An Analysis of Connectedness Dynamics between Risk-Neutral Equity and Treasury Volatilities

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Abstract

Macro-finance asset pricing models provide a rationale for connectedness dynamics between equity (VIX) and Treasury (MOVE) risk-neutral volatilities. In this paper, we study the total and directional connectedness, in the sense of spillovers effects, between risk-neutral volatilities from the equity and Treasury markets. In addition, we analyze the economic and monetary drivers of connectedness. Most of the time, but especially during bad economic times, we find significant net spillovers from Treasury to equity risk-neutral volatility. MOVE is a net sender of volatility to VIX. More precisely, the spillovers from MOVE to VIX increase significantly with higher financial uncertainty, risk aversion and credit risk.

Keywords: risk-neutral equity volatility; risk-neutral treasury volatility; total connectedness; directional connectedness; real and monetary economic drivers.

JEL classification: C32, E32, G12, G13

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1. Introduction

Macro-finance asset pricing models advocate that macroeconomic factors contribute to explaining the risk premia and volatility of both equity and Treasury bond returns. For example, if we employ the Epstein and Zin (1989, 1990) preferences, it is well known that the stochastic discount factor presents innovations in consumption, but also innovations in expected future consumption growth. Depending upon the level of risk aversion relative to the inverse of the elasticity of intertemporal substitution, the model generates negative (positive) bond risk premia because bonds do poorly (badly) in times of higher expected consumption growth. This procyclical or countercyclical behavior of risk premia also affects the volatility of risk-free interest rates. Under the habit formation model of Campbell and Cochrane (1999) and the extensions of Wachter (2006), and Verdelhan (2010), we have a similar mechanism through time-varying risk aversion and the tension between the intertemporal substitution term, associated with the behavior of surplus consumption, and the precautionary component of the risk-free interest rate. Depending on these two terms, the volatility of risk-free rates is different, and the interest rate is either procyclical (with a negative bond risk premia) or countercyclical (with a positive risk premia).[1] Overall, macro-finance models employ aggregate consumption growth and a (non-separable) recession related variable that accounts for most of the equity and bond risk premia, generate time-varying risk premia, and equity and interest rate volatility.[2]

[1] In the original paper of Campbell and Cochrane (1999), the parameters of the model and the sensitivity of surplus consumption to shocks in consumption are chosen so that the two effects exactly cancel, and the risk-free rate is constant. Wachter (2006) extends the model allowing for volatile interest rates and pro- or countercyclical bond risk premia.

[2] Both, Bansal, Kiku, and Yaron (2012), who incorporate persistent variation in the volatility of the consumption growth stochastic process of Bansal and Yaron (2004), and Watcher (2013), who employ time-varying probability of rare disasters, generate negative bond risk premia and interest rate volatility dominated by precautionary savings. Corradi, Distaso, and Mele (2013) analyze the macroeconomic factors that determine equity volatility, Ludvigson and Ng (2009) show that real and inflation macro factors predict

Motivated by the macro-finance literature, our key hypothesis is that risk-neutral volatilities of equity and Treasury bond returns are connected in the sense of existing spillover effects across the macroeconomic fears embedded in the equity and Treasury markets. It is particularly important to analyze risk-neutral volatilities rather than volatilities under the physical volatilities given that our hypothetical connection is generated by similar macro risk factors throughout the business cycle. To allow for volatilities under risk-neutral probabilities, that adjust for risk giving more weighting to bad states relative to good states, is consistent with the key role playing by macro risk factors in the true unobservable stochastic discount factor, which prices both equity and Treasury returns.

Established the foundations for connectedness between risk-neutral equity and Treasury volatilities, the main goal of this paper is to study the total and directional connectedness between them. Once again, connectedness in the sense of spillover effects between both implied volatilities. This is an empirical question. More precisely, by connectedness we mean the variance of the forecast error of a variable X_i that is due to a shock in another variable X_j. Consequently, our analysis employs the framework proposed by Diebold and Yilmaz (2014), which we think is especially convenient in our context. The idea is to understand how information is transmitted between these two implied volatilities given an economic, monetary or geopolitical shock.

To the best of our knowledge, this is the first evidence regarding the spillover effects between the risk-neutral volatilities of equity and Treasury markets, which we

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bond risk premia beyond forward rates, Ulrich (2012) document that economic uncertainty and central bank policies account for almost half of the variation of bond implied volatilities, and Bekaert, Engstrom, and Ermolov (2018) show that macro risk factors contribute to the variation of yields, risk premia and bond returns. See Cochrane (2017) for a review of macro-finance asset pricing models.

argue has relevant implications for risk management, monetary policy and financial stability.

The VIX Index is the risk-neutral, one-month expected stock market volatility for the S&P 500 Index. It is computed by averaging the weighted prices of puts and calls on the S&P 500 Index over a wide range of strike prices. It has become an extremely popular and useful measure of near-term market volatility. It is surprising that the large extant literature on implied volatility focuses almost exclusively on equity markets. Notable exceptions are Choi, Mueller, and Vedolin (2017) and Mueller, Sabtchevsky, Vedolin, and Whelan (2016), who analyze the market variance risk premium in both equity and Treasury markets, and Mele, Obayashi, and Shalen (2015), who study the information contained in VIX and the interest rate swap rate volatility index known as SRVX. However, none of these papers discuss how and why risk-neutral volatilities from the equity and Treasury markets are connected in the sense of spillover effects between them. It is true, however, that the traditional affine term structure literature implies that a portfolio of Treasury bonds spans interest rate volatility risk. This is the case because the quadratic variation of bond yields at a given maturity is a linear combination of the yields at different maturities. However, Andersen and Benzoni (2010), using high-frequency data, show that the interest rate volatility risk cannot be extracted from the cross-section of Treasury yields and, therefore, it is not spanned by a portfolio of bonds. This suggests that volatility risk dynamics is a relevant element for financial and monetary economics. This finding also highlights the importance of studying the relative dynamics of risk-neutral equity and Treasury volatility risks.

Indeed, the main contribution of this paper is to partially fill this gap by analyzing whether the risk-neutral equity and Treasury volatilities are connected and how the Great Recession and other financial and economic crises affect the directional and net connectedness between them. Specifically, how do economic conditions, risk aversion, and overall uncertainty affect the relative spillover effects of equity and Treasury bond risk-neutral volatilities? What are the relative effects of monetary and real economic activity on the directional connectedness of these volatilities?

We use the Merrill Lynch Option Volatility Estimate Index (MOVE), as Treasury implied volatility. This is a term structure weighted index of the normalized implied volatility on one-month Treasury options weighted on 2-, 5-, 10-, and 30-year contracts. It is therefore the equivalent of the VIX for Treasury bond returns and reflects a market-based measure of uncertainty about the composite future behavior of interest rates across different maturities of the yield curve. Current increases in MOVE suggests that the market is willing to pay more to hedge against unexpected movement in interest rates.

Overall, the total connectedness between the two risk-neutral volatilities is 28.8%. The directional connectedness from MOVE to VIX is on average significantly higher than from VIX to MOVE, but economic and geopolitical events significantly affect the relative connectedness between the two implied volatilities. Indeed, it is during bad economic times when the directional connectedness from MOVE to VIX is predominantly higher than the connection from VIX to MOVE. It is also important to point out that the relation between monetary and real effects, and the connectedness characteristics between these series depend on whether the U.S. government followed either an anti-inflationary or an output-based monetary policy as suggested by Campbell, Pflueger and Viceira (2015). Two introduce these two policy periods into the analysis, we divide our sample into two sub-periods: April 1988 to March 2001 and April 2001 to July 2017. During the later sub-period, characterized by a production-based monetary objective, there is a negative and significant relation between unexpected monetary policy actions and the spillovers from MOVE to VIX. Moreover, the relation is also negative with respect to the expected component of the change in the target Federal funds rate. This suggests that the overall effect of the target change is important. In fact, the relation between changes in the effective Federal funds rate or in the shadow rate and the spillovers from MOVE to VIX is also negative. If increases in the target and/or the effective (or shadow) rates signal future good economic times, this result is consistent with our previous results regarding the directional connectedness from MOVE to VIX during the business cycle. Interestingly, these significant results are not found for the directional connectedness from VIX to MOVE. Finally, although the relation between real activity and the spillover from MOVE to VIX is negative during the full sample period, the effect is especially strong during the second sub-period. This finding is also found when we employ measures of uncertainty, credit risk and risk aversion to characterize the current and future economic situation. On other hand, the negative association between the spillover from VIX to MOVE and real activity is exclusively observed during the second sub-period, and it is much weaker that the one from MOVE to VIX.

Our empirical evidence highlights the importance of the risk-neutral Treasury volatility and how strongly shocks in this volatility impact on the equity risk-neutral volatility. MOVE is a strong net sender of volatility to VIX, and this is particularly significant during contemporaneous and future bad economic times. Thus, for most of the sample period but especially during bad times, the spillover channel between risk-neutral volatilities occurs mainly through the Government fixed income market rather than through the equity market.

This paper proceeds as follows. Section 2 presents a brief discussion of the behavior of VIX and MOVE and describes the data employed in the analysis. Section 3 studies the formal total and directional connectedness between VIX and MOVE. Section 4 discusses the relation between monetary policy actions, real activity and connectedness dynamics at daily frequency, and Section 5 analyzes the economic drivers of connectedness at monthly frequency. Finally, Section 6 presents our conclusions. The Appendix, at the end of the paper, describes the statistical procedure employed in the paper, and display graphically alternative measures of risk-neutral Treasury volatilities.

2. A Preliminary Analysis of VIX and MOVE and Data Description

We collect daily and monthly data for VIX and MOVE from April 4, 1988 to October 5, 2017, where monthly data refer to the last observation in each month throughout the sample period.[3]

Figure 1 shows annualized daily behavior of VIX and MOVE. As expected, risk-neutral volatilities are countercyclical, and spikes during recessions and economic crises are much larger in equity than in Treasury volatilities. On a daily basis, the minimum (9.2%) and maximum (80.9%) levels for VIX were reached on October 5, 2017 and November 20, 2008, respectively, whereas for MOVE the minimum (4.7%) and maximum (26.5%) were observed in August 7, 2017 and October 10, 2008, respectively. On the other hand, using monthly data, the third highest level for MOVE is observed in July 2003 (16.1%), a month in which VIX presents an average level. As pointed out by Malkhozov, Mueller, Vedolin, and Venter (2016), this month coincides with the large

[3] VIX was downloaded from www.cboe.com and MOVE from Bloomberg. Since MOVE is available from April 1988 and VIX from January 1990, we employ VXO (the risk-neutral market volatility for the U.S. S&P100 index) from April 1988 to December 1989. Starting in January 2003, the CBOE launched the 10-year Treasury Note Volatility Index (TYVIX), which measures a constant 30-day risk-neutral expected volatility on 10-year Treasury Note futures prices. Given that MOVE is available for a much longer sample period, this research employs MOVE rather than TYVIX. The correlation between both series using monthly data (the quote in the last day of each month) from January 2003 to September 2017 is 0.953. Choi et al. (2017) construct implied variance for Treasuries for 5- 10-, and 30-year futures contracts. Their data on the 10-year maturity starts even before than MOVE, and it ends in September 2012. The correlation coefficient between both series from April 1988 to September 2012 is 0.845. Unfortunately, daily data on these series is not available on the Philippe Mueller's personal web page. Daily data are necessary for our research objectives. See the Appendix at the end of the paper.

bond-market sell-off due to mortgage hedging trading. The time-varying behavior of VIX and MOVE suggests that from the careful analysis of both risk-neutral volatilities, we may learn how relevant economic events affect the relative behavior of both markets, and how these events connect or produce spillovers between both markets.

In Figure 2, we show volatility for VIX and MOVE. This figure displays monthly volatility of both risk-neutral volatilities estimated with daily data within each month in our sample. This is a plausible measure of financial uncertainty in the equity and Treasury bond markets, respectively. As expected, VIX seems to be much more volatile than MOVE, with large spikes during times of recessions and bad economic news. However, the spikes of the two series tend to coincide in time. Indeed, to formally analyze the connectedness between equity and Treasury risk-neutral volatilities is the key objective of the paper.

