTYN, by applying the VIX methodology to the market prices of options on ten-year Treasury note futures. In particular, the formula employed by the CBOE for the calculation of the model-free implied variance, $MFIV_{CBOE}$, is:

$$MFIV_{CBOE} = \frac{1}{T}\left[2\exp(rT)\sum_{X_i} \frac{\Delta X_i}{X_i^2} Price(T, X_i) - \left(\frac{F_0}{X_{ATM}} - 1 \right)^2 \right], \qquad (5)$$

where $Price(T, X_i)$ denotes the market price of an OTM or ATM European-style option with time to maturity T and strike X_i, X_{ATM} is the first strike below the forward price F_0 ($X_{ATM} \leq F_0$), and the rest of variables are defined as before. Then, VXTYN is obtained through linear interpolation of $MFIV_{CBOE}$ with maturities that are closest (above and below) to the required 30-day maturity.[11]

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[10] 30 days is the horizon over which most volatility indices are calculated.
[11] See the CBOE website (http://www.cboe.com/micro/volatility/VXTYN/default.aspx) for further details on the calculation of VXTYN.

Jiang and Tian (2007) provide a full description of the procedure applied by the CBOE to approximate the model-free implied variance by Equation (5). More interestingly, Jiang and Tian (2007) highlight several types of approximation errors in the formula used by the CBOE to estimate the model-free implied variance. One type of approximation error is derived from the numerical integration scheme applied by the exchange to approximate the integral in Equation (2) as follows:

$$\int_{0}^{S_0 \exp(rT)} \frac{P(T,X)}{X^2} dX + \int_{S_0 \exp(rT)}^{\infty} \frac{C(T,X)}{X^2} dX \approx \sum_{X_i} \frac{\Delta X_i}{X_i^2} \text{Price}(T, X_i), \qquad (6)$$

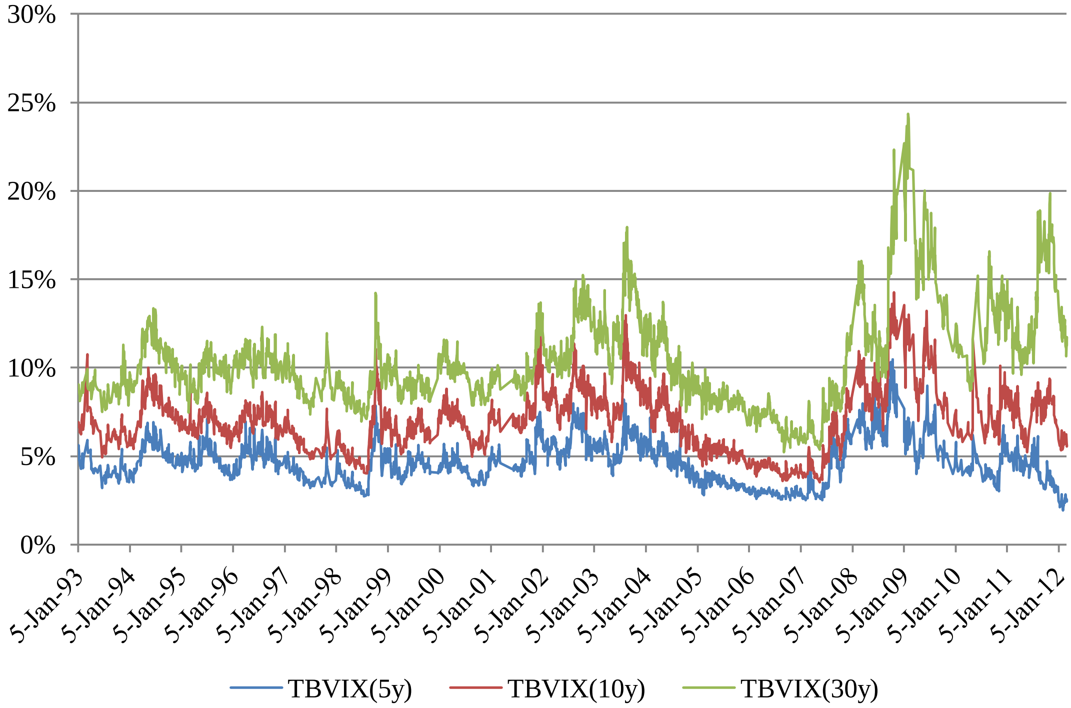
where the infinite range of strikes (from zero to infinity) is replaced by a finite range that spans from the lowest to the highest listed strikes for a given maturity. Another type of approximation error is due to the fact that the CBOE calculates the model-free implied variance using only market prices of options at listed strikes. Therefore, in this paper, we calculate the model-free implied variance in Equation (2) using trapezoidal integration as suggested by Jiang and Tian (2007), and we use interpolation and extrapolation techniques to obtain a wider range of strikes and option prices. Additionally, the CBOE treats the American-style options (i.e., Treasury futures options) as European based on the assumption that the early exercise premium of OTM options with short term to maturity is likely to be small. In this respect, following Tian (2011), we first extract European option prices from American option prices and then we calculate the model-free implied variance using the extracted European option prices.

