The Information Content of the Decomposed VVIX and VSKEW

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Abstract

We extract volatility and skewness from VIX options, namely VVIX and VSKEW, via a model-free methodology, and find that they show significant predictability in relation to market downturns, economic recessions and tail risk option returns. We further observe that the positive and negative components of VVIX, implied by VIX calls and puts, respectively, play asymmetric roles in forecasting, and that the positive component mainly contributes for the predictability of VVIX. All the results are robust after controlling for tail risk measures. Our findings confirm that distinctive information can be extracted from moments of VIX options, even though VIX and SPX markets are closely related. We also highlight the linkages between volatility markets and future financial and macroeconomic conditions.

Keywords: implied volatility and skewness, decomposition, VIX options, market downturns, economic recession, tail risk

JEL Classifications: G11; G12; G13

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1. Introduction

Trading in volatility instruments has been thriving recently, especially after the outburst of the Global Financial Crisis. Before the introduction of VIX derivatives, volatility trading was mainly carried out via over-the-counter market such as variance swaps. The launch of VIX derivatives however enabled investors direct access to volatility trading and efficient hedging of market fluctuations.[1] As one of the main VIX derivatives, VIX options which were introduced on Feb 24, 2006 have gained huge popularity ever since and are now ranked as the second most actively CBOE traded contracts.[2] The VIX option market is relatively new compared to the other traditional option markets such as SPX options, and it still provides opportunities for researchers and practitioners to explore various aspects of this market.

Option markets are forward-looking by nature, and thus contain rich information such as investors' beliefs about the distribution of future values of the underlying assets (e.g., Bliss and Panigirtzoglou, 2004; Hanke et al., 2020; Kostakis et al., 2011). Bliss and Panigirtzoglou (2004) estimate investors' risk aversion via the risk-neutral distribution implied by the U.S. equity option. Kostakis et al. (2011) improve the dynamic asset allocation by utilizing the information of S&P500 (SPX) implied distributions, and it is worthwhile to note that extreme market turmoil may largely impact the shape of implied distributions, and thus deteriorate the marking timing ability. More recently, Hanke et al. (2020) have also confirmed that the COVID-19 pandemic has significant impacts on the

[1] VIX index was firstly introduced by the Chicago Board Options Exchange (CBOE) in 1993, measureing the market's expectation of the near-term 30-day volatility.
[2] VIX futures which were introduced in 2004 are another main VIX derivative.

risk-neutral probability density distribution inferred by several index options. Volkert (2015) extends the analysis to the VIX option market by exploring the predictive information of distribution implied by VIX options, and the impact of financial crisis on its shape.

Another strand of literature directly focuses on the moments implied by option markets instead of the risk-neutral distribution. The studies are particular abundant with regard to the second-order moment, namely, the volatility, and how they impact the financial markets and overall economic conditions (e.g., Ang et al., 2006; Cao and Han, 2013; Jiang and Tian, 2005). Besides, implied volatility has been shown to be closely linked to industrial production and consumers' demand (Bloom, 2009). The linkage between implied moments and macroeconomy has further been confirmed by Gao et al. (2018) and Bevilacqua and Tunarub (2021), where the former use implied volatility of USO options and the latter focuses on implied skewness of SPX options.[3] There are some recent research focusing on the second moment of the VIX option implied distributions, namely, VVIX (e.g., Hollstein and Prokopczuk, 2018; Huang et al., 2019; Park, 2015).[4] Huang et al. (2019) find that VVIX is a significant pricing factor apart from the volatility itself, and it can predict near-term option returns and realized volatility. This predictability evidence is also confirmed by Hollstein and Prokopczuk (2018) with a longer sample period. Park (2015) argues s that VVIX contains market's perception of

[3] USO is an ETF designed to track the prices of West Texas Intermediate Light Sweet Crude Oil. Data of implied volatility of USO options are provided by Chicago Board Options Exchange (CBOE).

[4] VVIX was introduced by CBOE in 2012, also referred to as "volatility of volatility", and is used as a measure of the VIX's 30-day forward expected volatility. It is constructed the same way as VIX by using VIX options instead of SPX options.

tail risk, and thus can be used as a tail risk measure. However, studies of moments implied by VIX options are still very limited compared to the research using SPX options.

Furthermore, a growing body of literature has started to focus on the linkage between higher-order moments such as risk-neutral skewness and financial markets (e.g., Byun and Kim, 2013; Dennis and Mayhew, 2002; Liu and Faff; 2017). Implied skewness, a measure of asymmetry for the risk-neutral distribution, has close relationship with tail risks (e.g., Bevilacqua and Tunarub, 2021; Du and Kapadia, 2014). The additional pricing information of implied skewness over volatility has also been confirmed by Bali et al. (2013), and can be explained by investor sentiment (e.g., Han, 2008). Additionally, tail risk measures can be extracted from moments of implied distributions (e.g., Bollerslev and Todorov, 2011; Du and Kapadia, 2014; Gao et al., 2018). Notably, the methodologies of Bollerslev and Todorov (2011) and Du and Kapadia (2014) are largely confined to the availability and accuracy of deep out-of-money (DTOM) options, since they mainly compensate for the large rare jump events. However, there has been much less investigation on extracting valuable information about implied moments of the VIX market.

Recent studies put particular focus on the asymmetric roles of positive and negative components of option implied moments that play in relation to economic and financial conditions (e.g., Bevilacqua et al., 2019; Bevilacqua and Tunarub, 2021; Kilic and Shaliastovich, 2018). In particular, Kilic and Shaliastovich (2018) demonstrate that semivariance risk premiums constructed using SPX calls and puts exhibit asymmetric predictability. Bevilacqua and Tunarub (2021) find that the information content of skewness implied by SPX calls is related to market sentiment, whereas its downside component is closely linked to other tail risk measures. It is well-known that in volatility market, VIX index generally presents a pattern of rapid increases and slow decreases of market returns, which may lead to VIX calls work much more efficiently than VIX puts.[5] Bollen and Whaley (2004) attribute the asymmetric hedging effects of calls and puts to the net-buying pressure: i.e., during market downturns, investors with behavioral biases worry about the declining trend of the market in near term and thus tend to buy more out-of-money SPX puts for hedging downside risks. Therefore, it is worthwhile to investigate whether the upside and downside components of VIX implied moments, extracted from calls and puts, respectively, contain asymmetric market information or not.

In this paper, we mainly investigate whether implied volatility of VIX options contain distinctively predictive information for the future macroeconomic and financial conditions apart from implied volatility of SPX options. Additionally, motivated by recent studies investigating asymmetric information of decomposed moments implied calls or puts only, we also examine the asymmetric predictability of upside (downside) volatility implied by VIX calls (puts) separately (e.g., Bevilacqua and Tunarub, 2021; Kilic and Shaliastovich, 2018).In addition, we construct implied skewness of VIX options to measure the asymmetry of risk-neutral distribution inferred by VIX options, and then check its forecasting ability for future economic uncertainty and market recessions, as well as its pricing implications.