Table 1 contains summary statistics for VIX and MOVE obtained from monthly data from April 1988 to September 2017, using observations on the last day of each month. Over the full sample period, average risk-neutral volatility for the stock market is 19.5%, whereas the risk-neutral volatility for Treasuries is much lower at 9.7%. VIX is also much more volatile than MOVE, and accordingly, the range between the minimum and maximum values is from 9.5% to 59.9% for VIX, and 4.8% to 21.4% for MOVE.[4] VIX presents much higher positive skewness and kurtosis than MOVE. Finally, both implied volatilities are highly persistent with autocorrelation coefficients of 0.84 and 0.85 for VIX and MOVE, respectively. We also present average statistics for two non-overlapping sub-periods. The first one from April 1998 to March 2001, and the second one from April 2001 to September 2017. Although the average levels are certainly similar,

[4] To be precise, the coefficients of variation are 0.38 and 0.27 for VIX and MOVE, respectively.

the volatility and higher order moments of the two series present some intriguing differences. The volatility, positive skewness and kurtosis of the two series are higher in the second sub-period. The excess kurtosis of MOVE is even negative during the first sub-period suggesting that its distribution is less outlier-prone than the normal distribution. Even the autocorrelations are higher during the second sub-period. This is especially the case for MOVE, whose autocorrelation coefficient climbs from 0.69 to 0.88 from the first to the second sub-period.

To understand why we employ these two sub-periods, note that Campbell et al. (2015) not only show that the exposure of Treasury bonds to the equity market has changed considerably over time, but also that changes in the U.S. monetary policy are relevant drivers of such time-varying behavior between equities and Treasuries at the aggregate level. To confirm their evidence during our sample period, and for each month in our sample, we employ daily data within a given month to estimate a monthly Treasury market beta by regressing the daily Treasury excess bond return on the daily excess market return. We use the daily excess returns of a composite index of 5-, 10-, and 30-year horizons of Treasury bonds. Then, on monthly basis, we estimate an average rolling beta with data over three months starting in April 1988. These monthly Treasury betas display a time-varying behavior, which is consistent with the evidence reported by Campbell et al. (2015). Table 2 contains summary statistics of Treasury market betas and the effective *FED* funds rate, which is the volume-weighted average of the borrowing and lending rates across the banks using Federal funds. The overall beta is positive and small. However, the average Treasury beta from the beginning of the first sub-period to March 2001 is positive and as high as 0.310. On the other hand, the Treasury average beta from

April 2001 to June 2017 becomes negative and equal to -0.184.[5] Similarly, the average *FED* rate is higher during the first sub-period with a 3.34% average rate for the full sample period. These two sub-periods correspond to the data breaks employed by Campbell et al. (2015) to analyze the impact of monetary policy on Treasury risks. They attribute the positive beta in the first sub-period to the strongly anti-inflationary U.S. monetary policy, while the negative beta to the focus of monetary policy on output fluctuations, which made Treasury bonds act as hedgers to stock market declines. Figure 3 shows precisely this time-varying behavior of Treasury betas. These betas are positive during the first half of the sample period, but they become negative during most of the 2000s. This figure also displays the effective *FED* funds rate. As expected, the behavior of Treasury betas seems to be closely related to monetary policy.

A related way of understanding the break between these two sub-periods is provided by Bekaert et al. (2018), who employ non-Gaussian features in the U.S. macroeconomic data to estimate macro risk factors that generate supply and demand shocks. They define supply shocks as innovations that move inflation and real activity in the opposite directions, while demand shocks move inflation and real activity in the same direction. Indeed, the correlation between inflation and real activity innovations is -0.16 from April 1998 to March 2001, and 0.09 from April 2001 to October 2017. This suggests that, on average, our first period is characterized by supply shocks, while the second sub-period by demand shocks. The distinctive features of both sub-periods are very important to understand the differences we find in some of the empirical results reported later in the paper.

[5] #The analyses of this research when using monthly data end in June 2017 given the availability of some measures of aggregate uncertainty we employ through the paper.

We next describe the data used to analyze the main economic drivers of VIX and MOVE, which may help to understand the connectedness and spillovers between both volatilities. We do not have a formal theoretical model to guide the choice of economic drivers of connectedness between risk-neutral volatilities. However, it is reasonable to expect that relevant economic variables, affecting the spillover effects between risk-neutral volatilities of the two markets, must be related to sovereign interest rates and inflation, the stock market behavior, credit risk, real economic activity growth, and measures of uncertainty and risk aversion, which are the key components of risk-neutral volatilities as shown by Bekaert and Hoerova (2014). In fact, given the well-known relation between VIX and monetary policy, Bekaert, Hoerova, and Lo Duca (2013) show that expansionary monetary policy decreases both the risk aversion and uncertainty components of VIX, although the effects of monetary policy are greater on risk aversion. Therefore, our interest on risk-neutral volatilities and the potential relation between connectedness and monetary policy strongly suggest that measures of uncertainty and risk aversion may clarify the spillover effects between equity and Treasury risk-neutral volatilities.

We employ two variables regarding the behavior of interest rates. First, the slope of the term structure denoted as *TERM*, which is the difference between the yield on the 10-year government bond and the 3-month Treasury bill rate. *TERM* is one of the most popular forecasting instruments of real activity. Increases in the slope of the term structure have been shown to predict higher future growth rates of economic activity, whereas decreases in the slope tend to predict bad economic times.[6] Moreover, Choi et al. (2017) employ an options panel data set on Treasury futures to show that the term structure of

[6] Among many others, see Stock and Watson (2003).

risk-neutral variances is downward sloping and significantly related to economic conditions. Given that MOVE includes data on 2-, 5-, 10-, and 30-year contracts, it seems reasonable to include *TERM* in the regression model. Second, to account for inflation risk, we employ expected inflation for a one-year horizon denoted as *EINF*. Expected inflation is downloaded from the Federal Reserve Bank of Cleveland website. The Cleveland fed's model employs Treasury yields, inflation rate data, inflation swaps, and survey-based measures of future inflation to estimate expected inflation to alternative horizons. Expected inflation is also a relevant signal for future real activity. Positive (negative) inflation shocks may suggest good (bad) news for future economic growth.

González-Urteaga and Rubio (2016) show that the default premium (*DEF*) is a key factor explaining the cross-sectional variation of equity volatility risk premia. It seems therefore natural to employ the default spread, calculated as the difference between Moody's yield on Baa corporate bonds and the 10-year government bond yield, as a potentially relevant explanatory variable of the time-varying behavior of VIX and MOVE.

As a measure of real economic activity, we employ the monthly growth rate of the Industrial Production Index (*IPI*) published by the Federal Reserve Bank of St. Louis, FRED database. In addition, and given the well-known leverage effect, we include the S&P 500 excess market portfolio return (*EXCMKET*), and the excess return of the composite index of 5-, 10-, and 30-year horizons of Treasury bonds (*TRYRET*) to represent Government bond returns given that MOVE is itself a maturity weighted index. As the industrial production index, and the effective *FED* funds rate, the composite Treasury return is also downloaded from the FRED database.

As pointed out above, Bekaert and Hoerova (2014) show that the square of VIX reflects both market uncertainty (the expected market variance under the physical probability), and risk aversion (the variance risk premium or the expected premium from selling market variance). Both characteristics may explain the time-changing connectedness between VIX and MOVE. As measures of uncertainty, we employ the macroeconomic (*MUNC*) and financial uncertainty (*FUNC*) indices of Jurado, Ludvigson, and Ng (2015, hereafter JLN), defined as the combined conditional volatility of the unforecastable component of a large number of macroeconomic and financial variables, respectively. As an alternative proxy for uncertainty, we use the Baker, Bloom, and Davis (2016) Economic Policy Uncertainty (*EPU*) indicator, which counts the frequency of articles containing the words uncertain or uncertainty, economy or economics, and the following six policy words, Congress, deficit, central bank, legislation, regulation, and government. There is an increasingly popular literature on the relation and transmission mechanism between uncertainty and economic growth. Overall, there is a consensus that higher uncertainty leads to lower growth.[7]

As a proxy for risk aversion (*RA*), we employ the measure provided by the European Central Bank (ECB), which is available on monthly basis since December 1998. It is the first principal component of five currently available risk aversion indicators, namely Commerzbank Global Risk Perception, UBS FX Risk Index, Westpac's Risk Appetite Index, Bank of America Risk Aversion Indicator, and Credit Suisse Risk Appetite Index. A rise in the indicator denotes an increase in risk aversion. We extend the data by projecting the ECB risk aversion on the Chicago Fed National Financial Conditions from December 1998 to August 2017. The estimated coefficients are employed to construct a synthetic measure of risk aversion from April 1988 to November 1998.

[7] See Bloom (2014) for a review article on uncertainty and real activity growth.

Table 3 contains the pairwise correlation coefficients among all the economic variables described above. All signs are as expected. The slope of the term structure of interest rates shows a negative correlation with expected inflation and Treasury bond returns, and a positive correlation with the change in the effective *FED* funds rate. The economic activity measure presents negative correlations with uncertainty and risk aversion, whereas default is strong and positively correlated with both uncertainty and risk aversion. Expected inflation is highly negatively correlated with the default premium, and with economic policy and macroeconomic uncertainty. Interestingly, it is less negatively correlated with financial uncertainty and risk aversion. The excess market return has a relatively high negative correlation with financial uncertainty and, especially, with risk aversion. On the hand, the Treasury bond return is positively correlated with risk aversion. The change in the *FED* rate also has negative correlation with measures of uncertainty, risk aversion and default, and a positive correlation with real activity growth.

Since we later study the simultaneous drivers of connectedness, and given the high correlation among the uncertainty measures, risk aversion and default, we estimate pure risk aversion and default components by an OLS regression of risk aversion on financial uncertainty and default, and by another regression of default on financial uncertainty and risk aversion. The first series of residuals is the pure risk aversion proxy, which is denoted by *RESRA*, while the second series of residuals is the pure default component, denoted by *RESDEF*. Finally, when explaining connectedness simultaneously by *TERM* and changes in the effective *FED* funds rate, we employ the residuals from an OLS regression of *TERM* on the level of the *FED* funds rate. This third series of residuals is denoted by *RESTERM*.

3. The Connectedness between Risk-Neutral Equity and Treasury Volatilities

3.1 Total and Directional Connectedness

The stylized facts of international financial returns and the coordinated risk related to expected risk premia across asset classes during the Great Recession have motivated an increasing interest in the formal analysis of connectedness. In this section, we employ the methodological econometric framework of Diebold and Yilmaz (2012, 2014, 2015, 2016). Although, these authors have applied this framework to the analysis of volatilities across international markets, the analysis of connectedness between risk-neutral volatilities of equities and Treasuries is missing. In this section, we characterize the risk-neutral equity and Treasury volatility connectedness using the data described in the previous Section. If, as is often argued, VIX tracks the in-equity investor fear, MOVE gives the in-Treasury investor fear gauge. The analysis of connectedness between both volatilities helps calibrating the total and directional connection from both types of fears. Hence, our analysis studies whether the amount investors are willing to pay to hedge equity market risks is connected to the amount investors are willing to pay to hedge unexpected changes in credit risk-free interest rates. Even more important, our paper analyzes the directional connectedness between both types of hedging behavior.

Connectedness measures are obtained from the variance decomposition matrix associated with an N-variable vector autoregression framework, which allow us to infer the forecast error variance of each variable into parts attributable to the system shocks. It is well known that we must transform the vector autoregression (VAR) shocks to orthogonalization to proceed with variance decompositions. The traditional Cholesky VAR identification may be sensitive to ordering. Instead, we follow the usual approach in literature and employ the generalized approach of Koop, Pesaran, and Potter (1996), and Pesaran and Shin (1998), which does not require orthogonalized shocks but accounts for correlated shocks assuming normality. Therefore, given our focus on volatilities, approximate normality is obtained by taking natural logarithms.

