ORIGINAL ARTICLE

Spillover dynamics effects 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 and Treasury risk-neutral volatilities. In this paper, we study the total and directional connectedness, in the sense of spillover effects, between risk-neutral volatilities from the equity and Treasury markets. In addition, we analyze the economic and monetary drivers of connectedness dynamics. Most of the time, but especially during bad economic times, we find significant net spillovers from Treasury to equity risk-neutral volatility. The spillover channel between risk-neutral volatilities arises mainly through the government fixed income market.

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 risk factors contribute to explaining the risk premia and volatility of both equity and Treasury bond returns. We can characterize macro-finance models under two general specifications. The consumption-based model was represented by Epstein and Zin (1989), Campbell and Cochrane (1999), and Bansal and Yaron (2004), and the financial intermediary approach of Brunnermeier (2009), Krishnamurthy and He (2013), Brunnermeier and Sannikov (2014), and Adrian et al. (2014). Both specifications motivate our research.

On the one hand, as discussed by Cochrane (2017), consumption-based macrofinance models employ aggregate consumption growth and a (non-separable) recession-related variable that accounts for most of the equity and bond risk premia. Even more important to motivate our research is that the recession-based variable, which must be sensible enough to changes in marginal utility of consumption to price financial assets, generates equity and bond volatilities. However, to the best of our knowledge, there is no evidence about the links between these two volatilities. This is the goal of our paper. To be precise, we estimate and analyze the statistical and economic connections between risk-neutral volatilities of equity and Treasury bond returns.

To fully understand the relation between consumption-based macro-finance models and risk-neutral rather than realized volatilities, it is crucial to recognize that a potential channel through which these models incorporate the effects of risk-neutral volatilities is through the additional recession-related variable that the most popular macro-finance specifications incorporate in the stochastic discount factor. Note that the tendency for asset prices to decline when this recession-related variable is bad drives risk premia and, in addition, changes in the conditional density of this variable generate timevarying risk premia. The point is that this variable is directly associated with fears embedded in risk-neutral volatilities. In other words, volatilities under the risk-neutral probability adjust for risk by weighting bad states more than good states, which is consistent with the key role played by macro-risk factors in the true unobservable stochastic discount factor that price both equity and Treasury returns. Moreover, and in contrast to realized volatilities, risk-neutral volatilities are ex ante or forward-looking measures that can be extracted from option prices. Therefore, the information content of these risk-neutral measures reflects expectations about risk, and thus, they are closely related to expected risk premia as recently shown by Martin (2017). These insights have guided our decision of working with risk-neutral rather than realized volatilities.

Under this characterization, our hypothesis is that equity and Treasury bond riskneutral volatilities are connected in the sense of volatility spillover effects given the macroeconomic fears embedded in both markets throughout the business cycle. Both measures contain information about the risk aversion of participants in each of these markets. Under an intertemporal framework, risk aversion is countercyclical and especially high during recessions. Thus, we expect a positive connection between them. However, the magnitude of the effect of a macroeconomic negative shock in equity and Treasury bond markets should be different given the different risk nature of both

assets. Therefore, and additionally, we expect this connection to be time varying over the business cycle.

The consumption-based macro-finance models focusing on risk aversion is not the only possibility to justify the use of risk-neutral volatilities. As pointed out above, macro-finance models also include the so-called intermediary asset pricing models. Note that these models shift attention from measuring the stochastic discount factor of the representative household as the marginal rate of substitution of consumption to the growth rate of the marginal value of wealth of financial intermediaries. These intermediaries are now situated in the center stage of the asset pricing specification. To understand the connection with risk-neutral volatilities, it is essential to recall that intermediary financial models explicitly work in a segmented markets framework. These models give more weight to the role of borrowers than to the role of creditors. Debt time-varying capacity reflects the health of financial intermediaries. As margins increase in bad times, funding constraints tighten, and financial intermediaries are forced to deleverage. Of course, this scenario is consistent with an increase in the economy-wide risk aversion. To distinguish between consumption-based macro-finance models with the recession-related variable and the financial intermediary specification is not an easy task. In an important paper, Haddad and Muir (2021) show that indeed the participation of financial intermediaries matters because return predictability and risk premia variation are more pronounced for asset classes in which they are more active, like currencies, credit and option markets, while households concentrate on equities. Therefore, this alternative specification also motivates the use of risk-neutral volatilities extracted from option prices rather than realized volatilities. In any case, from our point of view, both motivations are equally valid, and our results do not favor either one.

As a measure of the equity risk-neutral volatility we employ the Chicago Board Options Exchange (CBOE) Volatility Index (the VIX). It has become an extremely popular and useful measure of near-term market volatility. It is surprising, however, that the vast literature on implied volatility focuses almost exclusively on equity markets. Notable exceptions are Choi et al. (2017), Mueller et al. (2016), Mele et al. (2015). We use the Merrill Lynch Option Volatility Estimate Index (the MOVE), as Treasury implied volatility. This is a term structure weighted index equivalent to the VIX for Treasury bond returns. It reflects a market-based measure of uncertainty about the composite future behavior of interest rates across different maturities of the yield curve.

Our aim is to study the spillover effects or connectedness between the VIX and the MOVE. By connectedness, we mean measures of how much future unexpected variation in the MOVE is explained by current shocks to the VIX and vice versa. To estimate connectedness, we employ the methodology proposed by Diebold and Yilmaz (2014), which is especially convenient in our context since it allows obtaining connectedness measures that capture not only the dynamic interactions between the variables along time, but also the directional connectedness from one to the other. For the total and directional connectedness measures, we first obtain unconditional estimated values using the full sample period, and, secondly and more important, a series of daily estimated values using rolling window subsamples to capture their time-varying pattern.

Using daily data from January 19, 1989, to September 29, 2017, we find that the directional connectedness from the Treasury to the equity is significantly higher than that from the equity to the Treasury. The directional connectedness from the MOVE to the VIX is 34.9%, while the directional connectedness from the VIX to the MOVE is 22.8%. Moreover, the level of the dynamic directional connectedness from the MOVE to the VIX is associated with recessions and geopolitical stressed US events. Indeed, it is predominantly higher during bad economic times (41.6%).

Therefore, our contribution shows that, for most of the sample period, but especially during bad times, the spillover channel between risk-neutral volatilities arises mainly through the government fixed income market, rather than through the equity market. This constitutes the key empirical finding of our paper. To further clarify the relevance of the reported fear connectedness transmission, it is also important to point out that the connectedness dynamics between realized equity and Treasury volatilities is extremely small relative to the connectedness between risk-neutral volatilities. To understand these differences, note that the risk premium associated with any tradeable asset is defined as the difference between the values under the physical and risk-neutral probabilities. Hence, the variance risk premium is the realized variance (the variance under the physical probability) minus the risk-neutral variance (the variance under the risk-neutral probability measure). Given that the effects are found in the risk-neutral volatilities, but not in the realized volatilities, we conclude that the risk-neutral volatility connectedness comes through the volatility risk premia associated with the equity and Treasury markets. As explained above, this is consistent with the key role of financial intermediaries in the option markets.

Our second analysis consists of investigating which are the drivers of the time variation of connectedness from a large set of state variables including real activity measures, economic and financial indicators, and monetary policy instruments. Inspired by the analysis of Campbell et al. (2020), who employ time-varying risk premia of stocks and bonds to explain the correlation between inflation and the output gap over the business cycle, we show that the relation between monetary and real effects, and the connectedness characteristics of the two series depends on whether the US government followed either an anti-inflationary or an output-supportive monetary policy. During the full sample period, but especially in the latter sub-period from April 2001 to July 2017, we find that decreases in real activity are associated with increases in the directional connectedness from the MOVE to the VIX, but not from the VIX to the MOVE. Overall, increases in variables signaling bad economic times, like credit spreads, risk aversion, or financial uncertainty are positive and significantly related to the volatility spillovers from the MOVE to the VIX, while they tend to be negatively related to the directional connectedness from the VIX to the MOVE.

This paper proceeds as follows: Sect. 2 is focused on the estimation of the connectedness dynamics between risk-neutral volatilities and their comparison with those estimated from realized volatilities. In Sect. 3, we study the relation between connectedness dynamics and a large set of potential economic and financial drivers. In Sect. 4, we discuss some economic implications of our results, and in Sect. 5 we present our conclusions. Additional information is provided in three Appendices at the end of the

paper: A) The details about the statistical procedure employed to estimate connectedness; B) the description of the state variables used as potential drivers; and C) a robustness analysis using an alternative risk-neutral Treasury volatility.

2 Connectedness between risk-neutral volatilities

The first step of our analysis is to estimate the connectedness between risk-neutral volatilities of the equity and the Treasury bond markets. Hence, in this section, we first describe the methodology employed and motivate the use of risk-neutral volatilities. Then, we present the data and report and discuss the main results. Finally, we compare the measures of connectedness estimated from option-model free volatilities with those obtained from realized volatilities.

2.1 Methodology: insights and motivation

The stylized facts of international financial returns and 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. We employ the methodological econometric framework of Diebold and Yilmaz (2012, 2014, 2015, 2016). These authors have applied this framework to the analysis of volatilities across international markets. However, the analysis of the connectedness between risk-neutral volatilities across asset classes is not part of their research.

A detailed description of the statistical approach of this methodology and the presentation of the different connectedness measures can be found in "Appendix A". The idea relies on the variance decomposition of the forecasting error using a vector autoregression (VAR) framework. Under this decomposition, the directional connectedness from one variable X_i to another variable X_j in the VAR system is the fraction of the H-step-ahead generalized error variances in forecasting X_j that are due to shocks in X_i.

Connectedness measures based on the variance decomposition are especially appropriate for many reasons. First, they are rigorous in theory and readily implemented in practice, and moreover, they are totally intuitive in the sense that inform about how much of the future unexpected variation of one variable is due to current shocks in another. Second, these connectedness measures are closely linked to recently proposed measures of various types of systemic risk, such as marginal expected shortfall (Acharya et al. 2017) and CoVaR (Adrian and Brunnermeier 2016). In particular, the Diebold and Yilmaz methodology presents the advantage that the variance decomposition is invariant to the ordering of the variables in the VAR system. Instead of attempting to orthogonalize shocks, the authors use the generalized VAR approach of Koop et al. (1996) and Pesaran and Shin (1998), which allows for correlated shocks but accounts appropriately for the correlation. Moreover, this methodology allows not only identifying the dynamics of the connectedness along time, but also expressing these measures as a percentage because they use normalized elements of the variance

decomposition matrix (Demirer et al. 2018). We could also rely on alternative iden-
tification schemes, such that the one in Bekaert et al. (2021), which does not require
any ordering of the variables. However, their procedure employs a multi-step estima-
tion process, which complicates the statistical inference because of the accumulation
of sampling errors. A formal direct comparison of both methodologies is outside the
scope of this paper.

In our case, the VAR dimension is two given by the VIX and the MOVE volatilities.
In contrast to ex post volatilities, the information content of these risk-neutral measures
reflects expectations about risk, and thus, they are closely related to expected risk
premia. They adjust for risk by weighting bad states more than good states, which is
consistent with the countercyclical time pattern of the true unobservable stochastic
discount factor that price both equity and Treasury returns. If, as often argued, the
VIX tracks in-equity investor fear, the MOVE provides a gauge of in-Treasury investor
fear. Hence, our analysis studies whether the amount investors are willing to pay to
hedge equity market risks is connected to the amount they are willing to pay to hedge
unexpected changes in risk-free interest rates. Since both ex ante volatilities react
upward during periods of negative shocks in macro-risk factors, we expect to find a
positive connection between them. Our paper analyzes not only total connectedness,
but also the directional connectedness between both types of volatilities, and the net
connectedness from the VIX to the MOVE.

In addition, there is evidence suggesting that the risk-neutral volatilities connection
are time varying. Campbell et al. (2020) is an example. The authors show that the
exposure of Treasury bonds to the equity market has changed considerably over time
and that this time-varying behavior is partly driven by the US monetary policy. A
positive exposure is associated with anti-inflationary US monetary policy, while neg-
ative Treasury betas are linked to monetary policy associated with output fluctuations,
which made Treasury bonds act as hedgers of stock market declines. In that sense, the
level of fears of participants in the two markets should be different depending not only
on the economic cycle, but also on the type of the monetary policy followed by the
US government. Alternatively, fears could also be different depending on the time-
varying behavior of the price of risk and the associated precautionary savings motive
discussed by Laarits (2020). Both reasons suggest that the connectedness between the
VIX and the MOVE is indeed time varying. To evaluate whether this is the case, we
estimate dynamic connectedness measures using rolling overlapped sample windows.
The objective of this analysis is, first, to confirm the potential time-varying pattern
of connectedness and next to identify which are the drivers explaining this dynamic
behavior. This second analysis is presented in Sect. 3.