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[5] VIX puts can still be used as a hedging tool, especially in the case when market goes through a turning around from downward towards upward.

To do so, we first construct an implied volatility and skewness using one-month VIX options, namely $VVIX$ and $VSKEW$, by applying the model-free methodology of Kozhan et al. (2013). Also, an upside (downside) implied volatility of the VIX market, denoted by $VVIX^{+}$ ($VVIX^{-}$), is constructed by using only VIX call (put) options by referring to the decomposition method of Kilic and Shaliastovich (2018). Next, we investigate the linkage with other financial and macroeconomic indicators. Specifically, we focus on the predictability of moments implied by VIX options in regard to the future market downturns, economic recession and tail risk hedging option returns.

We first find that moments implied by VIX options can work as efficient predictors for future market downturns and economic uncertainty. Besides, the upside and downside volatility implied by VIX options show asymmetric predictive ability, in terms of various forecasting horizons. The skewness implied by VIX options also provide additional forecasting information. In terms of asset pricing implications, the moments implied by VIX options can significantly predict returns of tail risk hedging portfolio, which is constructed using VIX calls or SPX puts. The predictability might be explained by the fact that increasing uncertainty in the volatility market is generally closely related to rising volatility of the equity market which in turn results in investors' over-pessimism regarding the future market conditions.

The remainder of the paper proceeds as follows. In section 2, we describe the data and methods of constructing the key variables and provide summary statistics of these variables. Section 3 explains our empirical results, including predictive analysis of future market downturns, economic uncertainty, and tail risk hedging option returns. Finally, section 4 concludes the paper.

2. Measures for Capturing Asymmetric Information in VIX Options Markets

2.1. Extracting positive and negative VVIX

In this section, we employ the model-free approach of Kozhan et al. (2013) to construct positive and negative volatility of VIX options. Specifically, risk-neutral variance is payoff of the variance contract as follows:

$$iv_{t,T} = e^{-r^f \tau} E_t^Q\left[g^v\left(R_{t,T}^u\right)\right] = v_{t,T}^L,$$

where $v_{t,T}^L$ is computed from the cross section of out-of-money (OTM) VIX options

$$v_{t,T}^L = \frac{2}{B_{t,T}} \int_{F_{t,T}}^{\infty} \frac{C(t,T,K)}{K^2} dK + \frac{2}{B_{t,T}} \int_0^{F_{t,T}} \frac{P(t,T,K)}{K^2} dK.$$

Furthermore, the positive and negative components of the risk-neutral variance are extracted from OTM calls and puts, respectively.

We further convert the risk-neutral variance of VIX options, together with their positive and negative components (i.e., $VVIX$, $VIXVIX^{+}$ and $VIXVIX^{-}$), following the conversion rule of the Chicago Board Exchange (CBOE). For example, the conversion of $VVIX$ is as [6]

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[6] The correlation between $VVIX$ we compute and VVIX provided by CBOE is highly correlated, with the value of 0.966.

$$VVIX_t = 100 \sqrt{\frac{365}{30} \mathrm{iv_{t,T}}}.$$

Notably, we apply the above equations for both 1- and 2-month VIX options, and then implement interpolation to get 30-day implied volatility at daily frequency.

2.2. Construction of VSKEW

Similarly, risk-neutral skewness is payoff of the skewness contract, which can be expressed as:

$$is_{t,T} = e^{-r^f \tau} E_t^Q\left[g^s\left(R_{t,T}^u\right)\right] = \frac{3\left(v_{t,T}^E - v_{t,T}^L\right)}{\left(v_{t,T}^L\right)^{3/2}}.$$

where $v_{t,T}^E$ is also computed from the cross section of OTM VIX options

$$v_{t,T}^E = \frac{2}{B_{t,T}} \int_{F_{t,T}}^{+\infty} \frac{C(t,T,K)}{KF_{t,T}} dK + \frac{2}{B_{t,T}} \int_0^{F_{t,T}} \frac{P(t,T,K)}{KF_{t,T}} dK.$$

Following the conversion rule of CBOE, $VSKEW$ can be written as

$$VSKEW_t = 100 - 10 is_{t,T}.$$

3. Data and Preliminary Findings

3.1. Data

The empirical analysis spans from January 1, 2010 to December 31, 2020, covering the periods associated with COVID19 outbreak. We use VIX and SPX option data obtained from Optionmetrics to construct the key variables. Before the construction, we filter out options with a zero close bid, the close ask greater than the close bid, prices violating no-arbitrage condition, or a Black–Scholes–implied volatility greater than 100% or less than 1%. The risk-free rates, which are used for constructing delta-hedged payoffs, are proxied by the 3-month London Interbank Offered Rate, obtained from the Federal Reserve Bank of St. Louis (FRED).

Table 1 reports the descriptive statistics for the risk-neutral moments of VIX options. It is interesting to note that $VVIX^+$ are positive skewed whereas $VVIX^-$ is negatively skewed, thus mixing these two variables would lead to loss of information associated with those asymmetries. Additionally, the skewness of VVIX is positive, indicating stronger influence of VVIX+ on the time-variation of VVIX.

[Insert Table 1 about here]

3.2. Preliminary Findings

To investigate the economic meanings of our suggested measures, we first explore the evolution of the risk-neutral moments of VIX options during the sample period and observe if those measures are linked to major events in the financial market. Figure 1 plots the time-series of the risk-neutral moments of VIX options at daily frequency. The figure shows that both $VVIX^+$ and VVIX show clear upward hikes two times for year 2010 and 2011, and those periods correspond to First and Second Stage Eurozone

Sovereign Debt Crisis, respectively. In contrast, VVIX^{-} had experienced less dramatic variations during that time. Also, such a more dramatic pattern of VVIX^{+} compared to VVIX^{-} are observed in year 2015 and 2016 that correspond to the period with several events causing global concerns.[7] In sum, VVIX^{+} appears to be related to economic crisis.

Table 2 presents the correlation among the risk-neutral moments of VIX options at monthly frequency. Note that throughout this paper, we take the end of month observations for constructing monthly frequency variables. The correlation between VVIX+ and VVIX is very high with the correlation coefficient of 0.85. Such a strong co-movement pattern can be also inferred by comparing the historical evolution of VVIX with that of VVIX^{+} as shown in Figure 1. This implies that VVIX^{+} mainly drives the movements of VVIX. In contrast, the correlation between VVIX^{+} and VVIX^{-} is relatively low with the correlation coefficient of 0.19, indicating that VIX calls and puts carry asymmetric information. The previous illustrative works imply that VVIX^{+} and VVIX can be proxies for capturing tail risk as those largely fluctuate around financial turmoil. Next, we investigate how the risk-neutral moments of VIX options are distinct from existing tail risk measures suggested by the related literature.