In our analysis, we follow Diebold and Yilmaz (2016) and employ a predictive horizon of H = 12 days. Moreover, we perform a dynamic analysis using a 200-day rolling-sample window, although we check the robustness of our empirical results employing also a 66-day rolling-window estimation. Given the similarities between the results, we discuss the findings for the 200-day rolling-window case.[8]

Table 4 presents the average percentages of alternative measures of the daily dynamic volatility connectedness. The first column reports the total volatility connectedness given by expression (A.7) in the Appendix for alternative sub-periods. The total connectedness between the risk-neutral volatilities is 28.8%. This is much lower than the numbers reported by Diebold and Yilmaz (2016) when studying the volatility connectedness of trans-Atlantic equity volatilities under the physical probability measure. The overall measure between equity and Treasury risk-neutral volatilities strongly changes over time as displayed in Figure 4, where we show the total monthly volatility connectedness calculated as the average daily percentages within each month from January 1989 to September 2017. The maximum level, observed in January 2008, is 42.8%, while the lowest level occurs in September 2009 reaching only 8.3%. This time-varying behavior can also be appreciated when we calculate average total connectedness for different sub-periods. During the anti-inflationary U.S. monetary policy sub-period, from January 1989 to March 2001, the average connectedness is 31.6%, but it is only 26.8% during the output-support U.S. monetary policy years, from April 2001 to October

[8] The Appendix at the end of the paper contains a brief and formal discussion of the statistical procedure employed in our analysis.

2017. It is also the case, that the total volatility connectedness is higher during the NBER recession dates reaching 32.5% relative to non-NBER 28.4% average connectedness.

Even more important is to analyze the directional connectedness between the risk-neutral volatilities. Column 2 of Table 4 shows the connectedness from VIX to MOVE given by equation (A.4), and the third column contains the connectedness from MOVE to VIX calculated from expression (A.5). The results are striking. Independently of the sub-period analyzed, the directional connectedness is always higher from MOVE to VIX than the other way around. The fourth column shows the net connectedness, estimated as in equation (A.6) from VIX to MOVE minus MOVE to VIX. Given that the spillovers mainly go from MOVE to VIX, the net connectedness is negative. Moreover, it is more negative during the second sub-period, and during the NBER recession months. Indeed, the directional connectedness from MOVE to VIX is as high as 41.6% during the NBER recession dates. Figure 5 displays the directional connectedness. Note that most of the time, the directional connectedness from MOVE to VIX is higher than from VIX to MOVE. This pattern is even clearer in Figure 6, where we show net connectedness. The pattern is negative in 95.1% of all months. Relatively important exceptions occur during March 2010, November and December 2013, and from January to May 2014.

We now test whether average net connectedness is equal to zero for the alternative sub-periods, and whether the net connectedness for a given quartile is also equal to zero. For the comparison of average connectedness, we employ the Wilcoxon rank-sum test under the null hypothesis that the two samples come from identical continuous distributions with the same mathematical expectation. For testing the null hypothesis for a given quartile, we use the Pearson's chi-squared test under the null hypothesis that the frequency distribution in the observed samples is consistent with a theoretical distribution. In our case with two samples, the statistic is given by

$$\sum_{i=1}^{2} \frac{\left(O_i^{<q} - E_i^{<q}\right)^2}{E_i^{<q}} + \sum_{i=1}^{2} \frac{\left(O_i^{\geq q} - E_i^{\geq q}\right)^2}{E_i^{\geq q}}, \quad (1)$$

where O_i is the observed frequency for sample *i* and E_i is the expected theoretical frequency for values lower than *q* and higher or equal to *q*. The expected frequency is estimated with the values of the two samples simultaneously and *q* indicates the quartile: 1 (percentile 0.25), 2 (percentile 0.50) or 3 (percentile 0.75). Under the null, the difference between the observed and the expected frequencies for the two samples is zero, and the statistic has a Chi-squared distribution with one degree of freedom. The results in Table 4 show that the average and the three quartiles of net connectedness between VIX to MOVE and MOVE to VIX are statistically different from zero in all cases and independently of the sub-period. Indeed, the Kolmogorov-Smirnov non-parametric test to compare the complete distribution values in the two samples has an associated *p*-value of 0.000. We can safely conclude that the spillovers come mainly from risk-neutral Treasury volatility to equity volatility, and that net connectedness is on average higher (in absolute value) when monetary policy is mainly concerned with production fluctuations rather than with inflation distress, and during NBER recession months.

3.2 Dynamic Connectedness and Economic and Geopolitical Events

In this sub-section, we explain the previous finding regarding the average connectedness between risk-neutral volatilities across alternative sub-periods by studying how the connectedness dynamic is associated with relevant economic and geopolitical events.

Table 5 contains a brief description of the relevant events together with the specific dates for which we identify an event. We separate all episodes in three groups.

The first one is concerned with the overall relevant economic and geopolitical events for the U.S. economy. The second one considers events with an international economic flavor, in which the distressed economic episodes affect mainly countries different from the U.S. Finally, we also include two sub-periods characterized by large bond market sell-offs in the U.S. market.

To understand connectedness dynamics, we run OLS regressions with Newey-West/HAC (1987) standard errors of the alternative measures of connectedness on a constant and a dummy variable that equals one when the sample observations are affected by any of the events described above,[9]

$$C_t^G = \beta_0 + \beta_1 D_t + \varepsilon_t, \tag{2}$$

where C_t^G is either total, directional or net connectedness between VIX and MOVE, and D_t takes the value of one if a set of daily observations is identified with any of the three type of events, and zero otherwise. Note that $\hat{\beta}_0$ is the mean of connectedness when there are no events, and $\hat{\beta}_1$ is the difference of connectedness during days for which there is an event and the days for which no event is identified.

Table 6 shows the results for the three groups of events. Panel A contains the results for the overall economic and geopolitical events for the U.S. economy. By paying attention to the slope coefficient $\hat{\beta}_1$, we note that during these times, the total system connectedness increases significantly by 3.08 points. This is consistent with the results reported in Table 4. Interestingly, however, the spillover from VIX to MOVE is positive

[9] The number of lags used in the HAC standard errors is given by the expression $0.75T^{1/3}$, where T is the total number of observations.

but it is not statistically different from zero. However, during these events the spillover from MOVE to VIX increases significantly by 4.95 points. Consequently, the net connectedness is negative and statistically different from zero. Hence, the strong average directional connectedness from MOVE to VIX reported in Table 4, which is especially high during the NBER recession months, seems to be due to the spillovers from risk-neutral Treasury volatility to VIX over relevant economic and geopolitical times. During these times, most of the action happens in the risk-neutral Treasury volatilities. Then, it is transmitted to the risk-neutral equity volatility. The characteristics of these identified events are correlated with the overall relatively low directional connectedness from VIX to MOVE, and the relatively high spillover from MOVE to VIX reported in Table 4.

Panel B shows the results using international events as the key driver of risk-neutral volatilities. The results are very different. The total system connectedness decreases significantly by 2.9 points. The net connectedness also goes down by a statistically significant 9.2 points. This reduction is due to the significant and strong decrease connectedness from VIX to MOVE, and to the positive and weak significant spillover from MOVE to VIX. Whenever there is an international economic crisis (not directly related to the U.S. economy), the spillover from VIX to MOVE is clearly reduced. However, the incremental spillover from MOVE to VIX remains positive with a Newey-West/HAC standard error-based *t*-statistic of 1.87.

Finally, in Panel C we display the results during strong bond market sell-offs. None of the slope coefficients are statistically different from zero. Although the directional connectedness from MOVE to VIX increases slightly with an adjusted *t*-statistic of 1.40.

4. Monetary Policy, Real Activity, and Connectedness Dynamics between VIX and MOVE

We now discuss the monetary and real activity effects on the total and directional connectedness between VIX and MOVE. Given that we have reasonable proxies for monetary and real activity at daily frequency, it seems reasonable to carry out the analysis at the highest possible frequency. We first discuss how monetary policy surprises affect connectedness using changes in the target *FED* funds rate, and then we study the relation between changes in the effective *FED* funds rate and connectedness. In both analyses, we employ the ADS real activity index of Aruoba, Diebold, and Scotti (2009), which is designed to track real economic conditions at high frequency.[10] The average value of the index is zero. Positive values indicate better-than-average conditions, whereas negative values represent worse-than-average conditions.

4.1 Monetary Policy Surprises and Real Activity Effects on Connectedness

The idea is to discern the connectedness reaction to monetary policy by focusing on unexpected policy decisions. In order to identify unexpected funds rate changes, we follow Kuttner (2001), and Bernanke and Kuttner (2005) who employ the price of the 30-day Federal funds futures contracts. This price reflects expectations of the effective Federal funds rate, averaged over the settlement month. We extract the surprise component from the change in the future's price relative to the day prior to the policy

[10] Data are downloaded from the Federal Reserve Bank of Philadelphia at https://www.philadelphiafed.org

decision. Given that the future's price is based on the monthly average federal funds rate, we scale the future rates by a factor associated with the number of days in the month of the change. Hence, the monetary policy surprise is given by,

$$\Delta FEDT^{u} = \frac{d}{d-t}\left(f_{m,t}^{0} - f_{m,t-1}^{0} \right), \tag{3}$$

where $\Delta FEDT^{u}$ is the unexpected target rate change, $f_{m,t}^{0}$ is the current month futures rate, and d is the number of days in month m. Consequently, the expected component is defined as

$$\Delta FEDT^{e} = \Delta FEDT - \Delta FEDT^{u}. \tag{4}$$

In the analysis, the sample of events corresponds to days for which we find that the funds rate target was changed. These are days that may coincide with a Federal Open Market Committee (FOMC) meeting, or days with intermeeting changes. Altogether, the sample contains 83 observations with 42 from June 1989 to March 2001, and 41 from April 2001 to July 2017.[11]

The effects of monetary policy surprises on the connectedness between VIX and MOVE are obtained from the following regression

$$ln C_{t}^{G} = \beta_{0} + \beta_{1}\Delta FEDT_{t}^{e} + \beta_{2}\Delta FEDT_{t}^{u} + \varepsilon_{t}, \tag{5}$$

where $ln C_{t}^{G}$ is the log of either total or directional connectedness between VIX and MOVE.

[11] The target rate changes are dated in relation to the day on which they become known. Note that prior to 1994, the FOMC did not issue monetary policy statements. For that sub-sample, the day in which the change is known corresponds to the day after the decision to change rates; this is to say, when the new target rate becomes effective.

Panel A of Table 7 reports the empirical results for the total and directional connectedness, and for the full sample period. The second line contains the results of regression (5) controlling also for real activity using the ADS activity index. We find a negative but very weakly significant relation between the unexpected change and total connectedness. In parentheses, we report the *t*-statistic calculated with HAC standard errors. This overall result is clarified when we distinguish between the directional connectedness from one risk-neutral volatility to the other. Monetary policy surprises are not significantly related to spillovers from VIX to MOVE. However, both expected and unexpected increases in the target funds rate decreases the directional connectedness from MOVE to VIX.

The analysis by sub-periods also clarifies the empirical results. During the first sub-period, we do not find any significant relation between connectedness and monetary policy surprises, at least when we control for real activity. In fact, the results reported for the full sample period seem to be explained exclusively from the results observed in the second sub-period. There is a significant negative relation between the expected and unexpected components of monetary policy rate changes and total connectedness, which is completely explained by the negative relation associated with the spillovers from MOVE to VIX. The directional connectedness from VIX to MOVE is not statistically related to monetary policy surprises.

The negative relation between the surprise component of the target *FED* funds rate change and the directional connectedness from MOVE to VIX, observed only during the second sub-period, suggests that an unexpected increase (decrease) in the target rate provides a strong signal of future good (bad) economic times. We already know that good (bad) economic times reduces (increases) the spillovers from MOVE to VIX. Therefore, this finding is just a different perspective on the same phenomenon. Bad (good) times increase (decrease) spillovers from MOVE to VIX. These effects seem to be rather strong because, even the expected component change in the target rate, is negatively associated with the spillovers from MOVE to VIX. The confirmation of good signals on the future real activity reduces the directional connectedness from Treasury to equity risk-neutral volatilities. Note that the fact that both components are relevant suggest that the overall total change is important. This issue is analyzed next using the effective *FED* funds rate overall the natural-time period rather than using an event-time period.

4.2 Monetary and Real Activity Effects on Connectedness

Given the importance of the expected and unexpected components of the target rate, and instead of using even-time to identify monetary policy surprises, we now employ the change in the effective *FED* funds rate to study whether connectedness and spillovers are associated with either monetary, real activity drivers or both. As before, we run OLS regressions with Newey-West/HAC standard errors for the full sample period but also for the two-subperiods from January 19, 1989 to March 30, 2001, and from April 2, 2001 to July 20, 2017,[12]

$$ln C_t^G = \beta_0 + \beta_1 FED_t + \beta_2 ADS_t + \varepsilon_t, \quad (6)$$

where $ln C_t^G$ is the log of either total or directional connectedness between VIX and MOVE, *FED* is the change in the effective *FED* funds rate, and *ADS* is the Aruoba et al. (2009) real activity index.