2.2 The VIX and the MOVE data

We collect daily and monthly data for the VIX and the MOVE from the CBOE and
Bloomberg, respectively, for the period between April 4, 1988, and September 29,
2017. The VIX is computed by averaging the weighted prices of one-month maturity
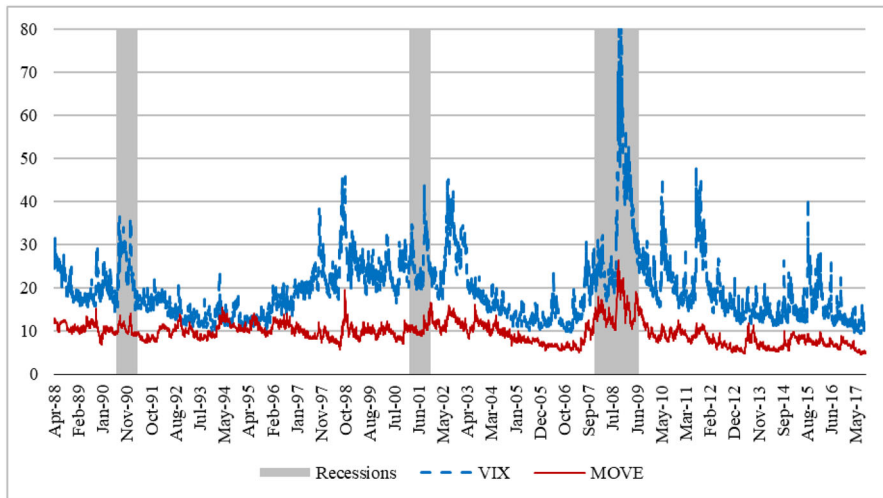puts and calls on the Standard & Poor (S&P) 500 Index over a wide range of strike

Fig. 1 The VIX and the MOVE. Daily data: April 4, 1988, to September 29, 2017

prices.[1] The MOVE is a term structure weighted index of the normalized implied volatility on one-month Treasury options weighted on two-, five-, 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 the MOVE suggest that the market is willing to pay more to hedge against unexpected movements in interest rates.[2]

Figure 1 shows the annualized daily behavior of the VIX and the MOVE, and Table 1 reports their descriptive statistics. As expected, risk-neutral volatilities are countercyclical, but the spikes during recessions and economic crises are much larger in equity volatility than in Treasury volatility. Over the full sample period, the average risk-neutral volatility for the stock market is 19.5%, whereas the risk-neutral volatility for the Treasury is much lower, at 9.7%. The VIX is also much more volatile than the MOVE, and accordingly, the range between the minimum and maximum values is higher for the VIX. The minimum (9.3%) and maximum (80.9%) levels for the VIX are reached on December 22, 1993, and on November 20, 2008, respectively, whereas the minimum (4.7%) and maximum (26.5%) for the MOVE are observed on August 7, 2017 and on October 10, 2008, respectively. On the other hand, the high value for the MOVE at the end of July 2003 (16.1%) is remarkable, a month in which the VIX is at average value. As pointed out by Malkhozov et al. (2016), this month coincides with the large bond market sell-off due to mortgage hedging trading.

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[1] The VIX data are available from January 1990 onwards. We employ the risk-neutral market volatility (VXO) for the U.S. S&P 100 Index from April 1988 to December 1989 to complete the data.

[2] 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. Our main results refer to the MOVE data because of the much longer sample period available for analysis. However, in "Appendix C", we also report evidence regarding TYVIX as a robustness analysis.

Table 1 Summary statistics of the VIX and the MOVE. Daily data: April 4, 1988, to September 29, 2017

	Full Sample Period		April 1988–March 2001		April 2001–September 2017	
	VIX	MOVE	VIX	MOVE	VIX	MOVE
Mean	0.1948	0.0965	0.1920	0.1021	0.1970	0.0921
Volatility	0.0768	0.0257	0.0570	0.0155	0.0894	0.0308
Minimum	0.0931	0.0469	0.0931	0.0575	0.0936	0.0469
Maximum	0.8086	0.2646	0.4574	0.1950	0.8086	0.2646
Skewness	2.1142	0.9657	0.8462	0.3693	2.1860	1.2879
Kurtosis	8.0302	2.7383	0.9361	0.6884	7.0653	2.3524
AR (1 month)	0.8405	0.8539	0.8089	0.6881	0.8525	0.8790
AR (5 days)	0.9326	0.9461	0.9177	0.8744	0.9373	0.9509
AR (1 day)	0.9808	0.9879	0.9768	0.9703	0.9873	0.9909

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&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 two-, five-, 10-, and 30-year contracts. The VIX and the MOVE series are at daily frequency. Autocorrelations are reported for 1- month, and 1- and 5- day lags. The monthly autocorrelation is estimated using the last day of each month

The different time-varying behavior of the VIX and the MOVE suggests that, from a careful analysis of both risk-neutral volatilities, we could learn how relevant economic events affect the relative behavior of both markets, as well as how these events connect or produce spillovers between both markets. Finally, the VIX presents much higher positive skewness and kurtosis than the MOVE and both implied volatilities are highly persistent.

To complete the picture, in Fig. 2, we show the monthly volatility for the VIX, and the MOVE estimated with daily data within each month. These volatilities are plausible measures of financial uncertainty in the equity and Treasury bond markets, respectively. As expected, the VIX is much more volatile than the MOVE, with large spikes during times of recessions and bad economic news. However, the spikes of the two series tend to coincide in time. These patterns further motivate a formal analysis of the connectedness between equity and Treasury risk-neutral volatilities.

As pointed out before, Campbell et al. (2020) show that the exposure of Treasury bonds to the equity market has changed considerably over time and that this time varying behavior is partly driven by the US monetary policy. To confirm these authors' evidence, we estimate rolling Treasury betas during our sample period. We employ daily excess returns of a composite index of the five-, 10-, and 30-year horizons of Treasury bonds and of the S&P 500 index and we estimate monthly Treasury market betas with daily data within the last three months.[3] Figure 3 (solid line) confirms the

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[3] Treasury bond returns data are obtained from the Federal Reserve Bank of St. Louis' Federal Reserve Economic Data (FRED) database (https://fred.stlouisfed.org/).
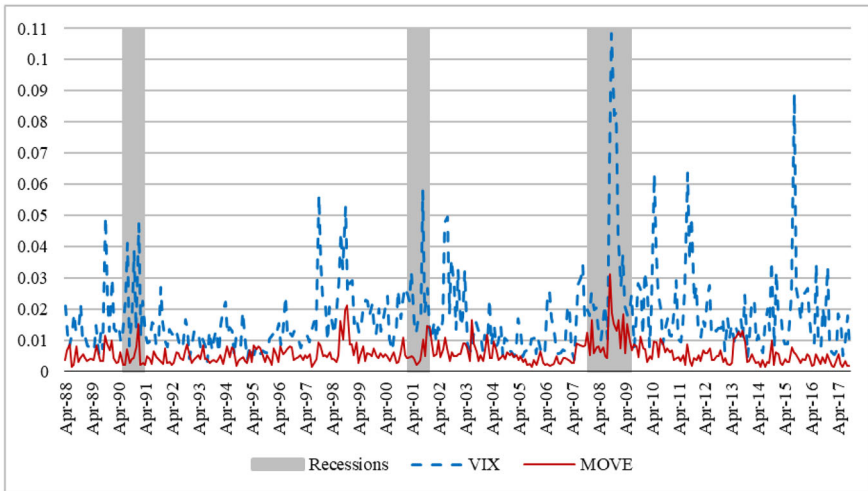
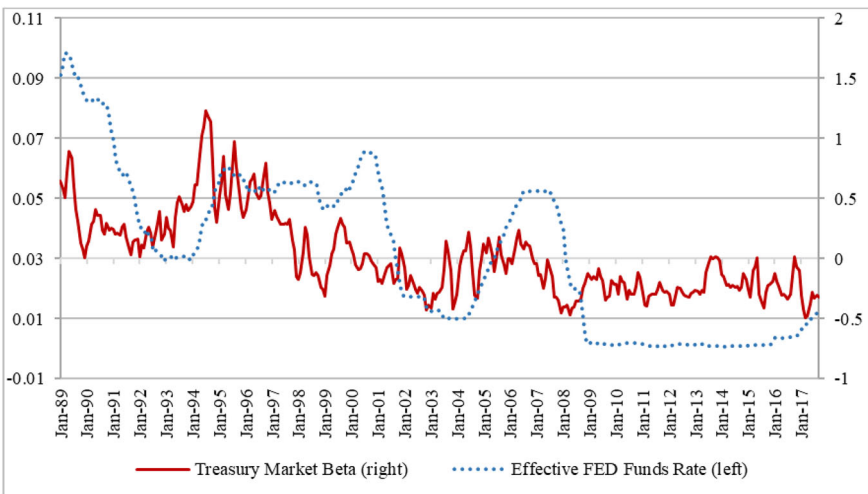**Fig. 2** Volatilities of the VIX and the MOVE. Monthly data: April 1988 to September 2017

Fig. 3 Treasury market beta and the effective FED funds rate: January 1989 to September 2017. Treasury market beta is estimated each month, from January 1989 to September 2017, using daily excess returns of a composite index of the five-, 10-, and 30-year horizons of Treasury bonds and of the S&P 500 index within the last three months

time-varying pattern of the Treasury market beta during our sample period. We use the data breaks from Campbell et al. (2020) to split the sample in two non-overlapping sub-periods, the first from April 1998 to March 2001, and the second from April 2001 to September 2017. Accordingly with the evidence in Campbell et al. (2020), the average Treasury market beta is positive in the first sub-period (0.31) while negative in the second (− 0.19). This different exposure of the Treasury bond market to the

equity market in the two sub-periods suggests that the relation between the VIX and the MOVE could also be different. This explains why we analyze the connectedness between them for both the full sample period and the two sub-periods separately. Campbell et al. (2020) attribute the positive beta to the strong anti-inflationary US monetary policy, and the negative beta to the focus of monetary policy on output fluctuations. Figure 3 also displays the effective *FED* funds rate which is the volume-weighted average of the borrowing and lending rates across banks using federal funds.[4] As expected, the behavior of Treasury betas seems to be closely related to monetary policy. In fact, the average *FED* funds rate is 5.7% until March 2001 and 1.4% during the second sub-period. The distinctive economic features of both sub-periods are very important for understanding the differences we find in some of the empirical results reported later in the paper across both sub-periods. A related way of understanding the break between these two sub-periods is provided by Bekaert et al. (2021), who employ non-Gaussian features in the US macroeconomic data to estimate macro-risk factors that generate supply and demand shocks. The authors define supply shocks as innovations that move inflation and real activity in opposite directions, while demand shocks move them 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 September 2017. This result suggests that, on average, our first sub-period is characterized by supply shocks, and the second sub-period by demand shocks. In addition, Laarits (2020) also shows that the covariance between stocks and government bonds between these two sub-periods changes from positive to negative. However, contrary to Campbell et al. (2020), this author argues that the precautionary savings, under a model with time-varying volatility of the price of risk of stocks, explain the variation in the stock–bond covariance regardless of the prevailing relationship between inflation and real growth.

In Table 1, we also present descriptive statistics of the VIX and the MOVE for the two sub-periods. Although the average levels are certainly similar in the two sub-periods, the volatility, and higher-order moments of the two series present intriguing differences. The volatility, positive skewness, and particularly the excess kurtosis of the two series are higher in the second sub-period. Even the autocorrelations are higher during the second sub-period, especially for the MOVE.

2.3 Connectedness measures: estimation results

In this section, we present the results of the alternative connectedness measures between the VIX and the MOVE estimated as described in "Appendix A". To approximate normality, we take natural logarithms of the original daily VIX and MOVE series. To provide additional information about the co-movements between risk-neutral volatilities, it is also useful to look at the correlation as a simpler measure of the link between these risk-neutral volatilities.

We first estimate both the correlation and connectedness between the VIX and the MOVE using the full sample period, from April 4, 1988, to September 29, 2017. Results are shown in Panel A of Table 2, where correlations are given in percentage terms for

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[4] The effective *FED* funds rate is downloaded from the FRED database.