4.3. Statistical properties

Figure 1 shows the daily evolution of the three volatility indices constructed using the five-, ten-, and 30-year Treasury futures options prices, which we denote as TBVIX(5y), TBVIX(10y) and TBVIX(30y), respectively, over the period from January 5, 1993, to February 29, 2012.[12]

[12] Although the common sample for data on the three types of options begins in May 1990, the five-year futures options are less liquid than ten- and 30-year options and, in particular, the number of observations per year for TBVIX(5y) before 1993 is below 70.

Figure 1. Daily levels of Treasury bond volatility indices constructed from five-, ten-, and 30-year Treasury futures options prices over the period from January 5, 1993, to February 29, 2012.



We can see that implied volatility is an increasing function of the maturity of the underlying government security. This is in line with the findings of Jones *et al.* (1998), based on the realized volatility of the daily excess returns of five-, ten- and 30-year Treasury securities. It is also consistent with the notion that longer maturity bond prices are more volatile because duration increases with maturity. The patterns of the three volatility indices look alike over the whole sample. Based on Table 2, the strongest correlation is reported for TBVIX(5y) and TBVIX(10y) both in levels (0.90) and daily logarithmic differences (0.55). Additionally, we report the cross-correlations among TBVIXs and the CBOE's ten-year Treasury note volatility index, VXTYN, over the period from January 28, 2008 to February 29, 2012. We obtain that TBVIX(10y) and VXTYN are highly correlated in levels (0.97), whereas the correlation coefficient for the volatility indices in daily logarithmic differences is 0.34. The relatively low correlation between the daily changes in TBVIX(10y) and VXTYN points out that the two volatility indices are not only different in terms of their construction but also in terms of their behavior.

We report the summary statistics of the implied volatility indices in the levels and first logarithmic differences in Table 2 (Panels A and B, respectively). The results show that, in addition to the mean, the standard deviation of the implied volatility of longer-term government securities is also higher. The first-order autocorrelation, the Jarque-Bera and the augmented Dickey-Fuller (ADF) test values, are also provided. We find that the three indices exhibit statistically significant autocorrelation both in the levels (positive) and first logarithmic differences (negative) and that they display positive skewness and excess kurtosis (i.e., they are not normally distributed). The Jarque-Bera test confirms this result. Similar findings for numerous equity-based volatility indices are documented in Jiang *et al.* (2012). Based on the ADF test, the unit root null hypothesis is rejected for the three indices both in levels and in first logarithmic differences.

Table 2. Summary statistics of the Treasury bond volatility indices. The Jarque-Bera and the augmented Dickey-Fuller (ADF) test values, the first-order autocorrelation ρ_1 and the cross-correlations among TBVIXs, as well as among TBVIXs and the CBOE's ten year Treasury note volatility index, VXTYN, over the period from January 28, 2008 to February 29, 2012, are also provided. The sample spans the period from January 5, 1993, to February 29, 2012.