The results are shown in Table 8. Panel A contains the total and directional connectedness for the full sample period. We do not find any significant relation between

[12] This the last day for which the ADS index was available when performing the corresponding regressions.

either monetary or real activity drivers and total connectedness. These effects are clarified when we observe the results regarding directional connectedness. Real effects are positive and significantly associated with the spillovers from VIX to MOVE, but changes in the effective *FED* rate do not show any relevant relation. On the other hand, there is a statistically very weak negative relation between changes in the *FED* rate and the spillover from MOVE to VIX, but a negative and highly significant association between real activity and the directional connectedness from MOVE to VIX. The effects of real activity on the spillovers between both volatilities have precisely the opposite sign. This explains why the effects of real activity on total connectedness is cancelled out. A worsening of economic and business conditions over the full sample period increases the spillovers from Treasury to equity risk-neutral volatility, but it diminishes the spillovers from VIX to MOVE.

The empirical results between both sub-periods are shown in Panels B and C of Table 8. In the first sub-period, total connectedness is clearly not related with changes in the effective rate, although the relation becomes negative with an adjusted *t*-statistic of -1.52 in the second sub-period. This behavior with respect to total connectedness in the second sub-period is explained by the negative and statistically significant relation between changes in the effective rate and the spillovers from MOVE to VIX. As in our previous analysis, an increase in the effective *FED* rate seems to be interpreted as a signal of good future economic conditions, which diminishes the spillover of risk-neutral volatility from fixed to equity markets. Recall that the first sub-period is characterized by an anti-inflationary monetary policy while the second sub-period is more output-policy oriented or, alternatively, the first sub-period is dominated on average by supply shocks while the second sub-period by demand shocks. No action is observed with respect to the directional connectedness from VIX to MOVE. These results are consistent with the findings reported in Table 7 using an event-time analysis.

Regarding real activity across both sub-periods, the relation between output and total connectedness is positive in the first sub-period and becomes negative during the second sub-period. In both cases, the relation is statistically significant. As before, this is clarified when we analyze directional connectedness. The analysis of real activity effects in the first sub-period shows a positive and statistically significant relation with the spillovers from VIX to MOVE, and a significantly negative relation with the directional connectedness from MOVE to VIX. Once again, bad real activity conditions reduce the spillover from VIX to MOVE but increase the directional connection from MOVE to VIX. Moving to the second sub-period, we observe a significant increase in total connectedness when there is a decline in real activity. This is because during the second sub-period, which is characterized by a strong financial and economic crisis, the negative relation between directional connectedness and real active is negative in both directions and not only from MOVE to VIX. Bad economic conditions make equity and Treasury risk-neutral volatilities to be more closely connected, although the effect is much larger from MOVE to VIX.

To summarize, independently of the period, if there is a decline in real activity, the directional connectedness from MOVE to VIX increases. However, the negative relation between real activity and the spillovers from VIX to MOVE is only observed in the second sub-period that includes the Great Recession. Monetary relations also depend on the sub-periods, which suggest the importance of different monetary policy objectives across sub-periods. In any case, as in the analysis of monetary policy surprises, the only negative and statistically significant relation between changes in the effective *FED* rate and connectedness dynamics are from MOVE to VIX during the second sub-period. The output-oriented monetary policy of this sub-period is a key characteristic to understand this result. Increases (decreases) in the effective rate are signals of good (bad) economic times. Consistently with the results regarding real activity, this makes the relation between changes in the effective *FED* funds rate and the spillovers from MOVE to VIX to be negative and estimated with relatively high precision. This paper detects an economically important connection between the risk-neutral volatility of Treasury bonds and monetary policy, which indirectly affects the risk-neutral equity volatility through significant spillover effects.

5. Economic Drivers of Connectedness between VIX and MOVE

Using monthly frequency, we now analyze the explanatory power of more general economic drivers that may explain the connectedness dynamics between risk-neutral equity and Treasury volatilities. Note that for most variables, we only have data at the monthly frequency. The variables employed are discussed and economically justified in Section 2.

Table 9 shows the results for the full sample period from the following regression model with monthly data,[13]

$$\begin{aligned} ln C_t^G = \beta_0 + \beta_1 TERM_t + \beta_2 EINF_t + \beta_3 TRYRET_t + \beta_4 FUNC_t \\ + \beta_5 RESRA_t + \beta_6 RESDEF_t + \beta_7 IPI_t + \beta_8 EXCMKT + \varepsilon_t , \end{aligned} \quad (7)$$

[13] By the same argument used in Section 2, we extract the *EPU* component not captured by either financial or macroeconomic uncertainty (*RESEPU*), and the macroeconomic uncertainty residual by regressing macro uncertainty on financial uncertainty and *EPU* (*RESMUNC*). Given the relatively less empirical significance of these two types of uncertainty measures, our reported regressions only include financial uncertainty and the residuals of risk aversion.

where lnC_t^G is the log of either total or directional connectedness between VIX and MOVE, and the explanatory variables have been defined previously in Section 2. All these variables have an economic justification, even though we recognize the lack of a theoretical model to explain the connectedness between risk-neutral volatilities. Note that we include monetary and real activity variables, the stock market risk premium, and uncertainty and risk aversion measures because the well-known influence that these variables have on (at least) risk-neutral equity volatility. Moreover, to understand directly the effects of monetary policy, and as alternative regression, we employ the change in the effective *FED* funds rate instead of expected inflation. In this alternative specification, instead of *TERM*, we use *RESTERM*, which is the residual of regressing *TERM* on the level of the *FED* funds rate as explained also in Section 2. The regression is then given by,

$$\begin{aligned} lnC_t^G = &\beta_0 + \beta_1 RESTERM_t + \beta_2 FED_t + \beta_3 TRYRET_t + \beta_4 FUNC_t \\ &+ \beta_5 RESRA_t + \beta_6 RESDEF_t + \beta_7 IPI_t + \beta_8 EXCMKT + \varepsilon_t . \end{aligned} \tag{8}$$

We must also recognize the potential distortions of traditional monetary policy instruments under the zero-bound interest rate setting. As an alternative to the change in the effective *FED* funds rate, we employ the change in the shadow interest rate of Wu and Xia (2016), which is the nominal interest rate that would prevail in the absence of its effective lower bound. The shadow rate is downloaded from their web page at https://sites.google.com/view/jingcynthiawu/. Note that this shadow rate can be negative, which pretends to capture the Fed's incremental easing due to unconventional monetary practices. Therefore, as a third alternative regression, we run model (8) using the change in the shadow rate instead of the change in the *FED* funds rate.

Panel A of Table 9 contains the results of total connectedness. Either *TERM* or *RESTERM* have a positive and statistically significant coefficient. Given that *TERM* is a powerful predictor of future real economic activity, it seems that the total system connectedness increases with future better economic prospects. On the other hand, adjusted risk aversion (*RESRA*) also presents a positive and, under expression (7), significant relation with total connectedness. The higher risk aversion in the economy, once we adjust for financial uncertainty and default, the higher the total connectedness. However, when we include changes in the *FED* rates, the magnitude of this coefficient clearly diminishes. Contrary to this case, the relation between total connectedness and default becomes negative and statistically different from zero precisely when we employ *FED* rates. There is also a negative relation with industrial production growth although the coefficient is estimated with low precision. Finally, the changes in both the effective and shadow rates are negative and significantly related to total connectedness, although the shadow coefficient is estimated with larger precision. These results are better understood when we analyze directional connectedness between VIX and MOVE and MOVE and VIX.

Panel B of Table 9 shows the results of the directional connectedness or spillovers from VIX to MOVE. Only, *TERM* (or *RESTERM*) has a positive and significant coefficient, which suggests that future good economic prospects increases the spillovers from VIX to MOVE. On the other hand, a decrease in either financial uncertainty or credit risk, as proxy by the default premium, increases the spillovers from VIX to MOVE. Therefore, positive financial news generates significant spillovers from VIX to MOVE. We do not find any significant relation with respect to changes in monetary policy rates. This is consistent with the results using daily data in Tables 7 and 8. Rather surprisingly, there is a weak negative relation between the contemporaneous growth of real activity and directional connectedness from VIX to MOVE but losses statistical precision once we include the *FED* rates in the analysis.[14] To conclude, future and contemporaneous good economic and financial news increase the spillovers from VIX to MOVE. Interestingly, along the full sample period, VIX becomes relatively more important in good times.

Panel C of Table 9 contains the empirical results of directional connectedness from MOVE to VIX. Higher expected inflation increases the directional connectedness from MOVE to VIX.[15] Moreover, as in our previous analysis, a tightening of monetary policy decreases significantly the spillovers from MOVE to VIX. Alternatively, a reduction in policy interest rates signals problematic future economic times and the directional connectedness from MOVE to VIX increases. On top of that, note that the signs of the coefficients associated with either financial uncertainty or default are precisely the opposite than the ones reported in Panel B for the equity risk-neutral volatility. Increases in financial uncertainty and default are associated with an increase in the spillover from MOVE to VIX, although the results lose statistical significance once we employ changes in the *FED* rates. The stronger positive and highly significant relation is found relative to risk aversion. It is clear from the results that increases in risk aversion

[14] To safe space, we do not report the evidence across the sub-periods. The positive relation with *TERM* is stronger during the first sub-period. The negative relation with financial uncertainty and default is larger in absolute value during the first and second sub-period, respectively. Finally, the relation with industrial production growth is positive and statistically different from zero during the first sub-period, but it becomes negative during the second sub-period. This is consistent with the results reported in Table 8. The adjusted *R*-squared of the regression is higher in the first sub-period. All results are available from the authors upon request.

[15] Note that *TERM*, a predictor of economic activity, is not statistically different from zero. However, once we adjust the slope of the term structure by the *FED* funds rate, *RESTERM* becomes statistically significant. This finding may simply reflect the fact that MOVE is a weighted average of four different Treasury maturities and, due to higher duration, the return volatility of long-term bonds is higher than the return volatility of short-term bonds.

are related to higher spillovers from MOVE to VIX. This is a striking result. MOVE becomes a net sender of volatility precisely when risk aversion is higher. Note that the results displayed in Panel B, when studying the transmission from VIX to MOVE, were not statistically significant. From a general economic point of view, the effects shown in Panel B of Table 9 are like to the ones reported in Table 8 using daily data. In this case, however, bad contemporaneous news about the economic situation is captured through higher financial uncertainty and default spread, but especially through higher risk aversion. There is also some evidence of a negative relation between Treasury excess returns and the connectedness from MOVE to VIX. Moreover, note that the signs of the spillover effects from MOVE to VIX explain the relation between risk aversion and total connectedness. On the opposite side, the directional connectedness from VIX to MOVE is what explains the relation between *TERM* and total connectedness. Overall, during bad economic times, the spillovers from MOVE to VIX increase. MOVE becomes a relatively more important sender of volatility to VIX in bad times.[16]

The results of Tables 6 through 9 are consistent in the sense that whenever the U.S. economy suffers from a distressed economic period characterized by either problematic economic or geopolitical events, higher risk aversion, higher credit risk (default) or a fall in real activity, the directional connectedness from MOVE to VIX increases. Under these circumstances, the volatility associated with the behavior of investors willing to pay a higher price to hedge future unexpected changes in interest rates

[16] The negative relation of changes in either the *FED* rate or the shadow rate with the spillovers from MOVE to VIX, and the positive relation with risk aversion and default are much stronger during the second than the first sub-period. In addition, the relation with industrial production growth becomes negative and statistically significant during the second sub-period. Given these results, the adjusted *R*-squared statistic is higher during the second sub-period. Overall, the results by sub-periods suggest that the focus of monetary policy on either anti-inflationary or output-based objectives has a relevant impact on the results. As before, these results are available from the authors upon request.

becomes the driver signal in the U.S. financial market, and the spillovers from MOVE to VIX becomes higher. The volatility of risk-neutral Treasury volatility seems to be especially sensitive to the current economic and geopolitical situation of the U.S. economy. These results are also consistent with the fact that, at daily frequency and during periods of output-based monetary policy, there is a negative relation between the tightness of monetary policy and the spillovers from MOVE to VIX, while the directional connectedness from MOVE to VIX is strongly counter-cyclical with respect to real activity. Consistent with these results, at least for the second sub-period, there is also a negative relation between unexpected and expected changes in the Federal target rate and the spillovers from MOVE to VIX. On the other hand, monetary policy surprises and/or changes in the effective *FED* rate do not seem to affect the directional connectedness from VIX to MOVE. Moreover, and contrary to the evidence found for the spillovers from MOVE to VIX, increases in financial uncertainty, risk aversion and credit risk makes lower the spillovers from VIX to MOVE. This is also true for the growth of industrial production during the first sub-period, although this effect changes the sign during the second sub-period that is strongly influenced by the Great Recession.