Table 2 Correlations and connectedness between risk-neutral equity and Treasury bond volatilities

Panel A: Correlations and connectedness measures for the whole period: April 4, 1988, to September 29, 2017

	Unconditional correlation	Total connectedness	Directional connectedness from the VIX to the MOVE	Directional connectedness from the MOVE to the VIX	Net connectedness from the VIX to the MOVE
Apr 1988–Sep 2017	61.61	13.73	10.25	17.21	− 6.96

Panel B: Average of dynamic correlations and connectedness measures: January 19, 1989, to September 29, 2017

	Average conditional correlation	Average total connectedness	Directional Connectedness from the VIX to the MOVE	Directional Connectedness from the MOVE to the VIX	Net Connectedness from the VIX to the MOVE	Net Connectedness Q1	Net Connectedness Q2	Net Connectedness Q3
Jan 1989–Sep 2017	39.83	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	35.04	31.63	26.39	36.86	− 10.47 (0.000)	− 13.93 (0.000)	− 9.24 (0.000)	− 7.21 (0.000)
Apr 2001–Sep 2017	43.37	26.76	20.13	33.38	− 13.25 (0.000)	− 15.23 (0.000)	− 13.74 (0.000)	− 10.37 (0.000)

Table 2 (continued)

Panel B: Average of dynamic correlations and connectedness measures: January 19, 1989, to September 29, 2017

	Average conditional correlation	Average total connectedness	Directional Connectedness from the VIX to the MOVE	Directional Connectedness from the MOVE to the VIX	Net Connectedness from the VIX to the MOVE	Net Connectedness Q1	Net Connectedness Q2	Net Connectedness Q3
NBER recessions	66.24	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	36.76	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 estimated unconditional correlations and connectedness measures for the full sample period, from April 4, 1988, to September 29, 2017, in Panel A, and average percentages of daily risk-neutral volatility conditional correlations and connectedness estimated over a 200-day rolling-sample window, in Panel B. In this case, the average refers to the full sample period, from January 19, 1989, to September 29, 2017, in the first row, and to alternative sub-periods in the rest of the rows. The first column shows the average conditional correlations, and the second column presents the average total connectedness across equity and Treasury risk-neutral volatilities. The third and fourth columns report directional connectedness from the VIX to the MOVE and from the MOVE to the VIX, respectively. The fifth column shows the net connectedness, which is equal to the difference between the directional connectedness from the VIX to the MOVE and from the MOVE to the VIX. The last three columns show the net connectedness for the three quartiles. We report in parentheses the non-parametric *p*-values associated with connectedness measures and the null hypothesis that the net connectedness between risk-neutral volatilities equals zero. Correlations are multiplied by 100 to report comparable numbers with connectedness measures

an easy comparison with connectedness. The unconditional correlation between the VIX and the MOVE is positive and equal to 61.6%, and the total connectedness value, given by expression (15) in "Appendix A", is 13.7%. Both numbers confirm the visual impression in Fig. 1 of positive co-movements between the VIX and the MOVE. It may be surprising to find this high unconditional correlation reported relative to the total connectedness measure. We come back to this point later when presenting the conditional analysis. An important issue, given the objective of the paper, comes from the directional connectedness measures. We find that, unconditionally, the spillovers mainly go from the MOVE to the VIX, since the directional connectedness in this case, calculated from expression (13), is 17.2% against the 10.3% value for the directional connectedness from the VIX to the MOVE calculated from (12). Consequently, net connectedness given by (14) is negative suggesting higher spillovers from the MOVE to the VIX than vice versa.

Although these unconditional measures may be useful as a first approximation, the most important analysis is associated with the time-varying behavior of the connectedness measures. Recall that our primary objective is to analyze how new information is transmitted across risk-neutral volatilities over the business cycle. Therefore, the core of the analysis should be dynamic. The first column of Panel B of Table 2 refers to the conditional correlation between the VIX and the MOVE estimated on daily basis with a 200-day rolling window to match the window length used to estimate connectedness dynamics as explained below. Then, note that the sample period for the conditional correlation starts on January 19, 1989. Confirming the visual impression in Fig. 1, the VIX and the MOVE are positively correlated showing an average correlation coefficient over the full sample of 39.8%. The difference between the unconditional and conditional average correlations suggests a time-varying behavior of the conditional correlation between the VIX and the MOVE. If we split the sample between the two sub-periods associated with monetary policies, we find that the average conditional correlation is lower during the anti-inflationary US monetary policy, from January 1989 to March 2001, than during the output-supportive US monetary policy regime, from April 2001 to September 2017 (35.0% versus 43.4%). Moreover, if we split the sample between the National Bureau of Economic Research (NBER) recession and non-recession dates, we find a much higher average conditional correlation during bad economic times (66.2% versus 36.8%).

The rest of columns shown in Panel B of Table 2 provide average values of the different dynamic connectedness measures. We estimate the directional and total risk-neutral volatilities connectedness each day by using the preceding 200-day sample window.[5] From the second column of Panel B of Table 2 onward, we show the average percentages of the alternative measures (total, directional and net) of the daily dynamic volatility connectedness. The three last columns display the first quartile (Q1), the median (Q2), and the third quartile (Q3) of the net connectedness distribution. The average total connectedness dynamics between the risk-neutral volatilities during the period between January 1989 and September 2017 is 28.8%, which is again lower than the average conditional correlation coefficient between the VIX and the MOVE. The

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[5] 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.

total connectedness dynamics measure presents a highly time-varying behavior, as displayed in Fig. 4a. The maximum level, observed on January 31, 2008, is 43.5%, while the lowest level occurs on September 9, 2009, reaching only 2.2%. This time-varying behavior can also be appreciated when we calculate the average total connectedness for different sub-periods. The average connectedness is 31.6% (26.8%) during the anti-inflationary (output-supportive) US monetary policy sub-period. Consistently with
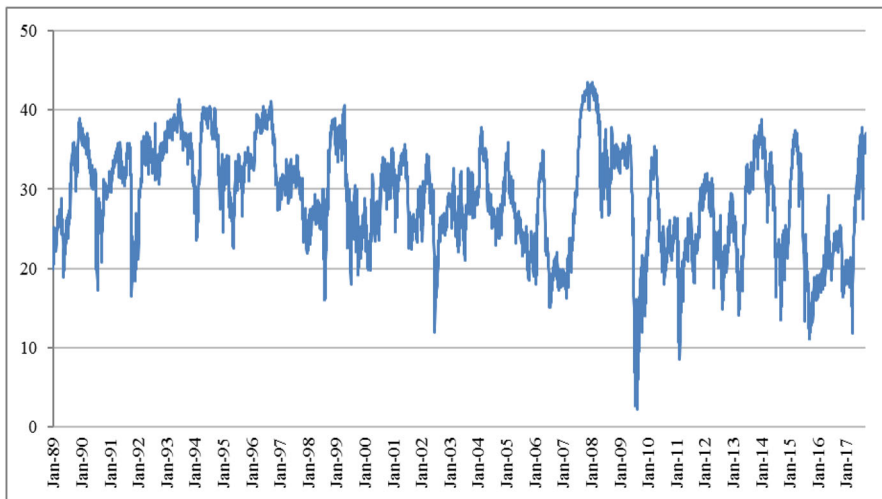
(a) Total connectedness between the VIX and the MOVE.
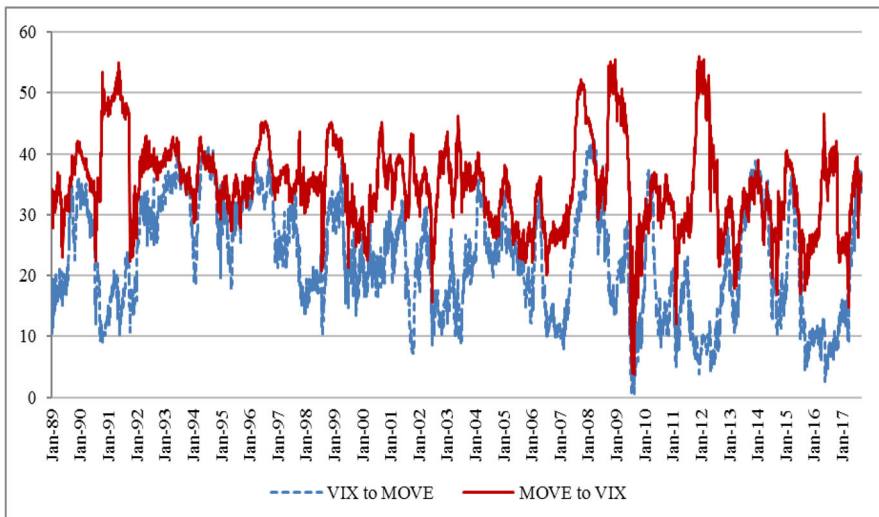
(b) Directional connectedness from the VIX to the MOVE, and from the MOVE to the VIX.

Fig. 4 Rolling total and directional risk-neutral volatilities connectedness. Daily data: January 19, 1989, to September 29, 2017. **a** Total connectedness between the VIX and the MOVE. **b** Directional connectedness from the VIX to the MOVE, and from the MOVE to the VIX

the results for the conditional correlation, total volatility connectedness is also higher during the NBER recession dates (32.5%), relative to the average non-NBER connectedness value (28.4%). Note that contrary to the full sample connectedness (13.7%), the average of the connectedness dynamics (28.8%) is obtained from a rolling procedure that generates a time-varying estimation of spillover effects. Consequently, the dynamic procedure is strongly affected by recessions where connectedness is higher. Then, it seems reasonable to observe that the full-sample unconditional estimation presents a lower connectedness.

Although both connectedness dynamics and the conditional correlation metrics show higher co-movements between the VIX and the MOVE during bad economic times, the unconditional and conditional correlations are particularly high. However, we should be careful when interpreting the numbers and comparing conditional correlations with connectedness dynamics. As pointed out by Diebold and Yilmaz (2015), the time-varying behavior of conditional correlation could simply be a spurious image of time-varying volatility. This is known as the "Stambaugh effect" as discussed by Ronn et al. (2009). The question is not that correlations increase during economic and financial crises, but whether they rise over and above what is expected given the effects of increasing volatility during bad times. This potential bias is not shared by the connectedness metrics because these measures are constructed from variance decomposition, which implies that they control for total variation.

Even more important than total connectedness is the analysis of directional connectedness. Columns three and four of Panel B of Table 2 display the average directional connectedness between the risk-neutral volatilities. As for the full sample unconditional estimation, we find again that the dynamic directional connectedness is mainly from the MOVE to the VIX. Hence, net connectedness dynamics is also negative on average. Moreover, it is more negative during the second sub-period, and during NBER recession dates. Indeed, the directional connectedness from the MOVE to the VIX is as high as 41.6% during recessions. The negative values of the net connectedness are shown not only for the average of the distribution, but also for the different quartiles, although they are lower in quartile 3. Figure 4b displays the two directional connectedness series. Note that, most of the time, the directional connectedness from the MOVE to the VIX is higher than that from the VIX to the MOVE. In fact, the net connectedness from the VIX to MOVE is negative in 94.2% of all days in our sample period. Relatively important exceptions occur during August and September 1993, March 2010, from September to December 2013, from January to May 2014, and September 2017.[6]

We now test whether net connectedness is equal to zero, which is equivalent to test that the directional connectedness from the VIX to the MOVE is equal to that from the MOVE to the VIX. The comparison is performed first in terms of the average, for which 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. In addition, we compare quartiles of the distribution with the Pearson's Chi-squared test under the null hypothesis that the frequency distribution in the observed samples

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[6] The results provided in "Appendix C", where we use the TYVIX instead of the MOVE are very similar; the directional connectedness from the VIX (TYVIX) to the TYVIX (VIX) is 19.3% (34.3%) and total and directional connectedness are larger on average during NBER recessions. See Table 11 for more details.

is consistent with a theoretical distribution. In our case with two samples, the statistic is given by:

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

where $i = 1$ ($i = 2$) represents the sample of directional connectedness from the VIX (MOVE) to the MOVE (VIX), 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, from 1 to 3. Under the null, the difference between the observed and expected frequencies for the two samples is zero, and the statistic has a Chi-squared distribution with one degree of freedom. The *p*-values associated with these tests are displayed in parenthesis in Panel B of Table 2 below the corresponding net connectedness descriptive statistics. The average and the three quartiles of the negative net connectedness from the VIX to the MOVE are statistically different from zero in all cases and sub-periods. It is true that we are applying these nonparametric tests to connectedness measures that have been estimated previously. This may generate additional noise that is not fully captured by our tests. However, given the highly significance levels found, we can safely conclude that the spillovers are mainly from risk-neutral Treasury volatility to equity volatility and that net connectedness is, on average, higher (in terms of absolute value) when monetary policy is mainly concerned with production fluctuations, rather than with inflationary distress, or when economic agents become especially sensitive to precautionary savings, and during NBER recession months.

Regarding the key directional analysis of connectedness, note that we cannot provide the previous intuitive and simple illustration using conditional correlations. The correlation is non-directional (the conditional correlation between the VIX and the MOVE is equal to the conditional correlation between the MOVE and the VIX). This clearly contrasts with the useful idea of pairwise directional connectedness that we employ in our research, which provides information about who is the net sender of volatility spillovers especially during bad economic times. To further illustrate this point, Table 3 shows the correlations between our alternative measures of connectedness and the conditional correlation between the VIX and the MOVE. First, the correlation with total connectedness is higher during the supportive-output monetary sub-period and during NBER recession dates. However, even more important is to note that the correlation between the conditional correlation and the directional connectedness from the MOVE to the VIX is what explains the positive correlation between total connectedness and the conditional correlation. Figure 5 illustrates this result. Note the closely related increases and decreases between the conditional correlation and the directional connectedness from the MOVE to the VIX. To conclude, most of the behavior observed in the time-varying conditional correlation is associated with the directional spillover volatility effects from the MOVE to the VIX.