[Insert Table 2 about here]

We select CATFIN, as suggested by Allen et al. (2012), downside market risk-neutral skewness (SKEW^{-}), and crash confidence index (CRASH) of the International Center for Finance at Yale SOM as other crash risk proxies, for comparison with our measures

[7] For example, Ukraine-Russia Conflict, Chinese Yuan Crisis, UK Brexit

extracted from VIX options. These crash risk measures are widely used in the related literature (e.g., Bevilacquaa and Tunaru, 2021; Brownlees et al., 2020). For constructing SKEW$^-$, we use SPX put option data.[8]

Table 3 shows the correlation between the risk-neutral moments of VIX options and the other crash risk measures at monthly frequency. Surprisingly, the correlation between VVIX$^+$ and CRASH (CATFIN) is low, with the correlation coefficient between -0.1 and 0.1. On the other hand, VVIX$^+$ and SKEW$^-$ share negative correlation (-0.16). The negative sign is consistent as SKEW$^-$ becomes more negative and VVIX$^+$ becomes more positive at economically bad times. In case of VVIX, the correlation coefficient associated with CRASH (CATFIN) is relatively high with the value of 0.13 (0.16). However, the correlation coefficient associated with SKEW$^-$ has inconsistent sign with the positive value of 0.24.

[Insert Table 3 about here]

Overall, the risk-neutral moments of VIX options and the other tail risk measures are not highly correlated with each other as the correlation coefficients range between -0.2 and 0.2 in most cases. This implies that VVIX$^+$ and VVIX, which show their relevance during financial turmoil, could serve as a tail risk measure and carry distinctive information from other tail risk proxies suggested in the literature. Our preliminary analysis shows that VVIX$^+$ can be a good proxy for the tail risk measure and carry distinctive information.

[8] CATFIN is provided by Turan Bali's personal website (https://sites.google.com/a/georgetown.edu/turan-bali) and CRASH is available at https://som.yale.edu/faculty-research/our-centers/international-center-finance/data. CRASH contains information about institutional investors' expectations of a crash in the next six months

4. Information Content of Decomposed VVIXs and VIX SKEW

4.1.Early warning indicator for recession or market downturn

Predictors of economic recession or downturn can be extracted from option markets, mainly by SPX options such as VIX and SKEW (e.g., Allenet al., 2012; Bakshi et al., 2011; Bevilacqua and Tunarub, 2021).[9] We are thus motivated to analyze whether moments implied by VIX options, namely, VVIX, VVIX^{+}, VVIX^{-}, and VSKEW can also sever as ex-ante predictors of future economic condition. Besides, VVIX^{+} and VVIX^{-} which are extracted from VIX calls and puts, respectively, and thus contain investors' heterogeneous beliefs, may also contain predictive information (e.g., Buraschi and Jiltsov, 2006; Feng et al., 2015; Feng et al., 2018). It is also acknowledged that skewness implied by SPX options represents information of investors' heterogeneous beliefs, market sentiment, and tail risks (e.g., Bevilacqua and Tunarub, 2021; Friesen et al., 2012).

We employ the following logistic regression to analyze the recession predictability,

$$logit(D_t) = \beta_0 + \beta_1 D_{t-h} + \beta_2 M_{t-h}^{VIX} + \varepsilon_t, \tag{7}$$

where M^{VIX} denotes one of the moments implied by VIX options, namely, VVIX, VVIX^{+}, VVIX^{-}, and VSKEW. D is a dummy variable with the value of 1 if economy is in recession and 0 otherwise We consider the U.S business cycle classification provided by the OECD and Economic Cycle Research Institute (ECRI) recession indicator which are widely used in related literature (e.g., Altug et al., 2012; Canova et al., 2012; Krolzig,

[9] VIX and SKEW stands for one-month implied volatility and skewness of SPX markets, and the data can be downloaded from CBOE website www.cboe.com/data/.

2001; Pedersen and Elmer, 2003). We also consider $MktDown$, a dummy variable related to stock market drops and the threshold value is set to be 3% here.[10]. We control the lagged term of the endogenous variable, with the lagged month $h = \{1, 3, 6, 12\}$.

Park (2015) points out that VVIX is closely related to tail risk. Hence, we also include the tail risk measure as controls for robustness check since it is well-known that tail risk measures can significantly predict economic recession and market downturns (e.g., Bollerslev et al., 2015; Gourio, 2009). Therefore, we run the following logistic regression:

$$logit(D_t) = \beta_0 + \beta_1 D_{t-h} + \beta_2 M_{t-h}^{VIX} + \beta_3 TR_{t-h} + \varepsilon_t, \quad (8)$$

where TR stands for the set of tail risk measures, including CRASH, CATFIN, and SKEW$^-$, with the forecasting horizon $h = \{1, 3, 6, 12\}$ months ahead.

The predicting results are reported in Table 4. We observe that VVIX exhibits significant predictability for ECRI recession indicator at various horizons from 3 to 12 months, whereas it shows short-term forecasting power for $MktDown$ at 1-month horizon. Even after controlling for the tail risk, the robustness tests generate similar results. Regarding the predictability of decomposed VVIX, VVIX$^+$, we can observe that significantly predict ECRI in 3- to 12-month ahead, even with higher R^2 and *t*-stat compared to the VVIX case. On the other hand, VIX$^-$, the downside component extracted from VIX puts, cannot predict any of the recession indicators. VVIX$^+$ is the only efficient predictor among the three implied volatilities for 12-month-ahead OECD recession indicator, which also highlights the fact that VVIX$^+$ is the dominant component for

[10] D will take the value of 1 if the recession indicator OECD or ECRI signals economic recession, and when $MktDown$ drops to the value equal to or less than 3%. More detailed explanations can be found in Appendix A1.

predictability of VVIX. The results remain robustness after controlling for the tail risk measures.

The above findings confirm the asymmetric predictive information of $VVIX^+$ and $VVIX^-$, thus we further check the predictability of VSKEW, the asymmetry measure calculated using VIX options. We observe that VSKEW can significantly forecast 12-month ahead ECRI and $MktDown$,before controlling for tail risks, and retains itss forecasting power for 12-month ahead ECRI even after incorporating control variables. These results suggest that VSKEW also contains forward-looking information of economic recessions, and is related to tail risk of the equity market.

It is worthwhile to note that the signs of all the predictors are positive, suggesting that the increasing uncertainty of volatility market is a signal for rising probability of economic recession. Table 4 shows that a 1% increase in $VVIX^+$ signals a 187.41% and 105.92% rise in the probability of recession in the next 6- and 12-month horizon, respectively.. The positive sign may be due to the fact that higher implied volatility of volatility market normally leads to higher realized volatility of equity market and indicates investors' over-pessimism in the near term, which is generally accompanied with low financial stability and higher probability of economic recession (Huang et al., 2019). Notably the volatility paradox proposed by Brunnermeier and Sannikov (2014) claiming that low realized volatility may lead to increase in the probability of systematic crisis actually uses realized volatility measure.