6. Conclusions

The financial crisis outbreak in the U.S. soon made a marked change in the form of a global Great Recession. Therefore, it is not surprising that most of the studies of connectedness dynamics are concerned with either volatilities across geographical areas or across international banks. The formal analysis of connectedness dynamics between risk-neutral volatilities of equities and Treasury bond returns for a given country is missing. This is exactly what we do in this research using U.S. data. Note that risk-neutral volatilities are a key instrument for risk management and policy authorities. At this point, we have long high frequency time series data series for risk-neutral volatilities for equity and Treasury bonds, that allows not only to study total and directional connectedness between them, but also to analyze their monetary and economic drivers over very different economic cycles.

Over most of the sample period, we show that spillovers from MOVE to VIX are higher than from VIX to MOVE. More importantly, the positive net spillovers from MOVE to VIX are especially relevant during bad economic times. With daily data, times of relevant economic and geopolitical events, and times of a decline in real activity provoke that the percentage of the forecast variation error in VIX that is due to shocks in MOVE is relatively high. In fact, the net difference is statistically significant, which suggests that VIX is a receiver of volatility relative to MOVE. Moreover, the directional connectedness from MOVE to VIX increases with risk aversion, financial uncertainty, and credit risk. MOVE is a net sender of volatility and this is especially the case during bad economic times. This result highlights the importance of Treasury bond markets relative to equity markets. Once these effects are properly understood, we would expect that monetary and economic policy authorities may increasingly pay more attention to the risk-neutral volatility of Treasury bond returns.

The orientation of monetary policy affects the characteristics of the connection between MOVE and VIX, but it does not seem to be significantly related to the spillovers from VIX to MOVE. Up to 2001, under an anti-inflationary monetary policy, changes in the *FED* rates are negative but weakly related to the spillovers from MOVE to VIX. On the other hand, under daily frequency, bad economic times increase significantly the spillovers from MOVE to VIX. However, the output-based monetary policy of lower interest rates after 2001, led to a strong and statistically negative relation between changes in the *FED* and shadow rates and the directional connectedness from MOVE to VIX.

Moreover, increases in both the expected and unexpected components of the Target *FED* funds rate reduces the spillovers from MOVE to VIX, but not those from VIX to MOVE.

The strong and consistent spillovers from MOVE to VIX reported in this paper, especially from April 2001 to June 2017, is a key contribution of our research. Future research should further clarify the economics behind these empirical results, although we can safely conclude that the behavior of the Treasury risk-neutral volatility contains much more relevant information than previously reported in literature.

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Table 1. Summary Statistics VIX and MOVE. April 1988-September 2017

	Full Sample Period		April 1988- March 2001		April 2001- September 2017	
	VIX	MOVE	VIX	MOVE	VIX	MOVE
Mean	0.1949	0.0965	0.1923	0.1017	0.1970	0.0925
Volatility	0.0731	0.0259	0.0582	0.0150	0.0831	0.0314
Minimum	0.0951	0.0481	0.1063	0.0579	0.0951	0.0481
Maximum	0.5989	0.2140	0.4428	0.1428	0.5989	0.2140
Skewness	1.7367	0.9999	1.0733	0.1779	1.8190	1.2993
Kurtosis	4.8872	2.6046	2.0733	-0.126	4.4547	2.1028
AR(1)	0.8405	0.8539	0.8089	0.6881	0.8525	0.8790

The VIX Index is the risk-neutral one-month expected stock market volatility for the US S&P 500 Index. It is computed by averaging the weighted prices of puts and calls on the S&P500 index over a wide range of strike prices. The MOVE Index is the Merrill Lynch Option Volatility Estimate Index. It is a term structure weighted index of the normalized implied volatility on one-month Treasury options, weighted on the 2-, 5-, 10-, and 30-year contracts. The statistics employ monthly data and observations on the last day of each month.

Table 2. Summary Statistics of Treasury Market Betas and the Effective FED Funds Rate. April 1988-June 2017

	Average Treasury Market Beta	Average FED Funds Rate
4/1988-6/2107	0.0354	0.0334
4/1998-3/2001	0.3095	0.0571
4/2001-6/2017	-0.1838	0.0144

The first two columns of this table report the average of the Treasury market beta and the effective *FED* funds rate for alternative sub-periods. The Treasury market beta is estimated with daily data within a given month. Then, on monthly basis, we estimate an average rolling beta with data over three months.

Table 3. Correlation Coefficients Among Economic Variables. April 1988-June 2017

	TERM	EINF	EPU	MUNC	FUNC	RA	DEF	IPI	EXC MKET	TRY RET	FED
TERM	1	-0.272	0.278	-0.010	0.002	-0.057	0.238	0.080	0.010	-0.174	0.098
EINF		1	-0.350	-0.248	-0.182	-0.018	-0.582	0.121	-0.041	0.014	-0.031
EPU			1	0.250	0.380	0.417	0.586	-0.226	-0.112	0.150	-0.307
MUNC				1	0.686	0.592	0.695	-0.451	-0.186	0.041	-0.284
FUNC					1	0.684	0.688	-0.296	-0.201	0.103	-0.319
RA						1	0.608	-0.326	-0.445	0.193	-0.374
DEF							1	-0.406	-0.111	0.110	-0.320
IPI								1	-0.006	-0.127	0.220
EXCMKET									1	-0.033	0.015
TRYRET										1	-0.152

This table contains the pairwise correlation coefficients for a set of economic variables estimated for the full sample period. *TERM* is the slope of the term structure of interest rates; *EINF* is the one-year expected inflation rate; *EPU* is the (log) of the economic policy uncertainty Index of Baker, Bloom, and Davis (BBD) (2016); *MUNC* is the macroeconomic uncertainty of Jurado, Ludvigson, and Ng (JLN) (2015); *FUNC* is the financial uncertainty of JLN (2015); *RA* is the European Central Bank measure of risk aversion; *DEF* is the default spread; *IPI* is the industrial production index growth; *EXCMKET* is the excess market portfolio return; *TRYRET* is the excess return of the composite Treasury bonds, and *FED* is the change in the effective Federal funds rate.

Table 4. Average Percentages of Daily Dynamic Risk-Neutral Equity and Treasury Volatility Connectedness. January 1989-September 2017

	Total Volatility Connectedness	Directional Connectedness from VIX to MOVE	Directional Connectedness from MOVE to VIX	Net Connectedness (From VIX to MOVE)	Net Connectedness Q1	Net Connectedness Q2	Net Connectedness Q3
Jan 1989-Oct 2017	28.83	22.79	34.86	-12.07 (0.000)	-14.56 (0.000)	-12.16 (0.000)	-8.11 (0.000)
Jan 1989-Mar 2001	31.63	26.39	36.86	-10.47 (0.000)	-13.93 (0.000)	-9.24 (0.000)	-7.21 (0.000)
Apr 2001-Oct 2017	26.76	20.13	33.38	-13.25 (0.000)	-15.23 (0.000)	-13.74 (0.000)	-10.37 (0.000)
NBER Recession	32.47	23.32	41.61	-18.29 (0.000)	-19.93 (0.000)	-19.36 (0.000)	-18.64 (0.000)
Non-NBER Recessions	28.39	22.73	34.06	-11.32 (0.000)	-13.95 (0.000)	-11.70 (0.000)	-7.36 (0.000)

This table shows the estimated connectedness with 7160 daily observations from January 19, 1989 through October 5, 2017. The numbers are average percentages of volatility connectedness estimated over 200-day rolling-sample window for the full sample and alternative sub-periods. The first column shows total connectedness across equity and Treasury risk-neutral volatilities. The second and third column represent directional connectedness from VIX to MOVE and from MOVE to VIX, respectively. The fourth column gives the net connectedness and is equal to the difference between the directional connectedness from VIX to MOVE and from MOVE to VIX. The last three columns show the net connectedness for the three quartiles. In parentheses, we report the non-parametric *p*-values associated with the null hypothesis that net connectedness between risk-neutral volatilities are equal to zero.

Table 5. Underlying Economic and Geopolitical Events. January 1989-September 2017

Panel A: Overall Relevant Economic and Geopolitical Events for the U.S. Economy	
Events	*Dates*
Beginning NBER recession months	July 1990
Gulf War I (Desert Storm)	December 24, 1990 – January 23, 1991
Clinton election by the Democratic Party	October 16, 1991 – October 30, 1991
Mexican Peso Crisis (peso devaluated against US $ and US bailout package)	December 9, 1994 – December 28, 1994 and January 12, 1995 – February 2, 1995
Asian currency crisis: Dow Jones Industrial plunged 7.2% on October 27, 1997, and the US economy suffered a drop in both consumption and spending confidence	September 18, 1997 – November 14, 1997
Russian debt crisis (the ruble was devaluated in August 17, 1998) and Long Term Capital Management bailout. The Pastor & Stambaugh market-wide illiquidity measured reached its highest level on September 30, 1998	August 13, 1998 – November 30, 1998
Bush election	November 1, 2000 – November 8, 2000
Beginning NBER recession months	March 2001
Gulf War II	March 20, 2003 – April 30, 2003
Beginning Great Recession and FOMC lowered the policy rate by 75 basis points	July 25, 2007 – December 12, 2007 and January 22, 2008
Bearn Stern crisis	March 3, 2008 – March 17, 2008
Bankruptcy of Lehman Brothers and second highest market-wide illiquidity of the Pastor & Stambaugh measure	September 15, 2008 and September 30, 2008
European Stock Market collapse	October 10, 2008
European Financial Crisis and euro contagion (Eurostat release on Greece, signed first economic adjustment for Greece, and IMF emergency financial net for the Eurozone)	April 1, 2010 – May 7, 2010
Attack Twin Towers: Market re-opened	September 17, 2001

US Fiscal Cliff and financial institutions problems with LIBOR manipulation	December 2, 2012 – December 31, 2012
Federal Government shutdown	October 1, 2013 – October 17, 2013
Brexit	June 8, 2016 – June 27, 2016
Trump election	November 1, 2016 – November 9, 2016
Panel B: International Economic Crises	
International involvement of the Gulf War I with the Security Council Resolution	November 12, 1990 – January 28, 1991
International Asian currency crisis	January 2, 1997 – June 30, 1998
International Euro zone banking and sovereign crisis (first meeting of the euro zone leaders, German and French agreement on Euro, LTRO plan, and Draghi speech)	January 4, 2010 – September 9, 2012
Panel C: Specific US Treasury Bond Crises	
Bond market sell-off	February 16, 1994 – April 14, 1994
Large bond-market sell-off due to mortgage hedging activities	July 2013

Table 6. Explaining Dynamic Connectedness by Economic and Geopolitical Events. Daily Data: January 1989-September 2017

Panel A: Overall Relevant Economic and Geopolitical Events for the U.S. Economy

	Total Volatility Connectedness	Directional Connectedness from VIX to MOVE	Directional Connectedness from MOVE to VIX	Net Volatility Connectedness (From VIX to MOVE)
$\hat{\beta}_0$	28.593 (94.41)	22.702 (53.39)	34.484 (106.4)	-11.782 (-26.03)
$\hat{\beta}_1$	3.075 (3.18)	1.202 (0.99)	4.947 (4.12)	-3.745 (-2.60)
R^2	0.015	0.001	0.033	0.010

Panel B: International Economic Crises

	Total Volatility Connectedness	Directional Connectedness from VIX to MOVE	Directional Connectedness from MOVE to VIX	Net Volatility Connectedness (From VIX to MOVE)
$\hat{\beta}_0$	29.261 (88.84)	23.922 (55.09)	34.601 (100.9)	-10.679 (-25.29)
$\hat{\beta}_1$	-2.867 (-4.77)	-7.460 (-7.96)	1.726 (1.87)	-9.187 (-6.44)
R^2	0.024	0.086	0.017	0.113

Panel C: Specific US Treasury Bond Crises

	Total Volatility Connectedness	Directional Connectedness from VIX to MOVE	Directional Connectedness from MOVE to VIX	Net Volatility Connectedness (From VIX to MOVE)
$\hat{\beta}_0$	28.828 (97.47)	22.810 (55.53)	34.847 (107.6)	-12.037 (-27.10)
$\hat{\beta}_1$	-0.034 (-0.02)	-1.864 (-0.51)	1.795 (1.40)	-3.659 (-0.92)
R^2	0.000	0.000	0.001	0.001

This table runs OLS regressions with daily data of several measures of connectedness on dummy variables, which are equal to 1 if there is an overall relevant economic and geopolitical event for the U.S. Economy (Panel A), international crises (Panel B), or a US Treasury bond specific crisis (Panel C), and zero otherwise. Volatility connectedness is estimated over 200-day rolling-sample window. The first column shows that total connectedness across equity and Treasury risk-neutral volatilities. The second and third column represent directional connectedness from VIX to MOVE and from MOVE to VIX, and the third columns displays the net connectedness, respectively. We report the *t*-statistic from Newey-West/ HAC standard errors.