Table 3 Correlation coefficients between the conditional correlation and the connectedness measures between the VIX and the MOVE. Daily Data: January 19, 1989, to September 29, 2017

	Total connectedness	Directional connectedness (VIX to MOVE)	Directional connectedness (MOVE to VIX)	Net directional connectedness (VIX to MOVE)
Jan 1989–Sep 2017	0.207	− 0.101	0.506	− 0.465
Jan 1989–Mar 2001	0.158	− 0.145	0.482	− 0.447
Apr 2001–Sep 2017	0.391	0.011	0.662	− 0.485
NBER Recessions	0.364	− 0.246	0.850	− 0.648
Non-NBER Recessions	0.146	− 0.107	0.427	− 0.423

This table shows estimated correlations between the conditional correlation and alternative connectedness measures. The first, second, third, and fourth columns report the correlations between the conditional correlation and total, directional connectedness from the VIX to the MOVE, directional connectedness from the MOVE to the VIX, and net connectedness calculated as the difference between the two directional connectedness, respectively. The conditional correlations and the connectedness measures are estimated over a 200-day rolling-sample window
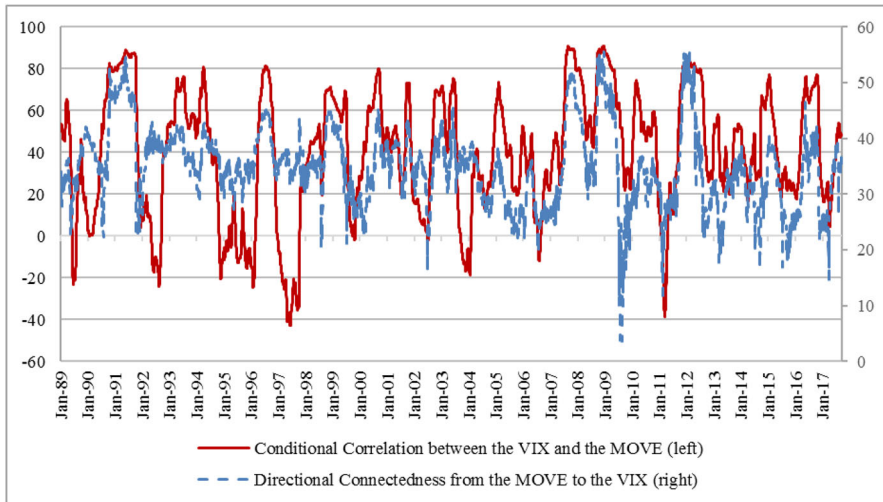

Fig. 5 Conditional correlation between the VIX and the MOVE and the directional connectedness dynamics from the MOVE to the VIX. Daily data: January 19, 1989, to September 19, 2017

2.4 Connectedness dynamics and economic and geopolitical events

In this section, we link the connectedness dynamics between risk-neutral volatilities and relevant economic and geopolitical events. The idea is to understand whether the

different average level of connectedness in different sub-periods is associated with these events.

Table 4 briefly describes the relevant events together with the specific dates for which we identify an event. We separate all episodes into three groups. The first is concerned with overall economic and geopolitical relevant to the US economy. The second one considers events with an international economic flavor in which the distressed economic episodes affect mainly countries other than the USA. Finally, we also include two sub-periods characterized by large bond market sell-offs in the US market.

We run OLS regressions with Newey–West (1987) heteroscedasticity- and autocorrelation-consistent HAC 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 into the three groups described above, and, additionally, when there is an official NBER recession in the US economy,[7]

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

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

Table 5 shows the results for four groups of events. Panel A presents the results for overall economic and geopolitical events affecting the USA. By paying attention to the slope coefficient, $\widehat{\beta}_1$, we note that, during these times, total system connectedness increases significantly by 3.08 points. This finding is consistent with the results reported in Table 2. Interestingly, the spillover from the VIX to the MOVE is positive but not statistically different from zero. However, during these events the spillover from the MOVE to the VIX increases significantly by 4.95 points. Consequently, net connectedness is negative and statistically different from zero. Hence, the strong average directional connectedness from the MOVE to the VIX reported in Table 2, which is especially high during NBER recessions, seems to be due to spillovers from risk-neutral Treasury volatility to the VIX during relevant economic and geopolitical stressed times. In these times, most of the action happens in the risk-neutral Treasury volatility, which is then transmitted to the risk-neutral equity volatility. The characteristics of these identified events are correlated with the overall relatively low directional connectedness from the VIX to the MOVE, and the relatively high spillover from the MOVE to the VIX reported in Table 2.

Panel B of Table 5 shows the results using international events as the key driver of risk-neutral volatilities. The results are very different. Total system connectedness decreases significantly by 2.9 points. The net connectedness also decreases by a statistically significant 9.2 points. This reduction is due to the significant and strong decrease in the connectedness from the VIX to the MOVE, and to the positive and

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[7] 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. We employ HAC standard errors in all our OLS regressions.

Table 4 Underlying economic and geopolitical events. Sample period: January 1989 to September 2017

Events	Dates
Panel A: Overall relevant economic and geopolitical events for the US economy	
NBER recession months	July 1990–March 1991
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 devalued 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 devalued in August 17, 1998) and Long Term Capital Management bailout. The Pastor & Stambaugh market-wide illiquidity peaks September 30, 1998	August 13, 1998–November 30, 1998
Bush election	November 1, 2000–November 8, 2000
NBER recession months	March 2001–October 2001
Market re-opens after the attack to Twin Towers	September 17, 2001
Gulf War II	March 20, 2003–April 30, 2003
Great Recession and FOMC reduces the policy rate by 75 basis points	December 2007–June 2009, and January 22, 2008
Bearn Sterns crisis	March 3, 2008–March 17, 2008
Bankruptcy of Lehman Brothers and second highest market-wide illiquidity Pastor & Stambaugh measure of illiquidity	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
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

Table 4 (continued)

Events	Dates
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

weak significant spillover from the MOVE to the VIX. Whenever there is an international economic crisis (not directly related to the US economy), spillover from the VIX to the MOVE is clearly reduced. However, the incremental spillover from the MOVE to the VIX remains positive. Panel C of Table 5 displays the results during strong bond market sell-offs. As seen, US Treasury bond crisis have no effect in any of the connectedness measures. Finally, Panel D shows the incremental effects on the alternative connectedness metrics when there is an official NBER recession in the US economy. The incremental effect on the directional connectedness from the VIX to the MOVE is not estimated with statistical precision, but the incremental impact from the MOVE to the VIX is even higher than in Panel A when we use not only recession dates, but also other relevant economic and geopolitical events. Although not reported in Table 5, the slope coefficient of regression (2), using the conditional correlation as the dependent variable and the dummy for NBER recession dates, is positive and statistically different from zero.

2.5 Connectedness between realized volatilities for equity and Treasury bond markets

It is well known that the risk-neutral volatility is the realized volatility adjusted by the risk premium. Thus, it may be useful to analyze whether the connectedness found between equity and Treasury risk-neutral volatilities is also observed for realized volatilities.
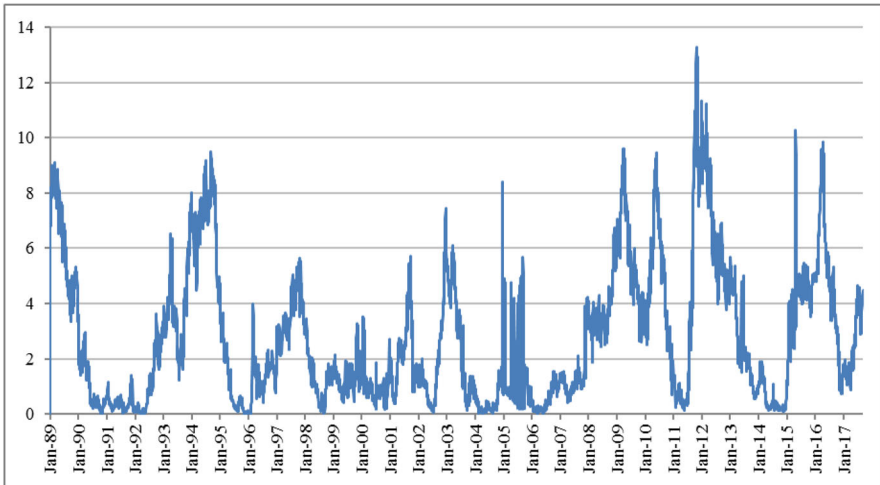
We approximate realized volatility as the daily square return of the S&P 500 index and the composite index of the five-, 10-, and 30-year horizons of Treasury bonds, for the equity and the Treasury bond markets, respectively. Then, we estimate the total connectedness dynamics, and the directional and net connectedness between them using 200-day rolling windows. Figure 6a displays the total realized volatility connectedness. As in the case of risk-neutral volatilities, total connectedness also changes throughout the sample period. However, its time-varying pattern is different from the behavior between risk-neutral volatilities. In fact, the correlation between both connectedness series is very close to zero. On the other hand, values for realized volatilities connectedness are much lower than the ones displayed in Fig. 4a. The maximum level of the realized volatilities connectedness, observed on November 10, 2011, is 13.3% and the connectedness is lower than 1% for the 32% of days in our sample period.

Table 5 Explaining connectedness dynamics by economic and geopolitical events. Daily data: January 19, 1989, to September 29, 2017
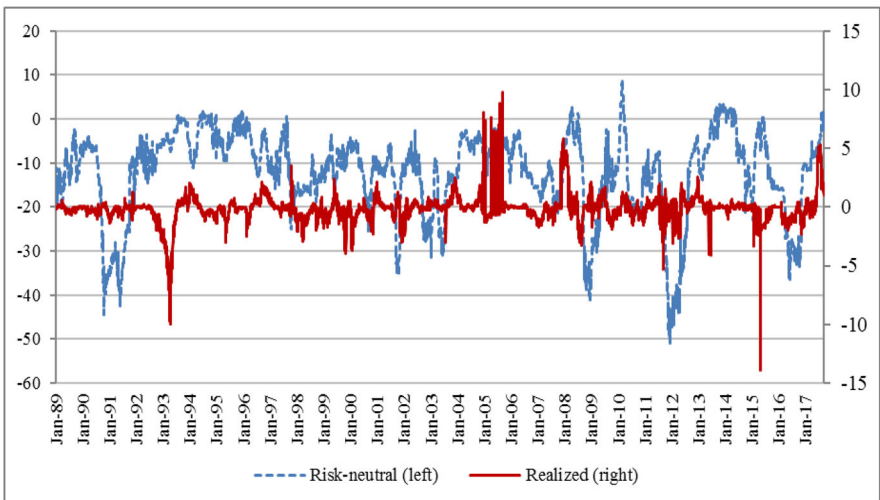
	Total connectedness	Directional connectedness from the VIX to the MOVE	Directional connectedness from the MOVE to the VIX	Net connectedness from the VIX to the MOVE
Panel A: Overall relevant economic and geopolitical events for the US economy				
$\hat{\beta}_0$	28.593	22.702	34.484	− 11.782
	(94.41)	(53.39)	(106.4)	(− 26.03)
$\hat{\beta}_1$	3.075	1.202	4.947	− 3.745
	(3.18)	(0.99)	(4.12)	(− 2.60)
R^2	0.015	0.001	0.033	0.010
Panel B: International economic crises				
$\hat{\beta}_0$	29.261	23.922	34.601	− 10.679
	(88.84)	(55.09)	(100.9)	(− 25.29)
$\hat{\beta}_1$	− 2.867	− 7.460	1.726	− 9.187
	(− 4.77)	(− 7.96)	(1.87)	(− 6.44)
R^2	0.024	0.086	0.017	0.113
Panel C: Specific US Treasury bond crises				
$\hat{\beta}_0$	28.828	22.810	34.847	− 12.037
	(97.47)	(55.53)	(107.6)	(− 27.10)
$\hat{\beta}_1$	− 0.034	− 1.864	1.795	− 3.659
	(− 0.02)	(− 0.51)	(1.40)	(− 0.92)
R^2	0.000	0.000	0.001	0.001
Panel D: NBER recession dates for the US economy				
$\hat{\beta}_0$	28.383	22.693	34.073	− 11.380
	(91.47)	(52.65)	(107.0)	(− 26.17)
$\hat{\beta}_1$	4.283	0.976	7.590	− 6.614
	(6.63)	(0.73)	(7.44)	(− 3.61)
R^2	0.039	0.001	0.104	0.042

This table shows the results of OLS regressions with daily data of several measures of connectedness on dummy variables that are equal to one if there is an overall relevant economic and geopolitical event for the US Economy (Panel A), an international crises (Panel B), a US Treasury bond specific crisis (Panel C), or a NBER official US recession (Panel D), and zero otherwise. $\hat{\beta}_0$ is the mean of connectedness between the VIX and the MOVE when there are no event, and $\hat{\beta}_1$ is the difference in connectedness between days with and without events. Volatility connectedness is estimated over a 200-day rolling-sample window. We report the *t*-statistic for Newey–West/ HAC standard errors in parentheses

Table 6 shows average values for total, directional, and net connectedness between realized equity and Treasury volatilities in different sample periods. It turns out that the magnitudes of the average connectedness measures are extremely small relative to the ones reported in Panel B of Table 2 for the case of risk-neutral volatilities. There is a slightly higher connectedness during recession periods in both total and directional connectedness, but the results overall suggest that spillover realized volatilities effects between the equity and Treasury markets are negligible. In the last column of Table 6,

(a) Total connectedness between realized volatilities estimated as the daily square return of the S&P 500 index and the composite index of the five-, 10-, and 30-year horizons of Treasury bonds.