	TBVIX(5y)	TBVIX(10y)	TBVIX(30y)
Panel A: Summary statistics for the levels of the volatility indices (percentages)			
Observations	3,130	3,130	3,130
Mean	4.73	7.01	10.39
Median	4.64	6.95	9.92
Maximum	10.46	14.24	24.36
Minimum	1.93	3.51	5.22
Std. deviation	1.23	1.72	2.62
Skewness	0.60	0.59	1.30
Kurtosis	3.72	3.74	5.84
Jarque-Bera	260.24**	257.22**	1,948.70**
ρ_1	0.95**	0.96**	0.97**
ADF	-4.87**	-4.75**	-4.15**
Cross correlation			
TBVIX(5y)	1		
TBVIX(10y)	0.90**	1	
TBVIX(30y)	0.68**	0.86**	1
VXTYN	0.83**	0.97**	0.79**
Panel B: Summary statistics for the first logarithmic differences of the volatility indices (in percentage terms)			
Observations	3,129	3,129	3,129
Mean	-0.02	-0.00	0.00
Median	-0.08	-0.14	-0.18
Maximum	41.29	58.76	37.70
Minimum	-37.98	-37.29	-26.28
Std. deviation	7.19	6.10	5.26
Skewness	0.0276	0.32	0.34
Kurtosis	6.0786	9.60	6.29
Jarque-Bera	1,236.08**	5,747.04**	1,480.26**
ρ_1	-0.21**	-0.22**	-0.16**
ADF	-31.92**	-35.44**	-28.71**
Cross correlation			
TBVIX(5y)	1		
TBVIX(10y)	0.55**	1	
TBVIX(30y)	0.49**	0.45**	1
VXTYN	0.42**	0.34**	0.26**

The null hypothesis of the Jarque-Bera test, the ADF test, the first-order autocorrelation and the cross-correlation is that the series is normally distributed, that the series has a unit root, that the first-order autocorrelation is zero and that the cross-correlation is zero, respectively. Two asterisks denote rejection of the null hypothesis at the 1% significance level.

5. The relationship of Treasury bond volatility indices and yield rates

We begin our analysis by investigating the contemporaneous relationship between changes in TBVIXs and Treasury yield rates for the respective times to maturity (i.e., five, ten and 30 years). To that end, we estimate the following regression equation using ordinary least squares, where we allow for asymmetries in the relationship:

$$\ln(TBVIX_t / TBVIX_{t-1}) = \alpha_0 + \alpha_1 \Delta yield_t + \alpha_2 D^+ \Delta yield_t + u_t \text{ , (7)}$$

where $\Delta yield_t$ denotes the daily change in the yield rate and the dummy variable D^+ characterizes days when the change in the yield rate is positive (i.e., $D^+ =1$ if $\Delta yield_t$ > 0, $D^+ = 0$ otherwise). The sample for TBVIX(5y) and the 5-year Treasury yield rates runs from January 5, 1993, to February 29, 2012, whereas data for ten- and 30-year TBVIXs and Treasury yield rates span the period from January 2, 1990, to February 29, 2012.

Table 3 displays the regression results. We find that only the regression coefficient for $\Delta yield_t$ is statistically significant at the 1% level in all cases. Therefore, there is no evidence of asymmetry. Moreover, the results suggest that the relationship between government yield rates and TBVIXs is positive. In particular, the estimated relative changes in TBVIXs associated with a 1% (100 basis points) change in Treasury yield rates are around 0.15%, with a sign similar to that of the yield rate change. This finding is in line with theory based on the Cox, Ingersoll and Ross (CIR) model (Cox *et al.*, 1985) about the dynamics of interest rates and bond prices. In particular, from the dynamics of bond prices in the CIR model, it follows that the volatility of bond returns increases when interest rates increase. In addition, we can also explain the positive relationship between changes in yield rates and the volatility of government security prices using the same risk perception argument employed for the equity market. Thus, a rise in the general perception of risk due to the arrival of news in the market may induce the sale of Treasury fixed-income securities, thereby decreasing their price and thus increasing their yield to maturity. At the same time, a rise in uncertainty may lead to the purchase of put options on Treasury securities as a hedge tool, which makes the market prices of options and, therefore, implied volatility increase.

Table 3. Estimates of the parameters for the asymmetric model.

	TBVIX(5y)	TBVIX(10y)	TBVIX(30y)
α_0	0.000 (0.00)	0.000 (0.00)	0.000 (0.00)
α_1	0.135** (0.03)	0.154** (0.02)	0.154** (0.02)
α_2	-0.072 (0.05)	-0.042 (0.03)	-0.029 (0.03)
Observations	3,251	5,210	5,512
Adjusted R^2	0.013	0.025	0.025

This table shows the regression coefficients for the following regression: $\ln(TBVIX_t / TBVIX_{t-1}) = \alpha_0 + \alpha_1 \Delta yield_t + \alpha_2 D^+ \Delta yield_t + u_t$. Newey and West's (1987) heteroskedasticity and autocorrelation consistent standard errors are provided in parentheses. Two asterisks denote statistical significance at the 1% significance level. The model is estimated over the period from January 5, 1993 (January 2, 1990) to February 29, 2012, for the five-year (ten- and 30-year) terms to maturity.