Table 7. Monetary Policy Target Rate Surprises, Real Activity Effects and the VIX-MOVE Total and Directional Connectedness. An Event Study Around Target Federal Funds Rate Changes: January 1989-July 2017.

Panel A: January 1989-July 2017														
Total Connectedness					VIX to MOVE					MOVE to VIX				
Const	Exp	Unexp	ADS Index	Adj R^2	Const	Exp	Unexp	ADS Index	Adj R^2	Const	Exp	Unexp	ADS Index	Adj R^2
3.369 (92.78)	-0.141 (-1.24)	-0.179 (-1.64)	-	0.073	3.093 (48.87)	0.229 (1.17)	0.139 (0.74)	-	0.024	3.554 (108.0)	-0.327 (-3.45)	-0.339 (-3.65)	-	0.271
3.379 (88.02)	-0.195 (-1.60)	-0.232 (-2.02)	0.035 (1.22)	0.073	3.150 (52.30)	-0.079 (-0.36)	-0.166 (-0.76)	0.198 (2.38)	0.116	3.543 (106.5)	-0.270 (-2.63)	-0.284 (-2.74)	-0.036 (-1.01)	0.272
Panel B: January 1989-March 2001														
Total Connectedness					VIX to MOVE					MOVE to VIX				
Const	Exp	Unexp	ADS Index	Adj R^2	Const	Exp	Unexp	ADS Index	Adj R^2	Const	Exp	Unexp	ADS Index	Adj R^2
3.405 (81.81)	0.069 (0.59)	0.036 (0.31)	-	-0.024	3.107 (40.96)	0.430 (2.13)	0.359 (1.86)	-	0.091	3.600 (82.41)	-0.123 (-1.18)	-0.140 (-1.30)	-	0.005
3.415 (80.40)	-0.010 (-0.08)	-0.039 (-0.35)	0.054 (1.69)	-0.015	3.173 (53.58)	-0.111 (-0.58)	-0.160 (-0.81)	0.370 (5.45)	0.455	3.586 (88.43)	-0.009 (-0.09)	-0.030 (-0.28)	-0.078 (-1.45)	0.038
Panel C: April 2001-July 2017														
Total Connectedness					VIX to MOVE					MOVE to VIX				
Const	Exp	Unexp	ADS Index	Adj R^2	Const	Exp	Unexp	ADS Index	Adj R^2	Const	Exp	Unexp	ADS Index	Adj R^2

3.339 (76.54)	-0.340 (-2.80)	-0.368 (-3.43)	-	0.290	3.086 (36.33)	0.049 (0.18)	-0.054 (-0.22)	-	-0.019	3.512 (117.3)	-0.525 (-6.97)	-0.514 (-7.50)	-	0.646
3.348 (64.80)	-0.377 (-2.24)	-0.406 (-2.68)	0.022 (0.51)	0.274	3.114 (29.24)	-0.058 (-0.14)	-0.166 (-0.44)	0.066 (0.60)	-0.037	3.510 (99.70)	-0.517 (-5.23)	-0.506 (-5.63)	-0.005 (-0.14)	0.636

This table runs OLS regressions with daily (event time) data of several measures of connectedness on the surprise (unexpected) and expected components of the Federal funds target rate change and real activity as represented by the ADS activity index of Arouba, Diebold, and Scotti (2009). Panel A shows the full sample period, and Panels B and C contain the results for the two-subperiods. The full sample consists of 83 target rate changes, and the first and second sub-periods have 42 and 41 changes, respectively. The first sub-period is characterized by an anti-inflationary monetary policy, while the second sub-period is characterized by output-based monetary policy. Volatility connectedness is estimated over 200-day rolling-sample window. The first column shows the total connectedness across equity and Treasury risk-neutral volatilities. The second and third column represent directional connectedness from VIX to MOVE and form MOVE to VIX, respectively. We report the *t*-statistic from Newey-West/ HAC standard errors.

Table 8. Real and Monetary Drivers of the VIX-MOVE Total and Directional Connectedness. Daily Data: January 1989-July 2017.

Panel A: January 19, 1989 to July 20, 2017											
Total Connectedness				VIX to MOVE				MOVE to VIX			
Const.	FED	ADS Index	Adj R^2	Const.	FED	ADS Index	Adj R^2	Const.	FED	ADS Index	Adj R^2
3.328 (284.4)	-0.502 (-1.01)	-0.007 (-0.63)	0.000	3.041 (140.5)	-0.097 (-0.11)	0.098 (4.17)	0.020	3.517 (364.0)	-0.721 (-1.54)	-0.065 (-5.48)	0.043
Panel B: January 19, 1989 to March 30, 2001											
Total Connectedness				VIX to MOVE				MOVE to VIX			
Const.	FED	ADS Index	Adj R^2	Const.	FED	ADS Index	Adj R^2	Const.	FED	ADS Index	Adj R^2
3.437 (347.9)	0.212 (0.56)	0.049 (3.13)	0.027	3.215 (188.6)	0.627 (0.86)	0.226 (6.78)	0.167	3.597 (389.9)	-0.028 (-0.07)	-0.041 (-2.41)	0.023
Panel C: April 2, 2001 to July 20, 2017											
Total Connectedness				VIX to MOVE				MOVE to VIX			
Const.	FED	ADS Index	Adj R^2	Const.	FED	ADS Index	Adj R^2	Const.	FED	ADS Index	Adj R^2
3.214 (205.1)	-4.787 (-1.52)	-0.095 (-8.32)	0.063	2.851 (91.62)	-3.610 (-0.67)	-0.060 (-2.27)	0.007	3.437 (255.8)	-5.194 (-1.93)	-0.120 (-9.56)	0.132

This table runs OLS regressions with daily data of several measures of connectedness on the effective FED funds rate change (*FED*) and real activity as represented by the ADS activity index of Arouba, Diebold, and Scotti (2009). Panel A shows the full sample period, and Panels B and C contain the results for the two-subperiods. The first sub-period is characterized by an anti-inflationary monetary policy, while the second sub-period is characterized by output-based monetary policy. Volatility connectedness is estimated over 200-day rolling-sample window. The first column shows the total connectedness across equity and Treasury risk-neutral volatilities. The second and third column represent directional connectedness from VIX to MOVE and from MOVE to VIX, respectively. We report the *t*-statistic from Newey-West/ HAC standard errors.

Table 9. Economic Drivers of the VIX-MOVE Total and Directional Connectedness. Monthly Data: January 1989-June 2017.

Panel A: Total Connectedness: January 1989-June 2017

Const	TERM	RES TERM	EINF	FED	Shadow Rate	TRY RET	FUNC	RES RA	RES DEF	IPI	EXC MKET	Adj R^2
3.170	4.031	-	4.275	-	-	-1.172	-0.014	5.103	-6.992	-4.098	0.297	0.121
(18.55)	(1.96)		(1.42)			(-1.72)	(-0.09)	(2.06)	(-1.25)	(-1.43)	(0.82)	
3.449	-	7.112	-	-0.278	-	-1.109	-0.127	3.625	-8.962	-4.170	0.078	0.182
(25.78)		(3.19)		(-2.57)		(-1.66)	(-0.85)	(1.55)	(-2.07)	(-1.40)	(0.22)	
3.457	-	6.889	-	-	-0.262	-1.185	-0.134	3.774	-8.612	-4.644	0.014	0.187
(26.20)		(3.07)			(-2.70)	(-1.81)	(-0.91)	(1.61)	(-2.06)	(-1.53)	(0.04)	

Panel B: Directional Connectedness from VIX to MOVE: January 1989-June 2017

Const	TERM	RES TERM	EINF	FED	Shadow Rate	TRY RET	FUNC	RES RA	RES DEF	IPI	EXC MKET	Adj R^2
3.311	8.552	-	1.590	-	-	-1.502	-0.515	0.566	-37.796	-9.246	-0.634	0.197
(10.29)	(2.28)		(0.26)			(-1.23)	(-1.99)	(0.13)	(-3.34)	(-1.81)	(-0.84)	
3.569	-	12.182	-	-0.274	-	-1.465	-0.587	-1.906	-32.133	-8.489	-1.028	0.225
(14.93)		(2.67)		(-1.16)		(-1.24)	(-2.21)	(-0.44)	(-3.43)	(-1.54)	(-1.33)	
3.593	-	11.964	-	-	-0.309	-1.584	-0.612	-1.981	-31.913	-8.965	-1.139	0.231
(15.33)		(2.62)			(-1.61)	(-1.35)	(-2.36)	(-0.46)	(-3.50)	(-1.58)	(-1.52)	

Panel C: Directional Connectedness from MOVE to VIX: January 1989-June 2017

Const	TERM	RES TERM	EINF	FED	Shadow Rate	TRY RET	FUNC	RES RA	RES DEF	IPI	EXC MKET	Adj R^2
3.120	1.448	-	5.649	-	-	-0.979	0.273	7.198	7.436	-1.740	0.714	0.159
(23.84)	(0.93)		(2.48)			(-1.94)	(2.57)	(4.01)	(1.62)	(-0.70)	(1.49)	
3.404	-	4.415	-	-0.274	-	-0.885	0.139	6.288	1.335	-2.314	0.595	0.207
(35.54)		(2.51)		(-3.83)		(-1.71)	(1.27)	(3.91)	(0.34)	(-0.94)	(1.28)	

3.403 (35.48)	-	4.196 (2.37)	-	-	-0.227 (-3.21)	-0.933 (-1.83)	0.143 (1.31)	6.577 (3.97)	1.759 (0.46)	-2.774 (-1.09)	0.561 (1.18)	0.202

This table runs OLS regressions with monthly data of several measures of connectedness on a set of economic drivers for the full sample period. Panel A shows total connectedness, and Panels B and C contain the results for the directional connectedness from VIX to MOVE and from MOVE to VIX, respectively. The second row of each panel contains the results with the effective *FED* funds rate, while the third row reports the results using the shadow interest rate. *TERM* is the slope of the term structure of interest rates; *EXPI* is the one-year expected inflation rate; *RESTERM* is the residual of *TERM* once is adjusted by the *FED* rate; *FED* is the change in the effective Federal funds rate; *Shadow rate* is the change in the shadow interest rate of Wu and Xia (2016); *TRYRET* is the excess return of the composite Treasury bonds; *FUNC* is the financial uncertainty of JLN (2015); *RESRA* is the European Central Bank measure of risk aversion adjusted by financial uncertainty and default; *RESDEF* is the residual of regressing the default spread on financial uncertainty and risk aversion; *IPI* is the industrial production index growth and *EXCMKET* is the excess market portfolio return. We report the *t*-statistic from Newey-West/ HAC standard errors.