(b) Net connectedness from the VIX to the MOVE versus net connectedness from the realized volatility of the S&P 500 to the realized volatility of the composite Treasury bond index.

Fig. 6 Rolling total realized volatility connectedness and comparison between net connectedness measures estimated with realized versus risk-neutral volatilities. Daily data: January 19, 1989, to September 19, 2017. **a** Total connectedness between realized volatilities estimated as the daily square return of the S&P 500 index and the composite index of the five-, 10-, and 30-year horizons of Treasury bonds. **b** Net connectedness from the VIX to the MOVE versus net connectedness from the realized volatility of the S&P 500 to the realized volatility of the composite Treasury bond index

Table 6 Average percentages of dynamic connectedness between realized equity and Treasury volatilities. Daily data: January 19, 1989, to September 29, 2017

	Total connectedness	Directional connectedness from the equity to the Treasury volatilities	Directional connectedness from the Treasury to the equity volatilities	Net connectedness from the equity to the Treasury volatilities
Jan 1989–Sep 2017	2.72	2.66	2.80	− 0.14 (0.000)
Jan 1989–Mar 2001	2.41	2.22	2.60	− 0.38 (0.000)
Apr 2001–Sep 2017	2.96	2.98	2.95	0.03 (0.735)
NBER Recession	3.15	3.23	3.06	− 0.17 (0.812)
Non-NBER Recessions	2.67	2.58	2.77	− 0.19 (0.000)

This table shows estimated connectedness with daily observations from January 19, 1989, through September 29, 2017. The numbers are the average percentages of realized volatility connectedness estimated over a 200-day rolling-sample window for the full sample and alternative sub-periods. The first column shows the total connectedness across equity and Treasury realized volatilities. The second and third columns report directional connectedness from the realized equity to the realized Treasury volatilities and from the realized Treasury to the equity volatilities, respectively. The fourth column shows the net connectedness, which is equal to the difference between the directional connectedness from the realized equity to the Treasury volatilities and from the Treasury to the equity volatilities. We report in parentheses the nonparametric p-values associated with the null hypothesis that the net connectedness between risk-neutral volatilities equals zero

we report the net connectedness from the equity to the Treasury volatilities. Although the magnitudes are very small, it remains true that for the full sample period, the first sub-period, and the non-NBER recession days, the average net connectedness is negative and statistically different from zero. We employ the same nonparametric test used in Table 2. Consequently, the Treasury market is a (weak) net sender of realized volatility to the equity market. However, during the sub-period including the Great Recession and the NBER recession days, the average net connectedness is not statistically different from zero. To illustrate these findings, in Fig. 6b we show the simultaneous time-varying behavior of net connectedness for both risk-neutral and realized volatilities. Risk-neutral net connectedness tends to display larger and many more positive and negative peaks than the realized net connectedness.

Therefore, we can conclude that the total and directional connected dynamics between risk-neutral volatilities rise mainly through the volatility risk premia associated with the equity and Treasury markets. Recall that risk-neutral volatilities are adjusted by risk because, relative to realized volatilities, they give more weight to bad economic times than to good states. Given the findings of Bekaert and Hoerova (2014), who argue that volatility risk premia reflect risk aversion, our results suggest that changes in risk aversion are transmitted from the Treasury to the equity market, especially during bad economic times. Alternatively, as shown by Haddad and Muir

(2021) under the intermediary-based framework, market segmentation between households and sophisticated financial intermediaries may also explain the difference in the results between risk-neutral volatilities, extracted from option prices, and realized volatilities estimated from stock market data.

3 Understanding the dynamics of connectedness between the VIX and the MOVE

Our objective is now to understand the dynamics of the connectedness between the VIX and the MOVE. Given the differences in connectedness between the two sub-periods characterized by different monetary policy targets regarding inflation and output and by the different exposures of government bonds to market returns, shown in Sect. 2, it is natural to suppose that there should be an association between the dynamics of connectedness and changes in monetary policy instruments and/or in real activity indicators. In Sect. 3.1, we discuss the monetary and real activity effects on the total and directional connectedness between the VIX and the MOVE. In this analysis, we employ daily data since we have reasonable proxies for monetary and real activity at this high frequency. Secondly, it is also reasonable to expect that relevant economic variables related to both equity and Treasury bond markets could affect the spillover effects between the risk-neutral volatilities of the two markets. In Sect. 3.2, we evaluate the role of a large set of variables including the slope of the term structure of interest rates, the default risk, inflation, the stock and the bond market's behavior, uncertainty, and risk aversion. Of course, we also include a measure of real activity growth and two monetary policy instruments. In this case, given the availability of data, the analysis is conducted at monthly frequency.

3.1 Monetary and real activity effects on connectedness

We employ the Aruoba et al. (2009) real activity index (ADS), which is designed to track real economic conditions at daily frequency.[8] Note that the way the ADS is constructed by the authors makes the series stationary and becomes unnecessary to take first differences. The average value of the index is zero. Positive values indicate above-average conditions, whereas negative values represent below-average conditions. The effective FED funds rate is used as a monetary policy indicator. Our monetary variable, which potentially explains the connectedness between the VIX and the MOVE, is the daily changes in the effective FED funds rate (ΔFED).

We study whether connectedness and spillovers are associated with either monetary drivers, real activity drivers, or both, through OLS regressions for the full sample period, as well as for the two sub-periods from January 19, 1989, to March 30, 2001, and from April 2, 2001, to July 20, 2017:

$$ lnC_t^G = \beta_0 + \beta_1 \Delta FED_t + \beta_2 ADS_t + \varepsilon_t, \tag{3} $$

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[8] Data are downloaded from the Federal Reserve Bank of Philadelphia's website (https://www.philadelphiafed.org).

where lnC_t^G is the logarithm of either the total or directional connectedness between the VIX and the MOVE.

The results are shown in Table 7. Panel A presents the results for the full sample. We find no significant relation between high-frequency real activity and total connectedness. This effect is clarified when we observe the results regarding directional connectedness. The directional connectedness from the VIX to the MOVE shows that real effects are now positive and significant. However, they are significantly negative for the directional connectedness from the MOVE to the VIX. Therefore, a worsening of economic conditions increases spillovers from Treasury to equity risk-neutral volatility, but it diminishes spillovers from the VIX to the MOVE. One the other hand, the monetary driver shows no relevant relation with any measure of connectedness.

The empirical results for sub-periods are shown in Panels B and C of Table 7. Total connectedness is not related to changes in the effective rate for any sub-period. The only weak significant relation is found between changes in the effective rate and the spillovers from the MOVE to the VIX in the second sub-period. An increase in ΔFED seems to be interpreted as a signal of good future economic conditions, which diminishes the spillover of risk-neutral volatility from the fixed to the equity markets. Recall that the first sub-period is characterized by an anti-inflationary monetary policy (supply shocks), while the second sub-period is more output-policy oriented (demand shocks). 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 with a high t-statistic. As before, this is clarified when we analyze the directional connectedness between volatilities. Results for the first sub-period are driven by the positive relation between ADS and the spillovers from the VIX to the MOVE, while the negative relation between ADS and total connectedness mainly comes from the directional connectedness from the MOVE to the VIX. In any case, during the second sub-period, which is characterized by a strong financial and economic crisis, the relation between directional connectedness and real activity is negative in both directions. As expected, given the previous results during bad economic times, the negative directional connectedness is much stronger from the MOVE to the VIX than vice versa, with a t-statistic as high as -9.6.

The weak relation reported between the effective FED funds rate and the connectedness measures in Table 7 calls for a more detailed analysis. We now explore an alternative monetary policy instrument, namely the FED funds target rate ($FEDT$). The idea is to discern the connectedness reaction to monetary policy by focusing on unexpected policy decisions. Therefore, we decompose the changes in the target rate ($\Delta FEDT$) into expected and unexpected changes following Kuttner (2001) and Bernanke and Kuttner (2005). The unexpected part ($\Delta FEDT^u$) is obtained from the change in the future's price of the 30-day Federal funds futures contracts relative to the day prior to the policy decision.[9] These future prices reflect expectations about the effective FED funds rate, averaged over the settlement month. Therefore, we scale the future rate change by a factor associated with the number of days in the month of the

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[9] Future prices are kindly provided by Danilo Leiva of the Bank of Spain.

Table 7 Real and monetary drivers of the connectedness between the VIX and the MOVE

	Total connectedness				VIX to MOVE				MOVE to VIX			
	Const	ΔFED	ADS	Adj R²	Const	ΔFED	ADS	Adj R²	Const	ΔFED	ADS	Adj R²
Panel A: January 19, 1989, to July 20, 2017												
	3.328	− 0.502	− 0.007	0.000	3.041	− 0.097	0.098	0.020	3.517	− 0.721	− 0.065	0.043
	(284.4)	(− 1.01)	(− 0.63)		(140.5)	(− 0.11)	(4.17)		(364.0)	(− 1.54)	(− 5.48)	
Panel B: January 19, 1989, to March 30, 2001												
	3.437	0.212	0.049	0.027	3.215	0.627	0.226	0.167	3.597	− 0.028	− 0.041	0.023
	(347.9)	(0.56)	(3.13)		(188.6)	(0.86)	(6.78)		(389.9)	(− 0.07)	(− 2.41)	
Panel C: April 2, 2001, to July 20, 2017												
	3.214	− 4.787	− 0.095	0.063	2.851	− 3.610	− 0.060	0.007	3.437	− 5.194	− 0.120	0.132
	(205.1)	(− 1.52)	(− 8.32)		(91.62)	(− 0.67)	(− 2.27)		(255.8)	(− 1.93)	(− 9.56)	

This table shows the results of OLS regressions with daily data of several measures of connectedness on the effective federal funds rate change (ΔFED) and real activity index of Aruoba et al. (2009), ADS. Panel A shows the full sample period, and Panels B and C report the results for two non-overlapped sub-periods. The first sub-period is characterized by an anti-inflationary monetary policy, while the second sub-period is characterized by an output-based monetary policy. Daily volatility connectedness is estimated over a 200-day rolling-sample window. The first four columns show the total connectedness across equity and Treasury risk-neutral volatilities. The second and third column-blocks report the directional connectedness from the VIX to the MOVE and from the MOVE to the VIX, respectively. We report the t-statistic for Newey–West/HAC standard errors in parentheses

change. Hence, the monetary policy surprise is given by:

$$\Delta FEDT^u = \frac{d}{d-t}\left(f_{m,t}^0 - f_{m,t-1}^0\right), \tag{4}$$

where $f_{m,t}^0$ is the current month futures rate, and d is the number of days in month m. Consequently, the expected component is defined as:

$$\Delta FEDT^e = \Delta FEDT - \Delta FEDT^u. \tag{5}$$

In this analysis, the sample of events corresponds to days for which we find that the target rate was changed, which could coincide with a Federal Open Market Committee (FOMC) meetings 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.[10]

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

$$lnC_t^G = \beta_0 + \beta_1 \Delta FEDT_t^e + \beta_2 \Delta FEDT_t^u + \beta_3 ADS_t + \varepsilon_t \tag{6}$$

Panel A of Table 8 reports the empirical results for the total and directional connectedness for the full sample period. We find a negative but weak significant relation between the unexpected change and total connectedness. The β_2 coefficient is estimated with more precision when we control for real activity. 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 the VIX to the MOVE. However, both expected and unexpected changes in the target rate are negative and significantly related to the directional connectedness from the MOVE to the VIX. Once again, signals of bad economic times make more important the spillovers from the MOVE to the VIX.

The analysis by sub-periods also clarifies the empirical results. During the first sub-period (Panel B of Table 8), we find no significant relation between connectedness and monetary policy surprises, at least when we control for real activity. Indeed, the results for the full sample period seem to be explained exclusively by the results observed in the second sub-period (Panel C of Table 8). In this 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 the MOVE to the VIX.