[Insert Table 4 about here]

Overall, the implied volatility of VIX options, similar to the volatility implied by SPX options, also contain predictive information of future macroeconomic conditions, and the main driving force comes from $VVIX^+$ which are extracted from VIX calls. The asymmetric predictability of $VVIX^+$ and $VVIX^-$ highlights the importance of VSKEW, the asymmetry measure implied by VIX options. The results can reflect the fact that increasing uncertainty in the volatility market is generally closely related with rising volatility of the equity market and investors' over-pessimism.

4.2.Linkage with economic uncertainty

In this section, we investigate whether VVIX contains forecasting information about future economic uncertainty, and whether its predictability can be equally attributed to the upside and downside components, namely, $VVIX^+$ and $VVIX^-$. We put particular focus on the role of $VVIX^+$, which is extracted from VIX calls, due to the fact that VIX shows stronger reaction to market downturns, and thus VIX calls are more popular than VIX puts for hedging against high degrees of market turmoil, especially during the sharp market declines.

To achieve this goal, several uncertainty indicators used for tracking the economic, political and geopolitical uncertainty are employed, including the Macroecnomic Uncertainty Index (MUI) of Jurado et al. (2015), the Economic Policy Uncertainty (EPU) index proposed by Baker et al. (2016), and the GeoPolitical Risk (GRP) index of Caldara and Iacoviello (2018). Our predictive model specification is as follows:

$$Indicator_t = \beta_0 + \beta_1 Indicator_{t-h} + \beta_2 M_{t-h}^{VIX} + \varepsilon_t, \quad (9)$$

where M^{VIX} denotes one of the moments implied by VIX options, namely, VVIX, VVIX$^+$, VVIX$^-$, and VSKEW. $Indicator$ is one of the several economic uncertainty indicators, namely, MUI, EPU and GPR. The lagged term of the endogenous variable is also considered, where h denotes the number . of lagged months, with $h = \{1, 3, 6, 12\}$.

Furthermore, we include the tail risk measures as controls by running the following predictive regression:

$$Indicator_t = \beta_0 + \beta_1 Indicator_{t-h} + \beta_2 M_{t-h}^{VIX} + \beta_3 TR_{t-h} + \varepsilon_t, \quad (10)$$

where TR stands for the set of tail risk measures, including CRASH, CATFIN, and SKEW$^-$.

The results are presented in Table 5. We observe that the implied volatility of VIX options, no matter decomposed or not, exhibit significant predictive ability, even though differ in forecasting horizons. Specifically, without controlling for tail risks, VVIX positively and significantly predict EPU up to 6 months. In contrast, VVIX$^+$ and VVIX$^-$ exhibit asymmetric forecasting ability; that is, VVIX$^+$ can significantly and positively predict 12-month-ahead EPU, whereas VVIX$^-$ only exhibits positive forecasting power on short-term horizons within 3 months. The predictive results without controlling for tail risks for MUI are very similar to those of EPU, and we can observe that VVIX and VVIX$^-$ show predictive ability from 1- to 6-month horizons, and VVIX$^+$ can predict at longer horizon of 12-month ahead. Regarding the case of GPR, only VVIX$^+$ remains efficient as a 3-

month forward predictor. Including tail risks into the robustness check has little impacts on the results.

Considering the asymmetric predictability of $VVIX^+$ and $VVIX^-$, we also check the forecasting power of the asymmetry measure VSKEW. We find that VSKEW can significantly predict 12-month forward EPU and MUI, but not at short horizons, and it shows forecasting ability for GPR from 1- to 12-month horizons. However, the predictability of VSKEW is no longer valid after controlling for tail risk measures, indicating that similar to SKEW of equity market the risk information content of VSKEW is mainly about tail risks (e,g., Bevilacqua and Tunarub, 2021).

On the whole, we observe that VVIX, together with $VVIX^+$ and $VVIX^-$, contains significant predictive power of future macroeconomic uncertainty which can be proxied by indicators such as EPU, GPR and MUI. Besides, VSKEW also contains predictive information of the uncertainty indices, and the driving force is the tail risk that VSKEW stands for.

5. Asset Pricing Implications: Predicting Tail Risk Hedging Option Returns

We have so far shown that $VVIX^+$ and $VVIX^-$ exhibit asymmetric forecasting ability for future macroeconomic conditions, and $VVIX^+$ is the component mainly attributing to the predictability of VVIX. Moreover, due to the fact that option market contains forward-looking information for the latent tail risk factor, several studies have tried to develop option implied tail risk measures and the related pricing implications (e.g., Bollerslev and

Todorov, 2011; Du and Kapadia, 2012; Park, 2015). In this section, we further explore the information content of moments implied by VIX options from the perspective of asset pricing. Following Park (2015) we select delta-hedged portfolios of VIX calls and SPX puts as testing assets and then investigate the predictability of the moments implied by VIX options, namely, VVIX, VVIX$^+$, VVIX$^-$ and VSKEW.[11]

5.1.Payoffs of delta-hedged option portfolio

A delta-hedged option portfolio consists of longing an option and shorting delta units of its underlying asset, with net income investment at the risk-free rate. The gains of such a portfolio are thus insensitive to the underlying assets. Especially for the delta-hedged gains computed using out-of-money (OTM) options, they are more easily to be affected by risk factors associated with higher moments such as variance risk and tail risk (e.g., Bakshi et al., 2003; Park, 2015).[12]

Under daily rebalancing scheme, the payoff of a delta-hedged option portfolio from time t to maturity τ is expressed as:

$$\pi_{t,t+\tau} = O_{t+\tau} - O_t - \sum_{n=0}^{N-1} \Delta_{t_n}\left(F_{t_{n+1}} - F_{t_n}\right) - \sum_{n=0}^{N-1} r_{t_n}^{f} O_t \frac{\tau}{N}, \tag{11}$$

where $\pi_{t,t+\tau}$ is the delta-hedged portfolio payoff and O_t denote the option price at time t with time to maturity τ. F_t indicates the underlying asset price.[13] Δ_t is the option delta on day t_n and N is the total number of trading days from time t to $t+\tau$.

[11] VIX call options and SPX put options generate large positive payoffs in bad states of the economy, and thus are often used as hedging tools for market downturns.

[12] Note that delta is calculated by taking first derivative of the option price with respect to the price of the underlying asset. Here we use option delta implied by the model of Black and Scholes (1973).

[13] Notably, VIX options are written on VIX futures, and SPX options are written on S&P 500 index.