The documented positive correlation between changes in yield rates and TBVIXs, along with the negative yield-price relationship of government securities, has implications for the management of fixed-income portfolios. On the one hand, this correlation may affect the effectiveness of delta hedging strategies involving options on government debt securities. Thus, as yield rates rise (i.e., a fall in the price of Treasury securities), put options become more valuable, whereas call options become less valuable. However, the consequent increase in the implied volatility of Treasury securities because of yield rates rising would increase the price of both call and put options. Therefore, delta hedging would not be adequate because put (call) options prices would increase (decrease) more (less) than expected against changes in government security prices. Analogous reasoning can be applied to the case in which yield rates fall. On the other hand, this correlation suggests that investors can benefit from adding a long position in Treasury bond implied volatility futures and/or options to their fixed-income portfolios as diversification or hedging tools (see Chen *et al.*, 2011 for evidence in the equity market based on VIX futures and options; Moran and Dash, 2007; Szado, 2009).

6. The relationship of Treasury bond volatility indices with other volatility indices

In this section, we investigate the contemporaneous and dynamic relationship among six volatility indices: TBVIX(10y), TBVIX(30y), EVZ (US dollar/euro exchange rate volatility index), GVZ (Gold ETF volatility index), OVX (Crude oil ETF volatility index) and VIX (S&P 500 volatility index).[13] Due to data availability, the sample encompasses the date range June 3, 2008, to February 29, 2012.

In the first stage, we need to identify the time at which closing prices of volatility indices are measured. Thus, the closing prices of ETF options used to calculate EVZ, GVZ and OVX are measured at 4:00 pm ET, whereas S&P 500 options cease trading at 4:15 pm ET.[14] Because Treasury futures options stop trading at 3:00 pm ET, changes in the set of volatility indices that we use can be considered almost contemporaneous.

Table 4 reports the contemporaneous cross-correlation coefficients among the daily changes in the logarithm of TBVIX(10y), TBVIX(30y), EVZ, GVZ, OVX and VIX. The results show that there is a positive and statistically significant relationship between changes in TBVIXs and the rest of the volatility indices. Moreover, both TBVIX(10y) and TBVIX(30y) are equally correlated with the four volatility indices considered in this study (the correlation coefficients are approximately 10%). We can also see that the correlation of the equity market volatility index VIX with the foreign exchange and both commodity-based volatility indices is stronger than in the case of the fixed-income volatility indices. This suggests that there is more common information (i.e., news about economic fundamentals and unexpected events) that simultaneously affects uncertainty about the future development of the equity, foreign exchange, gold and oil markets than information that simultaneously affects the perception of uncertainty in the Treasury, foreign exchange, gold and oil markets. Put differently, linkages among the equity (Treasury), foreign exchange and commodity markets with respect to uncertainty are closer (weaker).

[13] TBVIX(5y) has not been included to avoid reducing the number of available observations for the entire set of volatility indices due to the lower liquidity of five-year Treasury note futures options.
[14] See the CBOE website.

Table 4. Cross-correlation coefficients among the daily changes in the logarithm of TBVIX(10y), TBVIX(30y), EVZ, GVZ, OVX and VIX over the period from June 3, 2008, to February 29, 2012 (911 observations).

	Δ *ln* TBVIX(10y)	Δ *ln* TBVIX(30y)	Δ *ln* EVZ	Δ *ln* GVZ	Δ *ln* OVX	Δ *ln* VIX
Δ *ln* TBVIX(10y)	1	0.27**	0.12**	0.13**	0.10**	0.13**
Δ *ln* TBVIX(30y)		1	0.10**	0.11**	0.10**	0.11**
Δ *ln* EVZ			1	0.34**	0.16**	0.36**
Δ *ln* GVZ				1	0.27**	0.41**
Δ *ln* OVX					1	0.48**
Δ *ln* VIX						1

Δ *ln* denotes the first logarithmic difference. Two asterisks denote statistical significance at the 1% significance level.