Summarizing the overall results of this subsection, we find that over the full sample period, but especially during the output-oriented monetary policy between April 2001 and July 2017, decreases (increases) in real activity index are associated with increases (decreases) in the directional connectedness from the MOVE to the VIX.

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[10] The target rate changes are dated relative to the day on which they became known. Note that prior to 1994, the FOMC did not issue monetary policy statements. For that subsample, the day on which the change became known corresponds to the day after the decision to change rates; this is to say, that day for which the new target becomes effective.

Our three monetary policy indicators (changes in effective *FED* funds rate, and the expected and unexpected changes in the *FED* target) show a negative estimated coefficient. The output-oriented monetary policy of the second sub-period seems to be an important characteristic to understand these results. At the same time, this sub-period is characterized by the negative market beta of government bond returns. Therefore, we should also recognize that, as argued by Laarits (2020), the precautionary savings motive with time-varying volatility of the price of risky assets may also be consistent with our results across both sub-periods. If the price of risk of risky assets is higher in the second sub-period, then stock prices would also drop more intensively increasing the expected risk premia. On the contrary, government bond prices are surely increasing in the price of risk because of precautionary savings. Interestingly, Laarits (2020) argues that the risk appetite measure constructed by Pflueger et al. (2020), defined as the difference between the average book-to-market ratio of low-volatility stocks and the average book-to-market ratio of high-volatility stocks, is being driven by the same underlying phenomenon behind the stock–bond covariance throughout the economic cycle. Indeed, Pflueger et al. (2020) recognize that precautionary savings motives help to explain the behavior of their perceived risk measure.

In any case, both the output-oriented focus of monetary policy and precautionary savings are associated with bad economic times in which there is also an increase in risk aversion. Note that the specification employed by Campbell and Cochrane (1999), which assumes away the precautionary savings simply by convenience, it is easily extended to allow for slightly volatile interest rates. Hence, as shown by Watcher (2006), this context avoids the exact cancelation between the precautionary savings and the intertemporal substitution terms. We tend to think that both risk aversion and precautionary savings are simultaneously excellent candidates to explain economic recessions. Without debating the ultimate motive of the time-varying exposure of government bonds to the stock market, the relation between changes in the federal fund target rates and volatility spillovers from the MOVE to the VIX is negative and highly significant between April 2001 and July 2017.

3.2 Economic drivers of connectedness

Using a monthly frequency and the OLS regression framework, we now analyze the explanatory power of more general economic drivers that could also explain the connectedness dynamics between risk-neutral equity and Treasury volatilities. Given the results of the previous subsection, we focus the analysis on the explanation of directional connectedness dynamics.

We do not have a formal theoretical model to guide the choice of the economic drivers. However, it is reasonable to expect that variables affecting the spillover effects between the risk-neutral volatilities of the two markets must be related to interest rates, inflation, real economic activity growth, the stock and the Treasury markets behavior, and measures of uncertainty and risk aversion. Next, we indicate our selected potential drivers. A detailed description of their construction and sources is in "Appendix B".

We use two popular indicators of future real activity: the slope of the term structure (*TERM*) and expected inflation (*EINF*). We employ the default spread (*DEF*) since

González-Urteaga and Rubio (2016) show that it is a key factor in explaining the cross-sectional variation of equity volatility risk premia. The growth rate of the Industrial Production Index (*IPI*) is used as a proxy of real economic activity at monthly frequency. In addition, and given the well-known leverage effect, we include both the excess return of the stock and Treasury bond markets (*EXCMKET* and *TRYRET*, respectively).

Bekaert and Hoerova (2014) show that the square of the 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). And Bekaert et al. (2013) show that expansionary monetary policy decreases both the risk aversion and uncertainty components of the VIX. Therefore, our interest in risk-neutral volatilities and the potential relation between connectedness and monetary policy strongly suggest that measures of uncertainty and risk aversion could clarify the spillover effects between equity and Treasury risk-neutral volatilities. As measures of uncertainty, we employ both the macroeconomic (*MUNC*) and the financial (*FUNC*) uncertainty indexes of Jurado et al. (2015), and the economic policy uncertainty indicator (*EPU*) of Baker et al. (2016). There is an increasingly popular literature on the relation and transmission mechanism between uncertainty and economic growth, concluding that greater uncertainty leads to lower growth.[11] As a proxy for risk aversion (*RA*), we use the measure provided by the European Central Bank (ECB).

Finally, we use the monthly change in the *FED* funds rate (ΔFED) or, alternatively, the change in the shadow interest rate (*SHADOW*) of Wu and Xia (2016), as the monetary policy indicators. When the name of any variable is preceded by *RES*, it refers to the residual of this variable with respect to all others that show high correlation with the variable in question. See "Appendix B" for details.

Table 9 shows the estimation results of the following regression

$$ lnC_t^G = \beta_0 + \beta_1 TERM_t + \beta_2 X_t + \beta_3 TRYRET_t + \beta_4 FUNC_t $$
$$ + \beta_5 RESRA_t + \beta_6 RESDEF_t + \beta_7 IPI_t + \beta_8 EXCMKT + \varepsilon_t \quad (7) $$

where lnC_t^G is the logarithm of directional connectedness in the last day of the corresponding month, and X_t is one of the monetary policy instruments: *EINF*, ΔFED or *SHADOW*. When we employ either ΔFED or *SHADOW*, we replace *TERM* by *RESTERM*.[12]

Panel A of Table 9 displays the results for the directional connectedness from the VIX to the MOVE. Only *TERM* (or *RESTERM*) has a positive and significant coefficient, which suggests that future good economic prospects increase the spillovers from the VIX to the MOVE. On the other hand, a decrease in either financial uncertainty or the default premium, a proxy for credit risk, increases spillovers from the VIX to the MOVE. Therefore, positive financial news generates significant spillovers from the VIX to the MOVE. We find no significant relation with respect to changes in monetary

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

[12] Other control variables discussed in "Appendix B", which are not included in Eq. (7), do not show any explanatory power with respect to connectedness dynamics.

Table 8 Monetary policy target rate surprises and real activity effects on connectedness between the VIX to and the MOVE. Daily data and sample period defined by target Federal funds rate changes

	Total connectedness					VIX to MOVE					MOVE to VIX				
	$Const$	$\Delta FEDT^e$	$\Delta FEDT^u$	ADS	$Adj\ R^2$	$Const$	$\Delta FEDT^e$	$\Delta FEDT^u$	ADS	$Adj\ R^2$	$Const$	$\Delta FEDT^e$	$\Delta FEDT^u$	ADS	$Adj\ R^2$
Panel A: January 19, 1989, to July 20, 2017															
	3.369	−0.141	−0.179	–	0.073	3.093	0.229	0.139	–	0.024	3.554	−0.327	−0.339	–	0.271
	(92.78)	(−1.24)	(−1.64)			(48.87)	(1.17)	(0.74)			(108.0)	(−3.45)	(−3.65)		
	3.379	−0.195	−0.232	0.035	0.073	3.150	−0.079	−0.166	0.198	0.116	3.543	−0.270	−0.284	−0.036	0.272
	(88.02)	(−1.60)	(−2.02)	(1.22)		(52.30)	(−0.36)	(−0.76)	(2.38)		(106.5)	(−2.63)	(−2.74)	(−1.01)	
Panel B: January 19, 1989, to March 30, 2001															
	3.405	0.069	0.036	–	0.024	3.107	0.430	0.359	–	0.091	3.600	−0.123	−0.140	–	0.005
	(81.81)	(0.59)	(0.31)			(40.96)	(2.13)	(1.86)			(82.41)	(−1.18)	(−1.30)		
	3.415	−0.010	−0.039	0.054	0.015	3.173	−0.111	−0.160	0.370	0.455	3.586	−0.009	−0.030	−0.078	0.038
	(80.40)	(−0.08)	(−0.35)	(1.69)		(53.58)	(−0.58)	(−0.81)	(5.45)		(88.43)	(−0.09)	(−0.28)	(−1.45)	
Panel C: April 2, 2001, to July 20, 2017															
	3.339	−0.340	−0.368	–	0.290	3.086	0.049	−0.054	–	0.019	3.512	−0.525	−0.514	–	0.646
	(76.54)	(−2.80)	(−3.43)			(36.33)	(0.18)	(−0.22)			(117.3)	(−6.97)	(−7.50)		
	3.348	−0.377	−0.406	0.022	0.274	3.114	−0.058	−0.166	0.066	0.037	3.510	−0.517	−0.506	−0.005	0.636
	(64.80)	(−2.24)	(−2.68)	(0.51)		(29.24)	(−0.14)	(−0.44)	(0.60)		(99.70)	(−5.23)	(−5.63)	(−0.14)	

This table reports the results of OLS regressions with daily (event time) data of connectedness on the surprise ($\Delta FEDT^u$) and expected ($\Delta FEDT^e$) components of the Federal funds target rate change and real activity index of Aruoba et al. (2009), ADS. Panel A shows the full sample period, and Panels B and C report the results for the two sub-periods. 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 an output-based monetary policy. Daily volatility connectedness is estimated over a 200-day rolling-sample window. The first four columns show the total connectedness across equity and Treasury risk-neutral volatilities. The second and third column-blocks report the directional connectedness from the VIX to the MOVE and from the MOVE to the VIX, respectively. We report the t-statistic for Newey–West/HAC standard errors in parentheses

Table 9 Economic drivers of the directional connectedness between the VIX and the MOVE. Monthly data: January 1989 to June 2017

Const	TERM	RESTERM	EINF	ΔFED	SHADOW	TRYRET	FUNC	RESRA	RESDEF	IPI	EXCMKET	Adj R²
Panel A: Directional Connectedness from the VIX to the MOVE												
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)	(–1.61)	(–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 B: Directional Connectedness from the MOVE to the VIX												
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	–	4.196	–	–	–0.227	–0.933	0.143	6.577	1.759	–2.774	0.561	0.202
(35.48)		(2.37)			(–3.21)	(–1.83)	(1.31)	(3.97)	(0.46)	(–1.09)	(1.18)	

This table shows the results of OLS regressions with monthly data of directional connectedness on a set of economic drivers for the full sample period. Panels A and B show the results for the directional connectedness from the VIX to the MOVE and from the MOVE to the VIX, respectively. The variable *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; *ΔFED* is the change in the effective Federal funds rate; *SHADOW* is the change in the shadow interest rate of Wu and Xia (2016); *TRYRET* is the excess return of composite Treasury bonds; *FUNC* is the financial uncertainty of Jurado et al. (2015); *RESRA* is the European Central Bank's 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 for Newey–West/HAC standard errors in parentheses

policy rates. This finding is consistent with the results using daily data in Tables 7 and 8.[13]

Panel B of Table 9 reports the empirical results of the directional connectedness from the MOVE to the VIX. Higher expected inflation increases this directional connectedness. 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 could simply reflect the fact that the 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 that of short-term bonds. As in subsection 3.1, a tightening of monetary policy significantly decreases spillovers from the MOVE to the VIX. Alternatively, a reduction in policy interest rates signals problematic future economic times and the directional connectedness from the MOVE to the VIX increases. Additionally, note that the signs of the coefficients associated with either financial uncertainty or default are precisely the opposite of those reported in Panel A. Increases in financial uncertainty and default are associated with an increase in the spillover from the MOVE to the VIX, although the results lose statistical significance once we employ changes in the *FED* rates. A stronger positive and highly significant relation is found relative to risk aversion. The MOVE becomes a net sender of volatility precisely when risk aversion is higher. This is consistent with the lack of connectedness between realized volatilities. Bad contemporaneous news about the economic situation is captured through greater financial uncertainty and default spreads, but especially through higher risk aversion. There is also evidence of a weak significant negative relation between Treasury excess returns and the connectedness from the MOVE to the VIX.[14]

To conclude, during bad economic times, spillovers from the MOVE to the VIX significantly increase in a very robust manner. The MOVE becomes a key sender of volatility to the VIX during financial and economic distressed times. Recall that the results reported in Table 9 could also be consistent with increases in margin risks suffered by financial intermediaries. As pointed out before, periods with increasing economy-wide risk aversion tend to coincide with periods characterized by a decreasing intermediary risk-bearing capacity.

The results of Table 7 through 9 are consistent, in the sense that, whenever the US economy suffers a distressed economic period characterized by problematic either economic or geopolitical events, greater risk aversion, higher credit risk (default),

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[13] To save space, we do not report the evidence across sub-periods in this table. 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 weak relation with *IPI* is positive and statistically different from zero during the first sub-period, but it becomes negative during the second sub-period. This finding is consistent with the results reported in Table 7. The adjusted *R*-squared value of the regression is higher in the first sub-period. All the results are available from the authors upon request.