Finally, the delta hedged payoff is scaled by the initial index level ($\pi_{t,t+\tau}/F_t$) that can be interpreted as a "return" and this is the main variable for the prediction. At the close of each option expiration, we choose monthly out-of-money (OTM) VIX calls and OTM SPX puts with nonzero open interest and nonzero trading volume.[14] We separate options by the moneyness and calculate an equal average of scaled delta-hedged payoffs for each group.[15]

Table 6 shows the summary statistics of the scaled delta-hedged payoffs constructed on one-month VIX calls (Panel A) and SPX puts (Panel B), grouped by moneyness. Across all moneyness and base assets, the scaled delta-hedged payoffs are negative on average, indicating that those strategies lose money for hedging crash risk.[16]

[Insert Table 6 about here]

5.2. Predicting payoffs of delta-hedged option portfolio

We employ the following model for testing the predictability of implied moments on delta-hedged option portfolios:

$$\frac{\pi_{t,t+\tau}}{F_t} = \alpha + \beta_1 M_t^{VIX} + \beta_2 SPPV_t + \gamma' CV + \epsilon_{t+\tau}, \qquad (12)$$

[14] We only focus on one-month options here, and thus avoid the term-structure issue due to different maturities of options.
[15] For VIX calls, deep out-of-money (DOTM) options are the ones with moneyness level (F/K) lower than 0.9 and OTM options are the ones with moneyness level between 0.9 and 1. For SPX puts, DOTM options are associated with the level higher than 1.1 and OTM options are associated with the level between 1 and 1.1
[16] For VIX calls, deep out-of-money (DOTM) options are the ones with moneyness level (F/K) lower than 0.9 and OTM options are the ones with moneyness level between 0.9 and 1. For SPX puts, DOTM options are associated with the level higher than 1.1 and OTM options are associated with the level between 1 and 1.1

where M^{VIX} denotes one of the moments implied by VIX options, namely, $VVIX$, $VVIX^{+}$, $VVIX^{-}$ and $VSKEW$. $SPPV_t$ is either VIX^{-} or $SKEW^{-}$, which are extracted from SPX puts. As these tail risk proxies might capture variations of delta-hedged SPX put option portfolio well, controlling their effect is needed. CV denotes control variables. Following Park (2015), we consider following five control variables for the model associated with delta-hedged SPX put option portfolio: $\Delta VIX_{t,t+\tau}$, $\Delta VIX^2_{t,t+\tau}$, $\Delta SPX_{t,t+\tau}$, $\Delta SPX^2_{t,t+\tau}$ and $\Delta SPX_{t,t+\tau} \cdot \Delta VIX_{t,t+\tau}$. $\Delta VIX_{t,t+\tau}$ is defined as $\log(VIX_{t+\tau}/VIX_t)$ and $\Delta SPX_{t,t+\tau}$ is defined as $\log(SPX_{t+\tau}/SPX_t)$. In case of delta-hedged VIX call option portfolio, we only consider $\Delta VIX_{t,t+\tau}$ and $\Delta VIX^2_{t,t+\tau}$ as control variables. Adding these realized variables could capture second-order (gamma) effects of price changes, hedging errors from the usage of Black-Scholes delta, and volatility risk, so that we can test the predictive relationship between moments implied by VIX options and tail risk hedging option returns more effectively.

Table 7 shows that $VVIX^{+}$ negatively predicts delta-hedged payoffs of VIX calls, even after controlling for VIX^{-} or $SKEW^{-}$. However, VIXX, $VVIX^{-}$, and VSKEW do not show any significant predictability patterns, implying that only information extracted from VIX call options matters. Meanwhile, the coefficients on VIX^{-} and $SKEW^{-}$ are not statistically significant indicating that the information extracted from SPX puts are not reflected in VIX call options price.

[Insert Table 7 about here]

Table 8 presents the results for delta-hedged payoffs of SPX puts. In contrast to the pattern for delta-hedged payoffs of VIX calls, we do not find any pattern that the measures based on VIX options negatively predict delta-hedged payoffs of SPX puts. In contrast, the coefficients on VIX^- are statistically significant at the 1% level for most cases.

[Insert Table 8 about here]

Overall, the information content of $VVIX^+$ is only reflected in delta-hedged VIX call option portfolios, but not in delta-hedged SPX put option portfolios. We interpret these results that $VVIX^+$ represents distinct risk sources from downside market risk which is mainly priced in SPX put options, and it is mainly reflected in for delta-hedged VIX call option portfolios.

6. Conclusions

We extract volatility and skewness from VIX options following the model-free methodology of Kozhan et al. (2013), and then implement the predictive analysis in the regards of market downturns, economic recessions and tail risk option returns. We further analyze the asymmetric information content of upside and downside volatility implied by VIX calls and puts, respectively, and find that the upside component is the main contributor for the predictability of VVIX. We further observe that the asymmetry measure of VIX market also exhibits significant predictability. All the results are robust after controlling for tail risk measures.

Our findings confirm that distinctive information can be extracted from moments of VIX options, even though VIX and SPX markets are closely related. We also highlight the linkages between volatility markets and future financial and macroeconomic conditions. We verify the moments implied by VIX options contain additional information than tail risks.

Appendix A.

Descriptions on Economic Recession and Market Downturns Indicators

- **OECD recession indicators**: It is one of the leading recession indicators, the moving trends of which are ahead of corresponding shifts in macroeconomic trends. The data is available at https://fred.stlouisfed.org/series/USARECM.
- **ECRI recession indicator**: It is provided by Economic Cycle Research Institute, and reflects the outlook for U.S. economic growth, inflation, employment, and real income. The data can be downloaded from www.businesscycle.com.
- $\boldsymbol{MktDown}$: Market downturns are modelled with a dummy variable, indicating 1 for a market downturn equal to or less than the critical value, namely 3% here, and 0 otherwise. And the market downturn is computed using CRSP value weighted returns.

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Table 1. Summary statistics

	Mean	Median	SD	Skew	Kurt	AR(1)	P10	P90
VVIX+	73.54	72.20	9.70	0.86	4.51	0.89	62.54	84.04
VVIX-	50.48	50.69	12.38	-0.26	4.08	0.82	37.69	66.03
VVIX	89.79	89.44	11.88	0.34	3.14	0.90	76.01	105.26
VSKEW	81.94	83.01	6.24	-0.39	3.41	0.90	74.42	88.67

***Note**:* The table shows the summary statistics of risk-neutral moments of VIX and SPX options, including VVIX+, VVIX-, VVIX, and VSKEW, where Mean refers to mean value, Median refers to median value, SD refers to standard deviation, Skew refers to skewness, Kurt refers to kurtosis, AR(1) refers to the first-order autocorrelation, P10 and P90 refer to the 10% and 90% percentiles, respectively. The sample period is from January 1, 2010, to December 31, 2020, at monthly frequency.

Table 2. Correlations

	VVIX+	*VVIX-*	*VVIX*	*VSKEW*
VVIX+	1			
VVIX-	0.19	1		
VVIX	0.85	0.66	1	
VSKEW	-0.13	0.79	0.34	1

Note: The table shows the sample correlation coefficients of risk-neutral moments of VIX options, including VVIX+, VVIX-, VVIX, and VSKEW. The sample period is from January 1, 2010, to December 31, 2020, at monthly frequency.