We further investigate whether the results are robust to the recent financial crisis period (from June 3, 2008, to June 30, 2009) and the post-crisis period (from July 1, 2009, to February 29, 2012).[15] We find that TBVIXs and the rest of the volatility indices are more closely correlated during the post-crisis period than during the crisis period, during which only the correlation coefficient for TBVIX(30y) and GVZ remains statistically significant. Thus, the connection among investors' short-term perception of uncertainty in the Treasury, foreign exchange, commodity and equity markets is not driven by the crisis.[16]

The positive correlation among the considered volatility indices also has implications for portfolio management. In particular, it may reduce the benefits of portfolio diversification with volatility products: the CBOE Futures Exchange currently offers futures on the 10-year Treasury note volatility index, GVZ, OVX and VIX.

Next, we investigate the presence of lead-lag relationships among the volatility indices. Thus, we perform Granger causality tests based on a VAR(3) model:

$$\Delta \ln VOL_t = \alpha + \sum_{l=1}^{3} \gamma_l \Delta \ln VOL_{t-l} + u_t, \quad (8)$$

[15] According to the National Bureau of Economic Research (NBER), June 2009 marks the end of the recessionary period.
[16] Results can be obtained from the authors upon request.

where $\Delta \ln VOL_t = \ln(VOL_t / VOL_{t-1})$ is a (6 x 1) vector of daily logarithmic changes in TBVIX(10y), TBVIX(30y), EVZ, GVZ, OVX and VIX, α is a 6 x 1 vector of intercepts, γ_l is a 6 x 6 matrix with γ_{ijl} being the coefficient of the *l*-day lagged *j*th volatility index used to explain changes in the *i*th volatility index, and u_t is a 6 x 1 vector of residuals. The lag length of the VAR is determined using the Akaike information criteria along with the Lagrange multiplier test for residual serial correlation. The null hypothesis of the Granger causality test is that the γ_{ijl} in Equation (8) are jointly zero.

The results of the Granger causality tests are provided in Table 5. We find that Granger causality between TBVIX(10y) and VIX significantly runs in both directions and that changes in TBVIX(30y) are also led by changes in VIX at a 1% significance level. However, there is no evidence of implied volatility spillovers between the Treasury market and the foreign exchange and commodity markets. Thus, this study's findings suggest that VIX changes could be applied to improve forecasts of the changes in TBVIXs (and vice versa), thereby providing valuable information for volatility risk management purposes in the equity and Treasury markets.

Table 5. Results of the Granger causality test for TBVIX(10y), TBVIX(30y), EVZ, GVZ, OVX and VIX based on a VAR(3) model.

Null hypothesis	
Δ *ln* GVZ does not Granger cause Δ *ln* EVZ	0.43
Δ *ln* OVX does not Granger cause Δ *ln* EVZ	6.46
Δ *ln* TBVIX(10y) does not Granger cause Δ *ln* EVZ	0.25
Δ *ln* TBVIX(30y) does not Granger cause Δ *ln* EVZ	2.66
Δ *ln* VIX does not Granger cause Δ *ln* EVZ	8.67*
Δ *ln* EVZ does not Granger cause Δ *ln* GVZ	2.23
Δ *ln* OVX does not Granger cause Δ *ln* GVZ	2.70
Δ *ln* TBVIX(10y) does not Granger cause Δ *ln* GVZ	5.65
Δ *ln* TBVIX(30y) does not Granger cause Δ *ln* GVZ	5.63
Δ *ln* VIX does not Granger cause Δ *ln* GVZ	5.44
Δ *ln* EVZ does not Granger cause Δ *ln* OVX	8.44*
Δ *ln* GVZ does not Granger cause Δ *ln* OVX	4.23
Δ *ln* TBVIX(10y) does not Granger cause Δ *ln* OVX	1.72
Δ *ln* TBVIX(30y) does not Granger cause Δ *ln* OVX	0.08
Δ *ln* VIX does not Granger cause Δ *ln* OVX	13.78**
Δ *ln* EVZ does not Granger cause Δ *ln* TBVIX(10Y)	1.80
Δ *ln* GVZ does not Granger cause Δ *ln* TBVIX(10Y)	2.34
Δ *ln* OVX does not Granger cause Δ *ln* TBVIX(10Y)	1.67
Δ *ln* TBVIX(30y) does not Granger cause Δ *ln* TBVIX(10Y)	15.49**
Δ *ln* VIX does not Granger cause Δ *ln* TBVIX(10Y)	17.94**
Δ *ln* EVZ does not Granger cause Δ *ln* TBVIX(30Y)	1.80
Δ *ln* GVZ does not Granger cause Δ *ln* TBVIX(30Y)	3.04
Δ *ln* OVX does not Granger cause Δ *ln* TBVIX(30Y)	6.09
Δ *ln* TBVIX(10y) does not Granger cause Δ *ln* TBVIX(30Y)	50.51**
Δ *ln* VIX does not Granger cause Δ *ln* TBVIX(30Y)	27.84**
Δ *ln* EVZ does not Granger cause Δ *ln* VIX	2.32
Δ *ln* GVZ does not Granger cause Δ *ln* VIX	0.65
Δ *ln* OVX does not Granger cause Δ *ln* VIX	5.88
Δ *ln* TBVIX(10y) does not Granger cause Δ *ln* VIX	8.01*
Δ *ln* TBVIX(30y) does not Granger cause Δ *ln* VIX	0.89