[14] The negative relation of changes in either the *FED* rate or the shadow rate with the spillovers from the MOVE to the VIX, and the positive relation with risk aversion and default are much stronger during the second sub-period than during the first. In addition, the relation with *IPI* becomes negative and statistically significant 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.

or a falling real activity, the directional connectedness from the MOVE to the 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 becomes the driver signal in the US financial market, and spillover from the MOVE to the VIX increases. The volatility of risk-neutral Treasury volatility seems to be especially sensitive to the current economic and geopolitical situation of the US economy. These results are also consistent with the fact that, at a 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 the MOVE to the VIX, while the directional connectedness from the MOVE to the 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 spillovers from the MOVE to the 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 the VIX to the MOVE. Moreover, and contrary to the evidence found for spillovers from the MOVE to the VIX, decreases in financial uncertainty, risk aversion, and credit risk increase spillovers from the VIX to the MOVE.[15]

4 Discussion

Our findings have relevant implications for risk management, monetary policy, financial stability, and the real economy. Note that there are several applications where the joint dynamics of risk-neutral volatilities of stocks and bonds are important.

First, the risk-neutral volatility co-movements provide the foundation for the coordination across the expected market risk premium and the credit spreads observed during financial crisis as reported by Cochrane (2017) and Muir (2017). As discussed in the introduction, relying on habit preferences, Cochrane (2017) emphasizes risk aversion, while Muir (2017), who focuses on intermediary-based theories, shows that equity risk premia and credit spreads spike intensively during financial relative to non-financial crises.[16]

Second, we could think about risk-neutral volatilities as proxies and/or predictors for conditional physical stock and bond return volatilities, which are the key inputs for portfolio allocation as discussed by Viceira (2012).

Third, as shown by Adrian et al. (2019), the joint dynamics of risk-neutral volatilities is relevant for modeling the risk-return trade-off and the flights-to-safety episodes between equity and Treasury bonds. These authors show that the nonlinearity in the

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[15] Overall conclusions remain the same when we employ the TYVIX instead of the MOVE as the risk-neutral Treasury volatility. See "Appendix C".

[16] Kuvshinov (2021) disputes this evidence using international data for equities, corporate bonds, and housing arguing that there is a co-movement puzzle across these three asset classes. He shows that excess volatility of asset classes cannot be explained by a common discount factor across them. On the other hand, as the author recognizes, both credit spreads and dividend yields increase in crisis generating positive discount rate news correlation. He shows that during wars the correlation is 0.08, while during banking crisis the correlation is higher and equal to 0.24. This is consistent with the evidence reported by Muir (2017).

risk-returns trade-offs for stocks and bonds are mirror images of each other. In fact, the VIX significantly forecasts stocks and bond returns only when these common non-linearities are included in the forecasting exercise. More importantly, they show that, under their nonlinear estimation framework, the VIX also predicts industrial production, manufacturing production, manufacturing capacity utilization, goods-producing employment, and total private nonfarm payroll. The VIX does predict future macroeconomic activity. Related to this finding, and using out-of-sample forecasting tests, González-Urteaga et al. (2019) show that the VIX and the MOVE complement each other when forecasting future industrial production growth. Both risk-neutral volatilities are equally necessary to significantly forecast real activity at the 3- and 6-month horizons. The evidence regarding the favorable predicting capacity of future real activity by risk-neutral volatilities is important since there is some debate about whether these volatilities have real effects on the economy. Bloom (2009) uses the VIX to calibrate the effects of uncertainty shocks to real activity, and he finds significant real effects on investment and employment. However, Berger et al. (2019) question that uncertainty and risk-neutral stock market volatility are interchangeable, which leaves open the question about the channel through which risk-neutral volatilities spills over the real economy. Our paper suggests that the significant spillovers from the MOVE to the VIX during bad times help explaining potential real effects of risk-neutral volatilities. Finally, Bekaert and Hoerova (2014) show that the equity variance risk premium has predictive power for future equity returns, and Choi et al. (2017) show that the slope of the term structure of implied risk-neutral variances are significantly related to future real activity.

5 Conclusions

The financial crisis outbreak in the USA soon made a marked change in the form of the 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. A formal analysis of the connectedness dynamics between the risk-neutral volatilities of equities and Treasury bond returns is lacking. This is exactly our goal in this research using US data. Note that risk-neutral volatilities are key instruments for risk management and policy authorities. Long time series for risk-neutral volatilities of equity and Treasury bonds are available at daily frequency, which allows us not only to study the total and directional connectedness between them, but also to analyze their monetary and economic drivers over very different economic cycles and data frequencies.

Over most of the sample period, we show that spillovers from the MOVE to the VIX are higher than from the VIX to the MOVE. More importantly, the positive net spillovers from the MOVE to the VIX are especially relevant during bad economic times. Times of relevant economic and geopolitical events and times of a decline in real activity indicate that the percentage of the forecast variation error in the VIX that is due to shocks in the MOVE is relatively high. The net difference is statistically significant, which indicates that the VIX is a receiver of volatility relative to the MOVE. Moreover, the directional connectedness from the MOVE to the VIX increases with risk

aversion, financial uncertainty, and credit risk. The MOVE is a net sender of volatility, especially during stressed financial and economic times. This result highlights the importance of Treasury bond markets relative to equity markets. However, we do not find any relevant evidence of connectedness between realized volatilities of equity and Treasury markets. This suggests that the connectedness dynamics we report rise through the volatility risk premia in the equity and Treasury markets. Indeed, this is especially true during bad times where the average net connectedness between realized volatilities is not statistically different from zero. The market segmentation between the option and stock markets is also consistent with the striking difference between the connectedness dynamics across risk-neutral relative to realized volatilities.

The orientation of monetary policy also affects the characteristics of the connection between the MOVE and the VIX, but it does not seem to be significantly related to spillovers from the VIX to the MOVE. Until 2001, under an anti-inflationary monetary policy and at daily frequency, surprises in monetary policy rates are not related to spillovers from the MOVE to the VIX. However, the output-based monetary policy of lower interest rates after 2001 leads to a strong and statistically negative relation between surprises in the target policy rate and the directional connectedness from the MOVE to the VIX. Importantly, this finding is not observed for the connectedness dynamic from the VIX to the MOVE. More generally, at the monthly frequency, we also find a significant negative relation between changes in either the *FED* fund rate or the shadow rate and the directional connectedness from the MOVE to the VIX. Once again, this is not found for the connection from the VIX to the MOVE. Note that these directional effects between the VIX and the MOVE are also consistent with the precautionary savings motives underlying the negative covariance between the stock market and the government bond returns.

The strong and consistent spillovers we find from the MOVE to the VIX, especially after April 2001, are a key contribution of our research. Future research should further clarify the economics behind these empirical results, although we can safely conclude that the risk-neutral Treasury volatility contains much more relevant information than previously reported in the literature. From the point of view of the economics underlying the empirical results, it would be helpful to distinguish between the effects of the economy-wide risk aversion and the bearing-risk capacity of financial intermediaries. Once these different effects are better understood, the monetary and economic policy authorities could manage more properly the information embedded in the risk-neutral volatility of Treasury bond returns.

Declarations

Appendix A: Connectedness methodology

We consider a covariance stationary N-variable VAR(P).

$$X_t = \sum_{p=1}^{P} \phi_p X_{t-p} + \varepsilon_t \tag{8}$$

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. In our dynamic analysis, we use the likelihood ratio test to determine the lag P of the VAR model for each rolling window.

To estimate the specific variance decomposition, we rewrite the VAR(P) model as a moving average representation.

$$X_t = \sum_{\tau=0}^{\infty} A_\tau \varepsilon_{t-\tau} \tag{9}$$

where the $N \times N$ coefficient matrices are estimated by $A_\tau = \phi_1 A_{\tau-1} + \phi_2 A_{\tau-2} + \cdots + \phi_P A_{\tau-P}$, with A_0 being the identity matrix and $A_{\tau-p} = 0$ for any $p > \tau$.

These moving average coefficients allow for the variance decomposition to parse the H-step-forecast error variances of each variable into proportions associated with shocks for the other variables in the total system. 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 are given by:

$$\tilde{C}^G_{j \to i}(H) = \frac{\sigma_{jj}^{-1} \sum_{h=0}^{H-1} \left(e_i' A_h e_j \right)^2}{\sum_{h=0}^{H-1} \left(e_i' A_h \Sigma A_h' e_i \right)^2} \tag{10}$$

where σ_{jj} is the squared root of the diagonal element jth of the variance–covariance matrix Σ and e_i is a Nx1 vector with one as the ith 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:

$$C^G_{j \to i}(H) = \frac{\tilde{C}^G_{j \to i}(H)}{\sum_{j=1}^{N} \tilde{C}^G_{j \to i}(H)} \times 100. \tag{11}$$

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 $C^G_{j \to i}(H)$ is the pairwise directional connectedness from X_j to X_i at a forecasting horizon H. It represents the percentage of variation in X_i that is due to shocks in X_j. It takes high values when the intensity of the directional connectedness or spillover from X_j to X_i is high. When there is no directional connectedness from one series to the others, the indicator equals zero.

In our application, X_t is a two-dimensional vector with the VIX and the MOVE variables. Note that to approximate normality, we take natural logarithms of the original daily VIX and MOVE series. Therefore, the directional connectedness from the VIX to the MOVE is.

$$C^G_{VIX \to MOVE}(H) = \frac{\tilde{C}^G_{VIX \to MOVE}(H)}{\tilde{C}^G_{VIX \to MOVE}(H) + \tilde{C}^G_{MOVE \to MOVE}(H)} \times 100 \tag{12}$$

It indicates the percentage of variation in the MOVE that is due to shocks in the VIX. Alternatively, the directional connectedness from the MOVE to the VIX is computed as.

$$C^G_{MOVE \to VIX}(H) = \frac{\tilde{C}^G_{MOVE \to VIX}(H)}{\tilde{C}^G_{VIX \to VIX}(H) + \tilde{C}^G_{MOVE \to VIX}(H)} \times 100 \tag{13}$$

and gives the percentage of variation in the VIX that is due to shocks in the MOVE.

Under this pairwise framework, we can also obtain the net directional connectedness from the VIX to the MOVE as the difference between the directional connectedness from the VIX to the MOVE and the directional connectedness from the MOVE to the

VIX:

$$Net\left[C^G_{VIX,MOVE}(H)\right] = C^G_{VIX \to MOVE}(H) - C^G_{MOVE \to VIX}(H) \qquad (14)$$

The net expression indicates the difference between the spillovers transmitted from the VIX to the MOVE and those transmitted from the MOVE to the VIX. Thus, a positive (negative) value implies a higher (lower) impact of the VIX than vice versa.

We can finally obtain a measure of total connectedness between the two variables as the ratio of the sum of the off-diagonal elements of the variance decomposition matrix to the sum of all its elements, which equals two by definition:

$$C^G(H) = \frac{C^G_{VIX \to MOVE}(H) + C^G_{MOVE \to VIX}(H)}{2} \times 100 \qquad (15)$$

We choose a forecasting horizon (H) of 12 days following the recommendation of Diebold and Yilmaz (2014, 2015, 2016). They point out that, although intuitively, there are more chances for connectedness to appear as H lengthens, the conditioning information also becomes progressively less valuable in the variance decompositions of the conditional forecast error. We check for the sensitivity of the results to the choice of the forecasting horizon, and we see that the dynamic behavior of total connectedness over the rolling windows is robust for forecasting horizons similar as the ones employed by Diebold and Yilmaz (2014, 2015, 2016). More precisely, they employ either 10 or 12 days in their empirical applications. They also perform several robustness tests for horizons between 6 and 18 days. The results are sensitive for the shortest horizons, but they stabilize in horizons near 10. For longer horizons, the conditioning information losses value. In our robustness tests, the connectedness between the VIX and the MOVE is very stable for horizons between 6 and 16 days, so that spillovers are practically indistinguishable.

Appendix B: Description of economic and financial variables used as drivers of connectedness at monthly frequency

The slope of the term structure (*TERM)* is computed as the difference between the yield on the 10-year government bond and the three-month Treasury bill rate, both series downloaded from the Federal Reserve web page (https://www.federalreserve.gov/data.htm). The variable *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 (Stock and Watson 2003).

Expected inflation data for a one-year horizon (*EINF*) are downloaded from the Federal Reserve Bank of Cleveland's website (https://www.clevelandfed.org/). The Cleveland Fed's model employs Treasury yields, inflation rate data, inflation swaps, and survey-based measures of future inflation to estimate expected inflation with alternative horizons. Expected inflation is also a relevant signal for future real activity.

Positive (negative) inflation shocks generally suggest good (bad) news for future economic growth.

The default premium (*DEF*) is another popular predictor of both real activity and financial returns. It is calculated as the difference between Moody's yield on Baa corporate bonds and the 10-year government bond yield, both series downloaded from the Federal Reserve web page (https://www.federalreserve.gov/data.htm).

The monthly growth rate of the Industrial Production Index (*IPI*) is obtained from the Federal Reserve Bank of St. Louis (FRED database: https://fred.stlouisfed.org/).