Table 3. Correlations between Risk-Neutral Moments of VIX Options and Other Tail Risk Measures

	VVIX+	*VVIX-*	*VVIX*	*VSKEW*
CRASH	-0.04	0.17	0.13	0.00
CATFIN	0.07	0.12	0.16	-0.24
SKEW-	-0.16	0.37	0.24	-0.62

***Note**:* The table shows the sample correlation coefficients between risk-neutral moments of VIX options and other tail risk measures used in the literature. The other tail risk measures are CATFIN suggested by Allen et al. (2012), downside market risk-neutral skewness (SKEW-) extracted from SPX put options, and crash confidence index (CRASH) provided by the International Center for Finance at Yale SOM. The sample period is from January 1, 2010, to December 31, 2020, at monthly frequency.

Table 4. Early Warning Indicator for Recession or Market Downturn

H		OECD	R^2(%)	ECRI	R^2(%)	$MktDown$	R^2(%)
1	$VVIX$	1.137	73.09	60.638	87.64	16.076**	6.35
	$VVIX^+$	-6.911	73.14	27.414	85.89	18.286**	3.47
	$VVIX^-$	6.678	73.16	120.819	88.32	10.850	3.15
	$VSKEW$	-0.179	73.14	-2.240	87.77	-0.086	0.94
	$VVIX\|TR$	9.420	74.61	98.582	90.55	16.709**	6.77
	$VVIX^+\|TR$	12.004	74.42	259.957	93.11	21.360**	4.95
	$VVIX^-\|TR$	27.550	75.46	168.089	90.20	11.454	3.50
	$VSKEW\|TR$	-1.607	76.33	-6.998	90.98	0.037	1.67
3	$VVIX$	-2.020	41.79	65.268**	72.90	2.063	1.58
	$VVIX^+$	5.775	41.87	83.791***	76.52	14.189	3.02
	$VVIX^-$	-4.299	41.94	-47.958	67.59	-31.515	3.29
	$VSKEW$	-0.080	41.78	0.683	67.62	0.690	4.52
	$VVIX\|TR$	7.590	49.92	13.990	93.15	-2.189	9.85
	$VVIX^+\|TR$	-3.528	49.42	5.596	93.11	14.100	10.81
	$VVIX^-\|TR$	16.278	50.54	21.534	93.14	-25.741	11.69
	$VSKEW\|TR$	-1.443	54.20	1.842	93.46	0.795	11.81
6	$VVIX$	-2.831	13.59	70.222***	55.39	5.466	1.64
	$VVIX^+$	17.061	14.91	89.296***	62.07	-17.253	2.39
	$VVIX^-$	-9.412	14.71	-38.611	44.24	12.359	3.23
	$VSKEW$	-0.070	13.50	0.661	1.11	-0.323	1.85
	$VVIX\|TR$	12.155	30.75	98.013**	79.30	0.862	9.23
	$VVIX^+\|TR$	14.712	30.10	187.411**	85.26	-16.289	10.04
	$VVIX^-\|TR$	8.884	29.89	-8.452	68.63	9.354	9.83
	$VSKEW\|TR$	-0.858	31.69	1.933	71.45	0.259	9.42
12	$VVIX$	3.071	1.56	41.962**	13.82	-14.20	1.85
	$VVIX^+$	26.512**	3.91	72.872***	26.23	5.995	0.56
	$VVIX^-$	-4.529	1.69	-62.996*	10.22	-60.551*	5.25
	$VSKEW$	0.188**	1.75	1.069*	12.53	0.943**	5.46
	$VVIX\|TR$	12.124	11.35	48.596**	31.23	-24.621	8.36
	$VVIX^+\|TR$	19.685*	11.11	105.920***	41.01	-12.047	6.57
	$VVIX^-\|TR$	8.566	10.51	-32.522	23.85	-66.504	9.79
	$VSKEW\|TR$	-0.498	10.98	1.641**	29.31	0.764	7.88

***Note**:* The table shows the results of the logistic predictive regressions between the risk-neutral moments of VIX options and economic recession (or market downturns) dummy (See Eqs.(7) and (8)). Recession dummy OECD has value of 1 if economy is in recession and 0 otherwise based on OECD business cycle classification whereas recession dummy ECRI is based on ECRI classification. $MktDown$ is a dummy variable indicating with one every market drop lower than 3%. We consider 1-, 3-, 6-, and 12-months forecasting horizons. "$|TR$" denotes models that control for the all set of tail risk measures: CRASH, CATFIN, SKEW-. The sample period is from January 1, 2010 to December 31, 2020 at monthly frequency. The regression coefficients the risk-neutral moments of VIX options and pseudo R-squared (R^2) are reported. Statistical significance levels are indicated as follows: *** (1%), ** (5%), and * (1%).

Table 5. Predicting Economic Uncertainty Indicator

H		EPU	R^2(%)	GPR	R^2(%)	MUI	R^2(%)
1	$VVIX$	798.226***	61.24	-8.216	37.98	0.608**	96.32
	$VVIX^+$	-7.981	50.69	362.871	39.55	-0.267	94.81
	$VVIX^-$	834.101***	61.75	-158.004***	38.71	0.677***	96.87
	$VSKEW$	-21.369	55.40	13.631**	41.20	-0.011	96.05
	$VVIX\|TR$	728.021***	63.19	167.778**	45.44	0.594***	97.28
	$VVIX^+\|TR$	368.443	55.49	317.950	45.72	0.007	95.70
	$VVIX^-\|TR$	748.390***	61.90	74.351	44.67	0.635***	97.39
	$VSKEW\|TR$	-16.377	56.26	-0.564	44.55	-0.013	96.01
3	$VVIX$	1053.173***	37.93	122.549	21.82	0.784***	87.17
	$VVIX^+$	731.946**	22.87	535.021*	24.73	0.330	82.21
	$VVIX^-$	808.158***	29.92	-67.411	21.41	0.657***	85.65
	$VSKEW$	-7.818	20.13	14.129**	24.78	-0.003	80.79
	$VVIX\|TR$	958.782***	42.83	285.525**	30.58	0.959***	86.94
	$VVIX^+\|TR$	1225.975***	36.46	544.299**	31.44	1.192***	85.50
	$VVIX^-\|TR$	665.452***	33.81	124.848	28.30	0.612**	85.16
	$VSKEW\|TR$	0.991	28.13	3.215	28.06	-0.005	84.10
6	$VVIX$	471.768**	16.31	-20.166	18.56	1.058***	56.50
	$VVIX^+$	1143.143	20.84	-70.050	18.60	1.722	53.79
	$VVIX^-$	41.003	12.63	3.068	18.55	0.632***	50.13
	$VSKEW$	8.730	13.39	13.896**	21.99	0.023	51.61
	$VVIX\|TR$	361.531	25.56	171.422	29.07	0.909**	60.99
	$VVIX^+\|TR$	1481.195**	35.66	-152.433	28.39	3.657**	68.95
	$VVIX^-\|TR$	-189.456	23.92	321.067***	30.47	-0.034	58.47
	$VSKEW\|TR$	13.072	24.44	-3.323	28.22	0.019	58.91
12	$VVIX$	331.120	3.18	-102.707	15.55	0.929	20.18
	$VVIX^+$	1952.583***	16.67	388.123	16.23	3.120**	29.83
	$VVIX^-$	-192.821	2.05	-203.983**	16.41	-2.888**	24.34
	$VSKEW$	20.367*	5.28	22.024***	23.44	0.053**	26.01
	$VVIX\|TR$	278.437	5.81	140.942	35.06	1.429*	31.56
	$VVIX^+\|TR$	1832.157***	15.82	-36.724	34.57	3.289***	37.99
	$VVIX^-\|TR$	-206.199	5.28	178.044	35.23	-1.258	29.06
	$VSKEW\|TR$	18.707	6.46	-5.496	34.82	0.038	30.18