Figure 1. VIX and MOVE: Daily Data from April 4, 1988-October 5, 2017

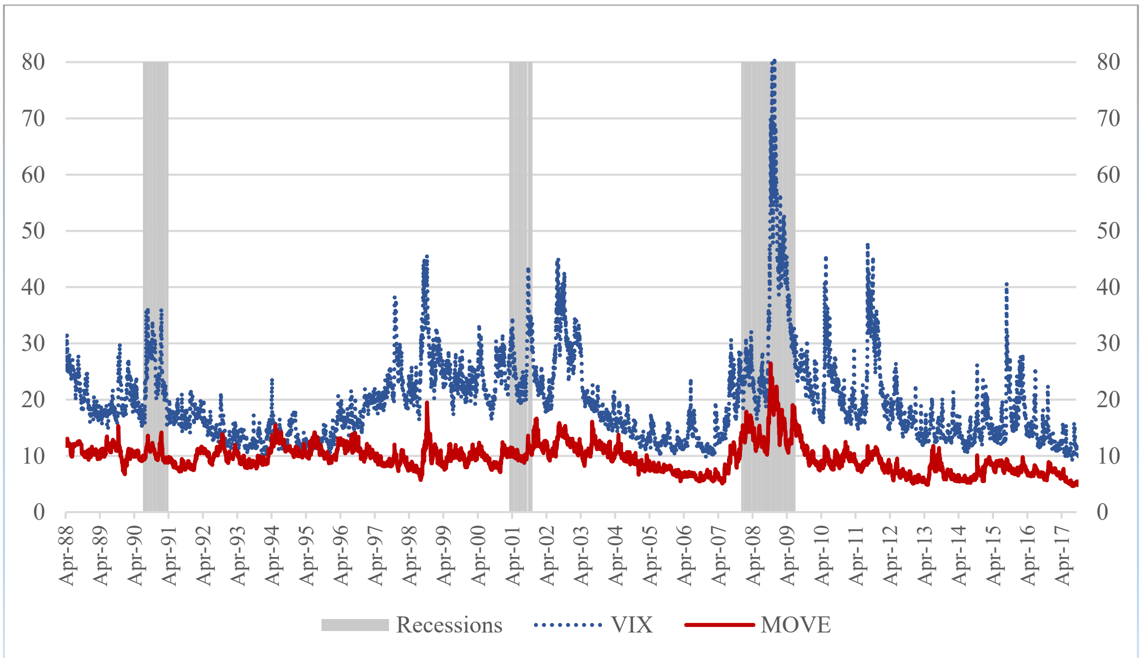


Figure 2. Monthly Volatilities of VIX and MOVE: Monthly Data from April 1988-September 2017

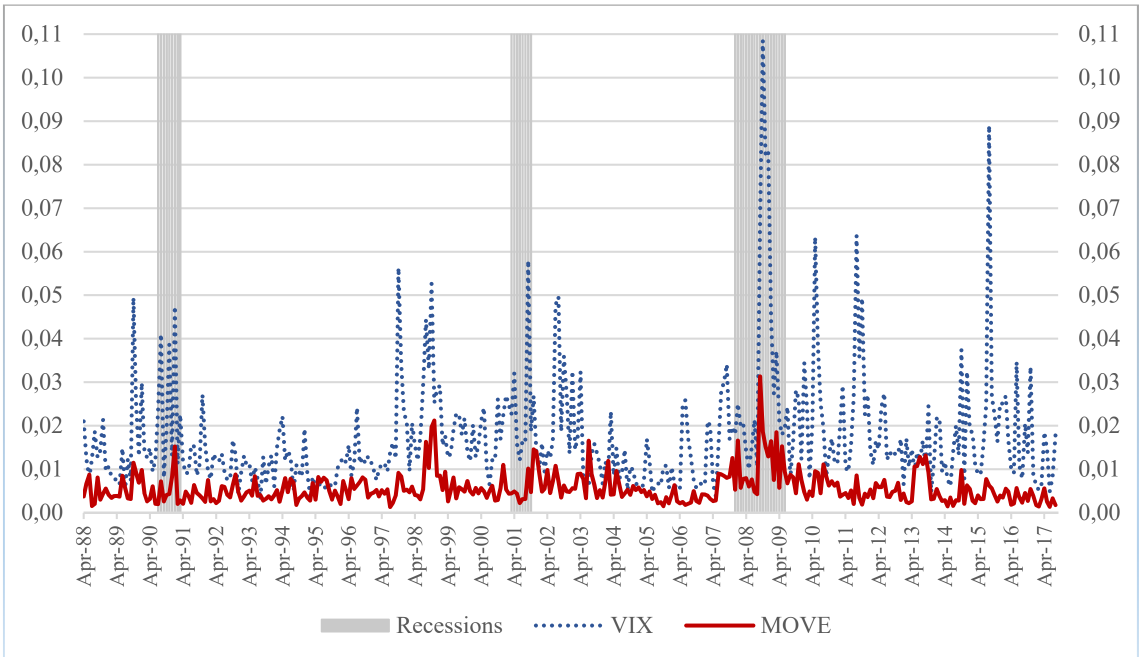


Figure 3. Treasury Market Beta and the Effective FED Funds Rate: January 1989-June 2017

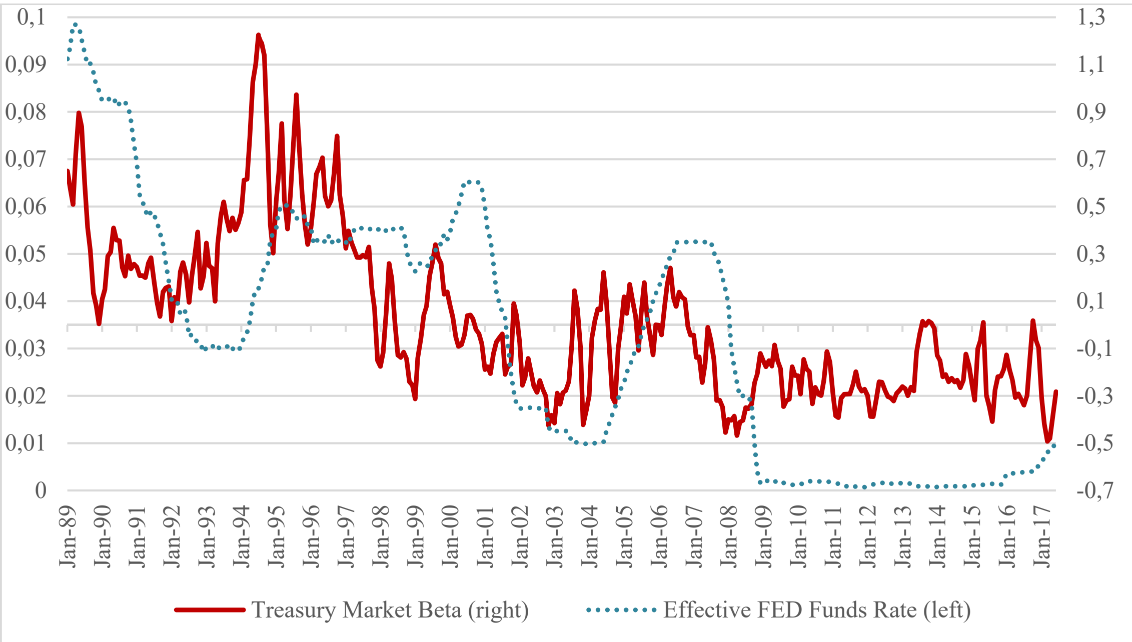


Figure 4. Rolling Total Volatility Connectedness: Monthly Data from Average Daily Connectedness within Each Month: January 1988-September 2017

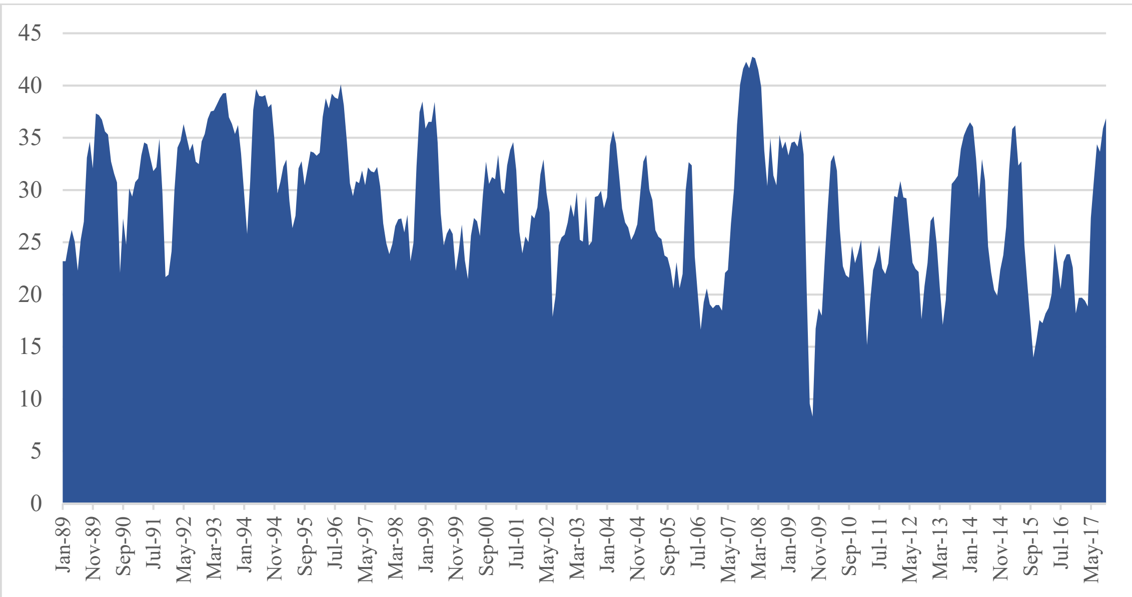


Figure 5. Directional Connectedness: Monthly Data from Average Daily Connectedness with Each Month: January 1989-September 2017

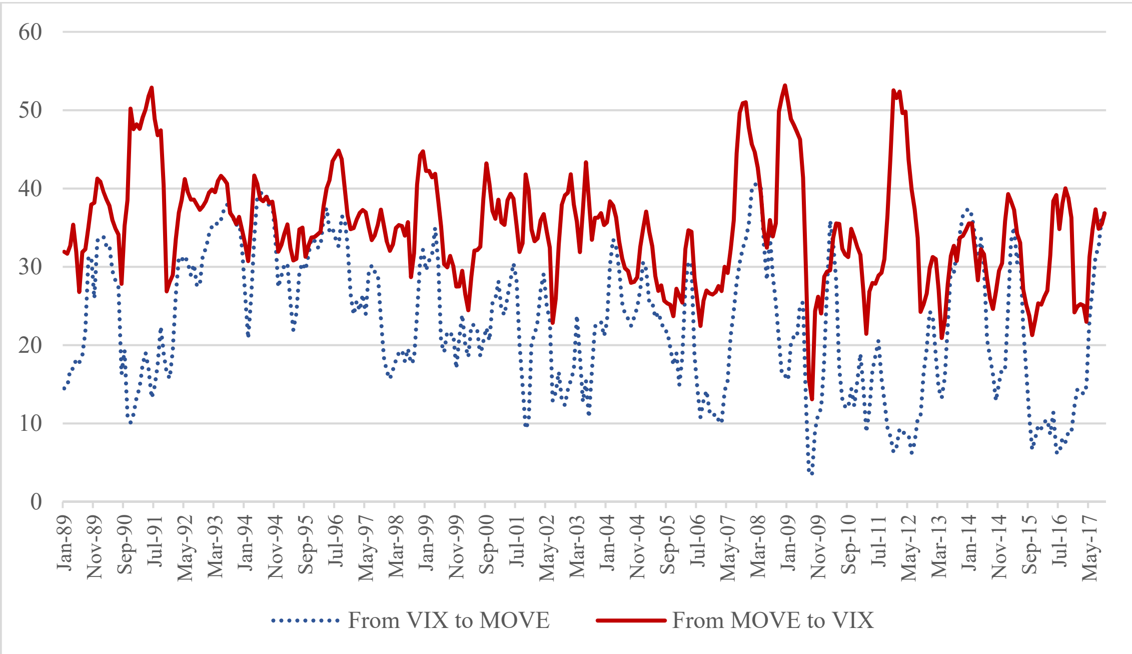
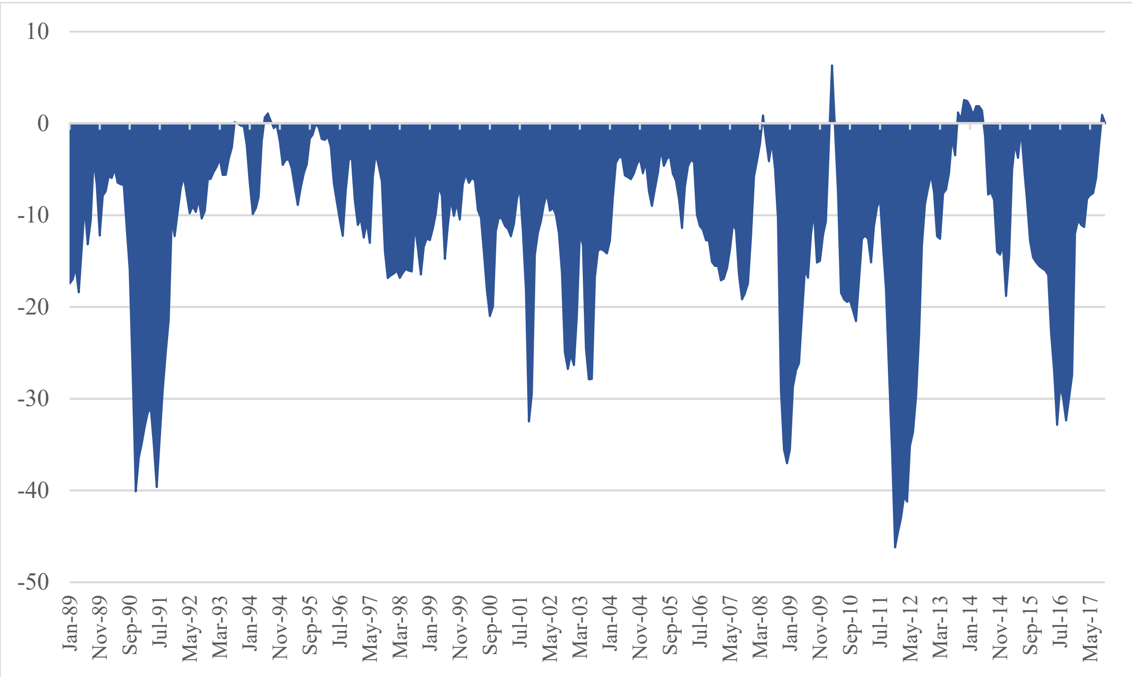