The excess return of the bond market (*TRYRET*) is computed as the difference between the return of the composite index of five-, 10-, and 30-year horizons of Treasury bonds, downloaded from FRED, and the proxy for the risk-free rate in the Kenneth French data library (https://mba.tuck.darmouth.edu). To compute the excess return of the stock market (*EXCMKET*), we employ the Standard and Poor (S&P) 500 index.

As measures of uncertainty, we employ both the macroeconomic index (*MUNC*) and financial uncertainty index (*FUNC*) of Jurado et al. (2015), 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 economic policy uncertainty indicator (*EPU*) of Baker et al. (2016), 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*.

As a proxy for risk aversion (*RA*), we employ the measure provided by the European Central Bank. It is the first principal component of five currently available risk aversion indicators, namely the Commerzbank's Global Risk Perception Index, the UBS FX Risk Index, Westpac's Risk Appetite Index, Bank of America's Risk Aversion Indicator, and Credit Suisse's Risk Appetite Index. A rise in the indicator denotes an increase in risk aversion. The series is available since December 1998. We extend the data by projecting the ECB risk aversion measure on the Chicago Fed's 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.

The effective FED funds rate is used as a monetary policy indicator. Data are obtained from the FRED database. Our variable, which potentially explains the connectedness between the VIX and the MOVE, is the monthly changes in the effective FED funds rate (ΔFED). We must recognize potential distortions of traditional monetary policy instruments in the zero-bound interest rate setting. Therefore, as an alternative proxy, 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 an effective lower bound. Note that this shadow rate can be negative, which captures the Fed's incremental easing due to unconventional monetary practices. The shadow rate was downloaded from the authors' web page at https://sites.google.com/view/jingcynthiawu/.

Table 10 reports the pairwise correlation coefficients among the economic variables described above at a monthly frequency. All the signs are as expected. The slope of the term structure of interest rates shows a negative correlation with expected inflation and

Table 10 Correlation coefficients among economic variables. Monthly data: April 1988 to June 2017

	EINF	EPU	MUNC	FUNC	RA	DEF	IPI	EXCMKET	TRYRET	ΔFED
TERM	− 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	–	− 0.186	0.041	− 0.284
FUNC				1	0.684	0.688	− 0.296	− 0.201	0.103	− 0.319
RA					1	0.608	–	− 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. The variable *TERM* is the slope of the term structure of interest rates; *EINF* is the one-year expected inflation rate; *EPU* is the (logarithm) of the economic policy uncertainty index of Baker et al. (2016); *MUNC* and *FUNC* are the macroeconomic and financial uncertainty of Jurado et al. (2015), respectively; *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 composite Treasury bonds, and *ΔFED* is the change in the effective Federal funds rate. Note that the sample period ends on June 2017 instead of September 2017 due to data availability of several variables

Treasury bond returns, and a positive correlation with the change in the effective *FED* funds rate (*ΔFED*). 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, as well as 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 other hand, the Treasury bond return is positively correlated with risk aversion. Change in the *FED* rate also has a negative correlation with measures of uncertainty, risk aversion, and default, and a positive correlation with real activity growth.

Since we study the simultaneous drivers of connectedness, and given the high correlation among the uncertainty measures, risk aversion and default, we estimate their pure components by an ordinary least squares (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 *RESRA*, and the second series of residuals is the pure default component, denoted *RESDEF*. By the same argument, 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*). 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 as *RESTERM*.

Appendix C: Robustness analysis with TYVIX

Starting in January 2003, the CBOE launched the 10-year Treasury Note Volatility Index, known as the TYVIX, which measures a constant 30-day risk-neutral expected volatility on 10-year Treasury note futures prices. Recall that the MOVE is a weighted index on alternative time-to-expiration contracts. In this appendix, we repeat all the analysis using the TYVIX instead of the MOVE as the risk-neutral Treasury volatility to evaluate the robustness of our results.[17]

First, we estimate the dynamic connectedness measures between the VIX and the TYVIX each day by using the preceding 200-day sample window. Note that now the sample period for connectedness series starts on October 29, 2003. The average values of connectedness dynamics are in Table 11 for the full sample and for NBER and non-NBER recession dates separately. The results confirm the evidence in Table 2; the directional connectedness from the Treasury to the equity risk-neutral volatility is higher than that from the equity to the Treasury, and this is especially true during bad times. In fact, numbers are very similar to those provided in Table 2. Figure 7

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[17] Choi et al. (2017) construct the Treasury implied variance for five-, 10-, and 30-year futures contracts. Their data on 10-year maturity start even before the MOVE data but, unfortunately, these series are not available at daily frequency.

Table 11 Average of dynamic connectedness between the VIX and the TYVIX. Daily data: October 29, 2003, to September 29, 2017
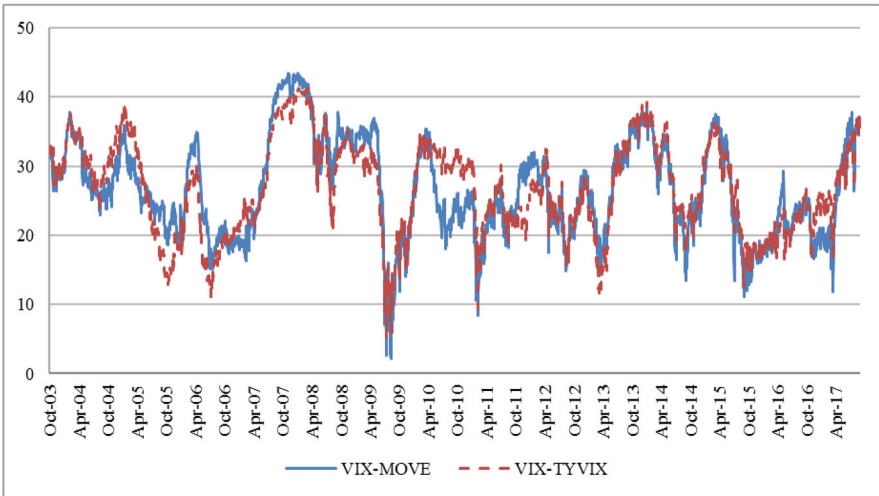
	Total Connectedness	Directional Connectedness from the VIX to the TYVIX	Directional Connectedness from the TYVIX to the VIX	Net Connectedness from the VIX to the TYVIX
All dates	26.76	19.25	34.27	− 15.02 (0.000)
NBER Recessions	33.61	22.36	44.87	− 22.51 (0.000)
Non-NBER Recessions	25.88	18.85	32.91	− 14.05 (0.000)

This table shows the average of connectedness measures computed daily with 200-day rolling window for the period between October 29, 2003 and September 29, 2017. The first (second and third) row provides the average for the full sample period (NBER and Non-NBER recession dates, respectively). The first column shows the total connectedness across equity risk-neutral volatility (VIX) and Treasury risk-neutral volatility (TYVIX). The second and third column report directional connectedness from the VIX to the TYVIX and from the TYVIX to the VIX, respectively. The fourth column shows the net connectedness, which is equal to the difference between the directional connectedness from the VIX to the TYVIX and from the TYVIX to the VIX. We report in parentheses the nonparametric p-values associated with the null hypothesis that the net connectedness between risk-neutral volatilities equals zero

displays the similarities in the behavior of total and net connectedness between the use of the MOVE or the TYVIX as the Treasury risk-neutral volatility.

Second, we repeat the estimation of regression (7) which evaluates the role of different economic and financial indicators on the connectedness dynamics. Table 12 shows the results for the directional connectedness from the VIX to the TYVIX in Panel A and for the directional connectedness from the TYVIX to the VIX in Panel B. To save space, we only present the results for the specification with highest R-squared in Table 8. Given that the sample period is shorter now we also provide the results for the connectedness series using the MOVE in the first row of each panel. The empirical results are nearly coincident between the use of the MOVE or the TYVIX and conclusions are the same as those extracted from Table 8.

A further technical clarification about these two alternative contracts is helpful. One may think that the cleanest source of data would be to use implied price volatility based on the futures exchange, since it employs publicly disclosed settlement prices. However, the structure of the futures contracts allows for a wide range of deliveries from 6.5 to 30 years. Without knowing whether the longest or shortest bond was deliverable, it is not possible to properly analyze implied price volatility. Instead, the MOVE index uses only constant on-the-run Treasuries and is a measure of US interest rate volatility that tracks the movement in US Treasury yield volatility implied by current prices of one-month over-the-counter options on 2-, 5-, 10-, and 30-year contracts. Note that the volatilities that are quoted for bond prices are yield volatilities rather than price volatilities. The concept of modified duration (the percentage changes in a bond price to changes in its yield) is used to convert a quoted yield volatility into

(a) Total connectedness between risk-neutral equity and Treasury volatilities
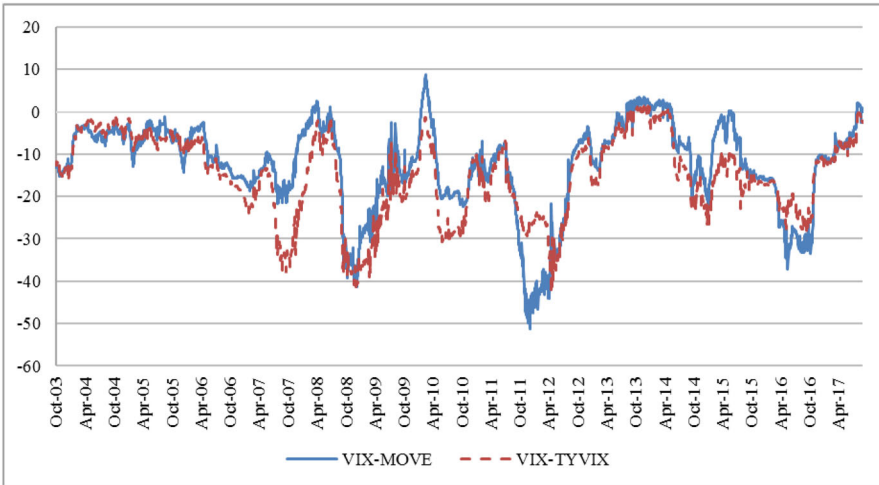
(b) Net connectedness from equity to Treasury risk-neutral volatilities

Fig. 7 Rolling total and net directional risk-neutral volatilities connectedness. Comparison between the MOVE and the TYVIX. Daily data: October 29, 2003, to September 29, 2017. **a** Total connectedness between risk-neutral equity and Treasury volatilities. **b** Net connectedness from equity to Treasury risk-neutral volatilities

a price volatility. The final price volatility is the product of duration, the yield of the bond, and the quoted yield volatility.

Table 12 Economic drivers of the directional connectedness between the VIX and Treasury risk-neutral volatilities. Monthly data: October 2003 to June 2017

Panel A: Directional Connectedness from the VIX to Treasury risk-neutral volatilities

	Const	RESTERM	SHADOW	TRYRET	FUNC	RESRA	RESDEF	IPI	EXCMKET	Adj R^2
MOVE	3.694	24.458	− 0.479	− 2.629	− 0.647	2.646	− 48.499	− 25.497	− 0.364	0.354
	(10.90)	(4.05)	(− 1.97)	(− 1.52)	(− 1.62)	(0.44)	(− 4.13)	(− 3.14)	(− 0.34)	
TYVIX	3.951	30.936	− 0.428	− 2.476	− 1.015	2.306	− 36.723	− 20.661	0.061	0.330
	(10.84)	(5.72)	(− 1.93)	(− 1.68)	(− 2.32)	(0.40)	(− 3.91)	(− 2.42)	(0.08)	

Panel B: Directional Connectedness from Treasury risk-neutral volatilities to the VIX

	Const	RESTERM	SHADOW	TRYRET	FUNC	RESRA	RESDEF	IPI	EXCMKET	Adj R^2
MOVE	3.311	0.119	− 0.220	− 1.148	0.158	8.962	9.688	− 4.538	0.820	0.275
	(22.07)	(0.04)	(− 2.30)	(− 1.56)	(0.91)	(3.34)	(1.61)	(− 1.33)	(1.78)	
TYVIX	3.325	3.685	− 0.216	− 0.385	0.224	7.384	1.962	− 4.124	0.760	0.254
	(21.35)	(1.46)	(− 2.03)	(− 0.45)	(1.21)	(2.64)	(0.35)	(− 1.10)	(1.31)	

This table shows the results of OLS regressions with monthly data of directional connectedness on a set of economic drivers for the full sample period. Panels A and B show the results for the directional connectedness from the VIX to Treasury risk-neutral volatilities (the MOVE and the TYVIX) and from Treasury risk-neutral volatilities to the VIX, respectively. The variable 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 is the change in the shadow interest rate of Wu and Xia (2016); TRYRET is the excess return of composite Treasury bonds; FUNC is the financial uncertainty of Jurado et al. (2015); RESRA is the European Central Bank's 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 for Newey–West/ HAC standard errors in parentheses

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