Note: The table shows the results of the predictive regressions between the risk-neutral moments of VIX options and economic uncertainty indicators. EPU denotes Economic Policy Uncertainty Index of Baker et al. (2016), GPR denotes Geo-Political Risk Index of Caldara and Iacoviello (2018), and MUI denotes Macroeconomic Uncertainty Index of Jurado et al. (2015). "$|TR$" denotes models that control for the all set of tail risk measures: CRASH, CATFIN, SKEW-. We consider 1-, 3-, 6-, and 12-months forecasting horizons. The sample period is from January 1, 2010 to December 31, 2020 at monthly frequency. The regression coefficients the risk-neutral moments of VIX options and adjusted R-squared (R^2) are reported. Statistical significance levels are indicated as follows: *** (1%), ** (5%), and * (1%).

Table 6. Summary Statistics for Scaled Payoffs of Delta-hedged Option Portfolios

	Mean	Median	SD	Skew	Kurt	AR(1)	P10	P90
Panel A: Scaled payoffs of delta-hedged VIX call option portfolios								
OTM ($0.9 < k < 1$)	-0.048	-0.017	0.360	-0.505	32.62	-0.102	-0.119	0.039
DOTM ($k < 0.9$)	-0.023	-0.058	0.514	7.948	81.136	-0.046	-0.218	0.131
Panel B: Scaled payoffs of delta-hedged SP500 put option portfolios								
OTM ($1 < k < 1.1$)	-0.127	-0.188	0.571	2.970	20.596	0.038	-0.617	0.452
DOTM ($1.1 < k$)	-0.003	-0.026	0.346	9.844	105.689	-0.032	-0.091	-0.005

***Note**:* The table shows the summary statistics for monthly scaled payoffs of delta-hedged option portfolios. Moneyness k is defined as F/K, where K is the strike price and F is the futures price. Mean refers to mean value, Median refers to median value, SD refers to standard deviation, Skew refers to skewness, Kurt refers to kurtosis, AR(1) refers to the first-order autocorrelation, P10 and P90 refer to the 10% and 90% percentiles, respectively. Note that we scale up the values in Panel B (except for Skew, Kurt and AR(1)), by 100 here. The sample period is from January 2010 to December 2020.

Table 7. Prediction on Delta-Hedged Payoffs of VIX Call Options Portfolios

	VVIX		*VVIX+*		*VVIX-*		*VSKEW*	
	OTM	DOTM	OTM	DOTM	OTM	DOTM	OTM	DOTM
				Panel A: Baseline model				
Constant	0.40	-0.21	0.74	-0.16**	-0.23	-0.40***	0.26	-0.36***
(*t*-stat)	(1.09)	(-0.93)	(1.54)	(-2.54)	(-0.79)	(-3.31)	(0.55)	(-2.75)
M^{VIX}	-9.52***	-3.08	-19.82**	-5.24**	-3.16	-1.65	-0.28*	-0.03
(*t*-stat)	(-2.88)	(-1.20)	(-2.47)	(-1.97)	(-1.61)	(-1.27)	(-1.68)	(-0.40)
R^2	0.39	0.85	0.40	0.85	0.37	0.85	0.38	0.85
				Panel B: Model controlling for *VIX-*				
Constant	0.41	-0.21**	0.75	-0.06	-0.11	-0.27**	1.18**	0.04
(*t*-stat)	(1.22)	(-2.48)	(1.62)	(-0.33)	(-0.61)	(-2.37)	(2.03)	(0.18)
M^{VIX}	-20.15**	-3.48	-19.66**	-5.15*	-0.15	1.70	-0.49**	-0.13
(*t*-stat)	(-2.46)	(-0.97)	(-2.37)	(-1.67)	(-0.02)	(0.60)	(-2.24)	(-1.19)
VIX-	0.06*	0.00	-0.00	-0.01	-0.01	-0.01	-0.03***	-0.02**
(*t*-stat)	(1.73)	(0.17)	(-0.11)	(-0.87)	(-0.54)	(-1.34)	(-2.62)	(-2.04)
R^2	0.40	0.85	0.40	0.85	0.34	0.85	0.38	0.85
				Panel C: Model controlling for *SKEW-*				
Constant	0.07	-0.28	0.64	-0.17	-0.48	-0.46**	0.61	-0.33
(*t*-stat)	(0.18)	(-0.58)	(1.09)	(-1.53)	(-1.17)	(-1.98)	(0.90)	(-0.88)
M^{VIX}	-9.94***	-3.18	-19.74**	-5.23**	-3.72**	-1.79	-0.33*	-0.04
(*t*-stat)	(-2.94)	(-1.19)	(-2.48)	(-1.98)	(-2.00)	(-1.39)	(-1.74)	(-0.38)
SKEW-	0.01	0.00	0.00	0.00	0.01	0.00	-0.00	-0.00
(*t*-stat)	(0.91)	(0.03)	(0.24)	(0.47)	(0.67)	(0.34)	(-0.59)	(-0.09)
R^2	0.39	0.85	0.40	0.85	0.37	0.85	0.37	0.85