Figure 6. Net Pairwise Connectedness Calculated between the Directional Connectedness from VIX to MOVE and from MOVE to VIX with Monthly Data from Average Daily Net Connectedness within Each Month: January 1989-September 2017



APPENDIX

1. Total and Net Connectedness between Risk-Neutral Equity and Treasury Volatilities

We consider a covariance stationary N-variable VAR(p)

$$X_t = \sum_{i=1}^{p} \phi_i X_{t-i} + \varepsilon_t \,, \tag{A.1}$$

where $\varepsilon_t \sim (0, \Sigma)$ is a vector of independently and identically distributed disturbances and X_t denotes an N-dimensional vector of variables. To estimate the specific variance decomposition we rewrite the VAR(p) model as a moving average representation $X_t = \sum_{i=0}^{\infty} A_i \varepsilon_{t-i}$, where the $N \times N$ coefficient matrices are estimated by $A_i = \phi_1 A_{i-1} + \phi_2 A_{i-2} + \dots + \phi_p A_{i-p}$, with A_0 being the identity matrix and $A_i = 0$ for $i <$ 0. The variance decompositions are transformations of these moving average coefficients, which allows the researcher to parse the H-step-forecast error variances of each variable into proportions associated with the system shocks.

The variance proportions defined as the fractions of the *H*-step-ahead generalized error variances in forecasting X_i that are due to shocks to X_j, for $H = 1,2,\ldots$, are given by

$$\tilde{C}^{G}_{j\to i}(H) = \frac{\sigma_{jj}^{-1}\sum_{h=0}^{H-1}\left(e_i' A_h e_j\right)^2}{\sum_{h=0}^{H-1}\left(e_i' A_h \Sigma A_h' e_i\right)^2},\ j=1,2,\ldots,N, \qquad \text{(A.2)}$$

where σ_{jj} is the standard deviation of the error term for the j^{th} equation, i.e. the squared root of the diagonal elements of the variance-covariance matrix Σ and e_i is the vector with one as the i^{th} element and zeros otherwise. This generalized variance decomposition eliminates the dependence of the connectedness effects on the ordering of the variables. Nevertheless, as the shocks to each variable are not orthogonalized, the row sum of the variance decomposition is not equal to 1. Thus, each entry of the variance decomposition matrix is normalized by the row sum as

$$C^{G}_{j\to i}(H) = \frac{\tilde{C}^{G}_{j\to i}(H)}{\sum_{j=1}^{N}\tilde{C}^{G}_{j\to i}(H)} \times 100,\ j=1,2,\ldots,N. \qquad \text{(A.3)}$$

Hence, the reported results are in percentage terms and note that, by construction $\sum_{j=1}^{N} C^{G}_{j\to i}(H) = 100$ and $\sum_{i,j=1}^{N} C^{G}_{j\to i}(H) = N \times 100$. The measure $C^{G}_{j\to i}(H)$ represents the pairwise directional connectedness from variable *j* to *i* at horizon *H*. It represents the percentage of variation in variable *i* that is due to shocks in variable *j*. It takes high values when the intensity of the directional connectedness or spillover from *j* to *i* is high. When there is no directional connectedness from one series to the others, the indicator equals zero.

In our application, we only have two risk-neutral volatilities. Let VIX be variable *j*, and MOVE variable *i*. Then,

$$C^{G}_{VIX \to MOVE}(H) = \frac{\tilde{C}^{G}_{VIX \to MOVE}(H)}{\tilde{C}^{G}_{VIX \to MOVE}(H) + \tilde{C}^{G}_{MOVE \to MOVE}(H)} \times 100, \qquad \text{(A.4)}$$

indicates the percentage of variation in MOVE that is due to shocks in VIX. Alternatively,

$$C^{G}_{MOVE \to VIX}(H) = \frac{\tilde{C}^{G}_{MOVE \to VIX}(H)}{\tilde{C}^{G}_{VIX \to VIX}(H) + \tilde{C}^{G}_{MOVE \to VIX}(H)} \times 100, \qquad \text{(A.5)}$$

gives the percentage of variation in VIX that is due to shocks in MOVE. Under this pairwise framework, we can also obtain the net directional connectedness, which is given by

$$Net\left[C^{G}_{VIX,MOVE}(H)\right] = C^{G}_{VIX \to MOVE}(H) - C^{G}_{MOVE \to VIX}(H), \qquad \text{(A.6)}$$

where the net expression indicates the difference between the spillovers transmitted from VIX to MOVE and those transmitted from MOVE to VIX. Thus, a positive (negative) value implies a higher (lower) impact of VIX than vice versa. We can finally obtain a measure of total system connectedness given by the ratio of the sum of the off-diagonal elements of the variance decomposition matrix to the sum of all its elements,

$$C^{G}(H) = \frac{C^{G}_{VIX \to MOVE}(H) + C^{G}_{MOVE \to VIX}(H)}{C^{G}_{VIX \to VIX}(H) + C^{G}_{VIX \to MOVE}(H) + C^{G}_{MOVE \to MOVE}(H) + C^{G}_{MOVE \to VIX}(H)} \times 100$$

$$\Rightarrow C^{G}(H) = \frac{C^{G}_{VIX \to MOVE}(H) + C^{G}_{MOVE \to VIX}(H)}{2} \times 100.$$

(A.7)

2. Alternative Measures of Risk-Neutral Treasury Bond Volatilities

We have monthly data from the implied volatility estimates by Choi, Mueller, and Vedolin (2017), and from the 10-year Treasury bond implied volatility proposed by CBEO known as VXTYN. Note that MOVE is a weighted index on the 2, 5, 10, and 30-year contracts.

Figure A.1. Treasury Implied Volatilities and MOVE: January 1990-September 2012

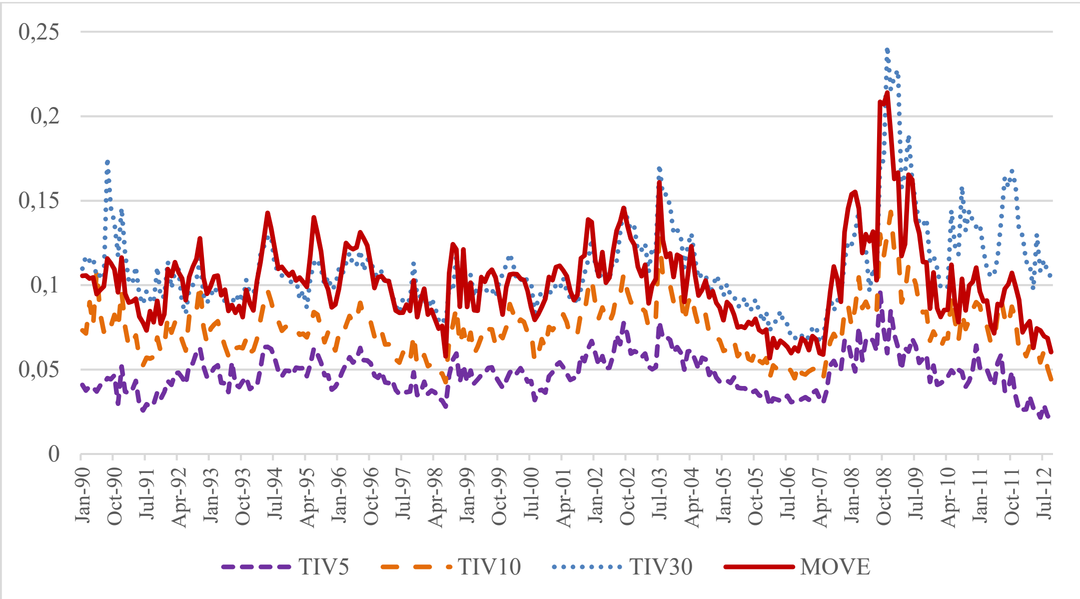
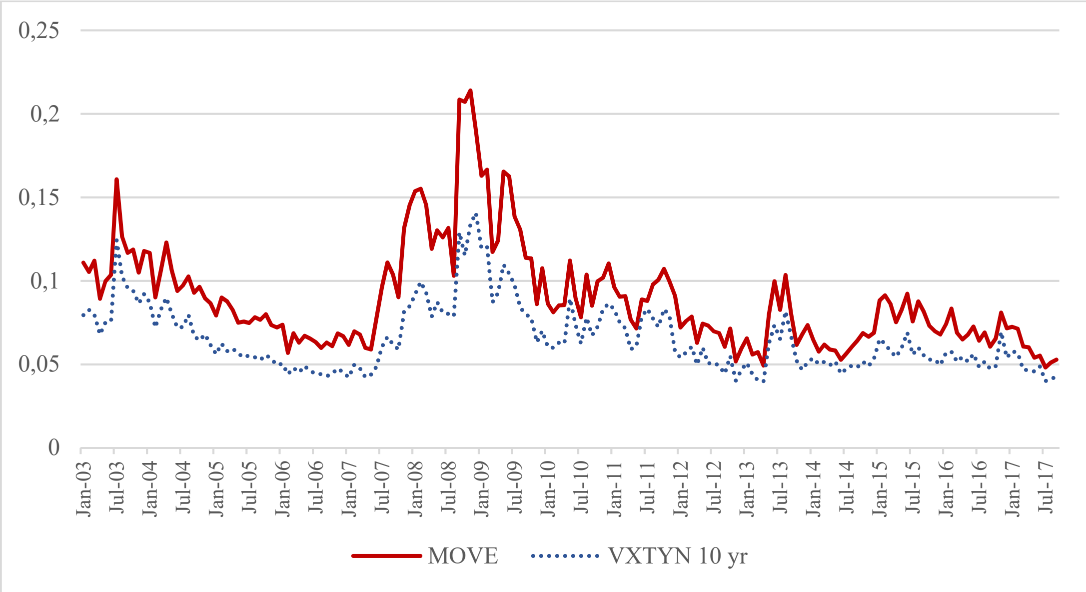


Figure A.2. VXTYN and MOVE: January 2003-September 2017


0,25
0,2
0,15
0,1
0,05
0
Jan-03
Jul-03
Jan-04
Jul-04
Jan-05
Jul-05
Jan-06
Jul-06
Jan-07
Jul-07
Jan-08
Jul-08
Jan-09
Jul-09
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Jul-10
Jan-11
Jul-11
Jan-12
Jul-12
Jan-13
Jul-13
Jan-14
Jul-14
Jan-15
Jul-15
Jan-16
Jul-16
Jan-17
Jul-17
MOVE
VXTYN 10 yr