Δ *ln* denotes the first logarithmic difference. One and two asterisks denote rejection of the null hypothesis at the 5% and 1% significance level, respectively. The VAR(3) model is estimated over the period from June 3, 2008, to February 29, 2012.

7. The effect of scheduled macroeconomic news announcements and unexpected events on Treasury market uncertainty

First, we analyze the effect that scheduled news announcements regarding the state of the economy have on the daily logarithmic changes of TBVIXs. In particular, for announcements occurring before 3:00 pm ET on day *t*, we use the logarithmic change in TBVIX from the previous business day to that day, whereas for announcements released after 3:00 pm ET on day *t*, we employ the logarithmic change in TBVIX from that day to the next business day.

To examine the significance and relative importance of the different news announcements listed in Table 1, we estimate the following regression equation:

$$\ln(TBVIX_t / TBVIX_{t-1}) = \alpha + \sum_{k=1}^{K} \beta_k D_{kt} + u_t , \quad (9)$$

where the dummy variable D_{kt} equals one if announcement k is made on day t and zero otherwise and $K = 6$.

The regression results based on Equation (9) are reported in Table 6. Similar to the evidence reported for equity-based volatility indices, the coefficients of the statistically significant dummy variables for the news release days are negative in all cases. We find that the dummies for the CPI, GDP and non-farm payrolls (NFP) reports, along with the dummy for the FOMC meeting days, consistently affect the three volatility indices. PPI announcement days are also statistically significant for explaining changes in TBVIX(30y). As for the positive and statistically significant sign of the intercept in the three equations, Ederington and Lee (1996) hypothesize that implied volatility will tend to increase on days with no scheduled announcements. Adjusted R^2 values for the three regressions are approximately 8%.

In line with findings for the equity market (see e.g., Graham *et al.,* 2003; Nikkinen and Sahlström, 2004a), this study's results show that the employment announcement has the most pronounced effect on Treasury market implied volatility.[17] The significant fall of Treasury bond implied volatility indices following the employment release can encourage the design of trading strategies that involve volatility futures (see e.g., Krieger *et al.*, 2012). Thus, one might design a profitable strategy by shorting a futures contract on the recently introduced CBOE 10-year Treasury note volatility index.

[17] This should come as no surprise because employment is the first (government) announcement of the month, and therefore, it is part of the information content of subsequent announcements and has already been reflected in option prices.

Table 6. Impact of scheduled news announcements on TBVIXs.

Announcement (k)	TBVIX(5y) β_k	TBVIX(10y) β_k	TBVIX(30y) β_k
Panel A: US news announcements			
Intercept	0.442**	0.359**	0.366**
	(0.162)	(0.113)	(0.083)
CPI	-2.115**	-1.194*	-1.111**
	(0.796)	(0.522)	(0.406)
GDP	-2.648**	-1.371**	-1.431**
	(0.646)	(0.429)	(0.339)
NFP	-5.045**	-4.024**	-4.489**
	(0.892)	(0.501)	(0.445)
PPI	-0.119	-0.289	-1.100**
	(0.798)	(0.442)	(0.340)
CCI	1.331	-0.391	-0.302
	(0.717)	(0.458)	(0.350)
FOMC	-1.828*	-3.367**	-1.532**
	(0.847)	(0.444)	(0.482)
u_{t-1}	-20.717**	-22.425**	-18.959**
	(2.843)	(2.392)	(2.347)
Adjusted R^2	0.084	0.085	0.080

This table shows the regression coefficients for the following regression (x 10^2): $\ln(TBVIX_t / TBVIX_{t-1}) = \alpha + \sum_{k=1}^{K} \beta_k D_{kt} + u_t$. The Ljung and Box statistic indicates the presence of significant first-order autocorrelation in the residuals, and thus, an AR(1) term is added to the regressions. Newey and West's (1987) heteroskedasticity and autocorrelation consistent standard errors are provided inside parentheses. One and two asterisks denote statistical significance at the 5% and 1% significance level, respectively. The model is estimated over the period from January 2, 1998, to February 29, 2012.

Next, we investigate whether abnormal levels of TBVIX(10y) and TBVIX(30y) can be related to unexpected market or world events. To that end, Table 7 displays percentiles of TBVIXs over the period from January 2, 1986, to February 29, 2012. We characterize a behavior as normal if the probability of observing such behavior is below 90% (90th percentile). Thus, TBVIX(10y) levels above 9.46% and TBVIX(30y) levels above 15.22% are characterized as abnormal. Based on these data, we attempt to identify periods over which TBVIXs have remained above such levels. We find that Treasury bond implied volatility is extraordinarily high coinciding with some stock market crashes (from October 1987 to January 1988, and August 2002, only for TBVIX(10y)), as well as following the downgrade of US debt (from August to November 2011, only for TBVIX(30y)) and during the recent financial crisis (from September 2008 to August 2009).

Table 7. Percentiles of TBVIX(10y) and TBVIX(30y) from January 2, 1986, to February 29, 2012.

	Observations	5%	10%	25%	50%	75%	90%	95%
TBVIX(10y)	6,066	4.42	5.01	6.04	7.08	8.13	9.46	10.56
TBVIX(30y)	6,537	7.26	7.96	8.88	10.10	12.12	15.22	17.15

Thus, this study's overall results show that scheduled macroeconomic news announcements reduce short-term market uncertainty in the Treasury market, whereas remarkable stock market downturns and financial turmoil increase investors' perception of uncertainty about the development of government security prices.

8. Conclusions

This study offers a thorough investigation of the properties of US Treasury bond volatility indices (TBVIXs) and their implications for portfolio management. To that end, we calculate three different implied volatility indices using the market prices of exchange-traded futures options on five- and ten-year Treasury notes and 30-year Treasury bonds over a sample of more than 20 years. We construct TBVIXs in a model-free way (i.e., in the style of equity-based volatility indices such as VIX) based on the concept of the model-free implied variance. To calculate the model-free implied variance, we address two implementation issues. First, the model-free implied variance requires using European option prices, whereas Treasury futures options are American-style. Thus, we employ the Barone-Adesi and Whaley (1987) model to extract European option prices from American option prices. The second obstacle relates to the requirement for option prices over an infinite range of strikes. We address this issue by using interpolation and extrapolation techniques.

Based on TBVIXs, we analyze whether widely investigated properties of equity-based volatility indices (i.e., their relationship with the underlying assets; the contemporaneous and dynamic relationship between international equity market volatility indices; and their response to scheduled news announcements on economic fundamentals and unexpected events) apply to fixed-income volatility indices. Thus, we find a statistically significant positive relationship between changes in the yield rates of underlying government securities and TBVIXs. The results are consistent for the three Treasury security maturities. Moreover, our analysis shows no evidence of asymmetry in the relationship. With respect to the interaction of TBVIXs with other volatility indices, we show that contemporaneous changes in TBVIXs and four CBOE volatility indices based on different asset classes (i.e., US dollar/euro exchange rate; gold and oil prices; S&P 500) are positively correlated. In addition, the results from the VAR analysis reveal that past changes in TBVIXs contain statistically significant information for explaining current changes in VIX (and vice versa). With respect to the effect of scheduled news announcements on TBVIXs, we find that the three volatility indices systematically fall following news releases, with the strongest effect reported for the employment announcement. In turn, unexpected market events such as remarkable stock market downturns and the current financial crisis contribute to create uncertainty in the Treasury market.

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