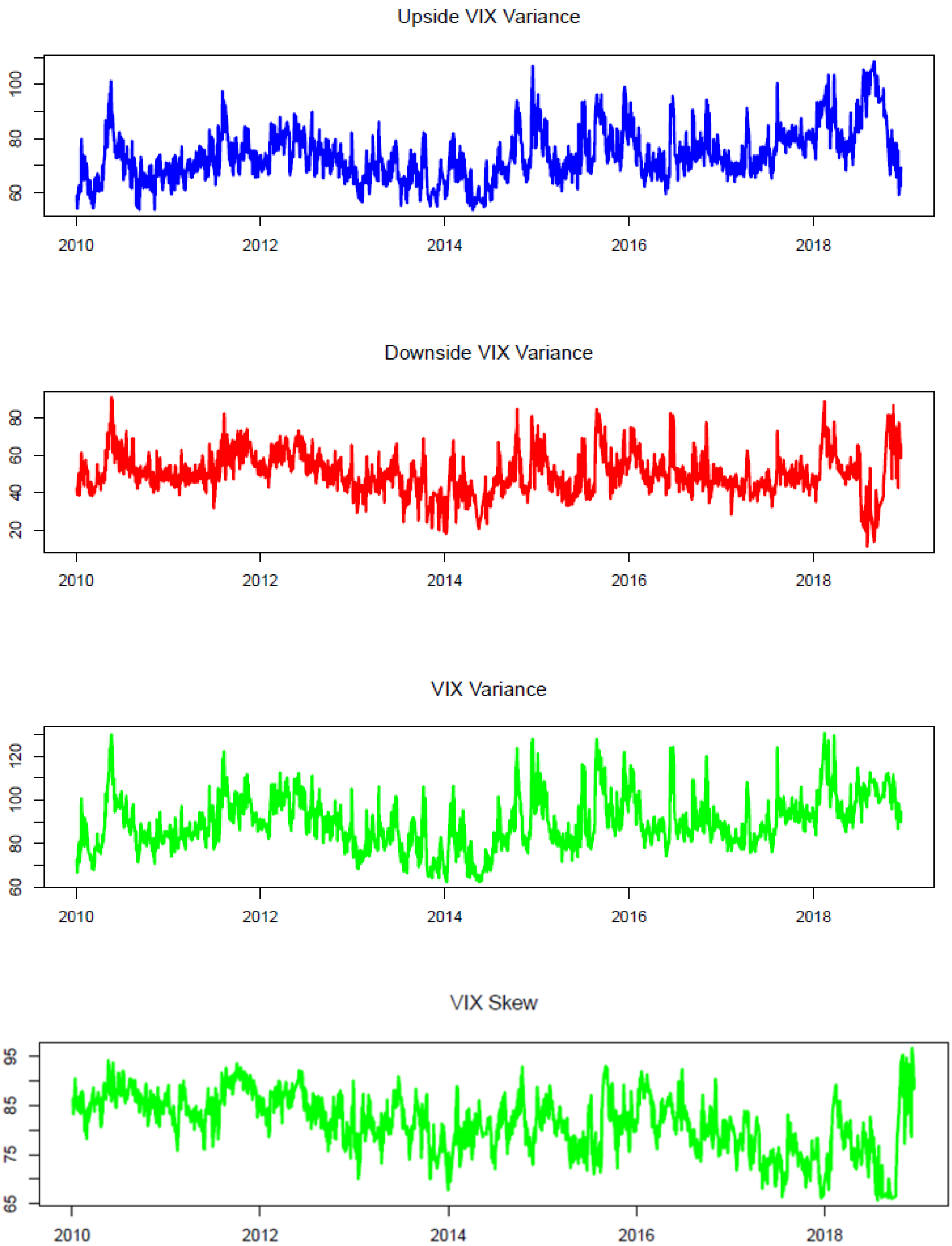
***Note**:* The table shows one-month ahead predictive regressions on the scaled payoffs of delta-hedged *VIX call* option portfolios. M^{VIX} denotes the risk-neutral moments of VIX options. *VIX-* denotes the implied downside risk-neutral market variance and *SKEW-* is the implied downside risk-neutral market skewness. Both *VIX-* and *SKEW-* are extracted from SPX puts. The data sample ranges from January 2010 to December 2020. The numbers in parentheses are Newey and West (1987) robust *t*-statistics, significant at the 1%, 5%, and 10% levels, denoted respectively by ***, **, and *.

Table 8. Prediction on Delta-Hedged Payoffs of SPX Put Options Portfolios

	VVIX		*VVIX+*		*VVIX-*		*VSKEW*	
	OTM	DOTM	OTM	DOTM	OTM	DOTM	OTM	DOTM
				Panel A: Baseline model				
Constant	-0.36***	0.05**	-0.28***	-0.03*	-0.25***	-0.02	-0.26*	-0.17***
(t-stat)	(-6.38)	(2.05)	(-3.41)	(-1.70)	(-5.33)	(-1.45)	(-1.68)	(-4.52)
M^{VIX}	2.04**	-1.52***	1.36	-0.58**	2.20**	-1.95***	0.02	0.06***
(t-stat)	(2.10)	(-4.12)	(0.90)	(-2.22)	(2.12)	(-6.41)	(0.38)	(3.08)
R^2	0.58	0.94	0.56	0.92	0.57	0.94	0.56	0.93
				Panel B: Model controlling for *VIX-*				
Constant	-0.33***	0.06***	-0.24**	0.04*	-0.04	0.06***	-0.16	0.02
(t-stat)	(-4.65)	(3.99)	(-2.48)	(1.74)	(-0.59)	(2.79)	(-0.75)	(0.65)
M^{VIX}	6.63***	0.04	1.90	0.52	6.40***	-0.47	0.00	0.02
(t-stat)	(4.15)	(0.10)	(1.28)	(1.34)	(3.59)	(-0.81)	(0.01)	(1.56)
VIX-	-0.03***	-0.01***	-0.01	-0.01***	-0.02***	-0.01***	-0.00	-0.01***
(t-stat)	(-4.48)	(-5.12)	(-0.92)	(-9.09)	(-3.36)	(-3.19)	(-0.75)	(-5.62)
R^2	0.63	0.96	0.56	0.96	0.61	0.96	0.56	0.96
				Panel C: Model controlling for *SKEW-*				
Constant	-0.02	0.12***	0.05	0.06*	0.11	0.04*	0.28	-0.13**
(t-stat)	(-0.21)	(3.91)	(0.39)	(1.78)	(1.02)	(1.69)	(1.17)	(-2.22)
M^{VIX}	2.32***	-1.46***	1.02	-0.77**	2.81***	-1.86***	-0.05	0.05**
(t-stat)	(2.69)	(-4.08)	(0.77)	(-2.22)	(2.83)	(-5.82)	(-0.85)	(2.53)
SKEW-	-0.01***	-0.00***	-0.01***	-0.00***	-0.01***	-0.00**	-0.01***	-0.00
(t-stat)	(-3.04)	(-3.27)	(-2.86)	(-3.10)	(-3.32)	(-2.40)	(-2.98)	(-0.97)
R^2	0.61	0.94	0.59	0.92	0.61	0.95	0.59	0.93

***Note**:* The table shows one-month ahead predictive regressions on the scaled payoffs of delta-hedged *SPX put* option portfolios. M^{VIX} denotes the risk-neutral moments of VIX options. *VIX-* denotes the implied downside risk-neutral market variance and *SKEW-* is the implied downside risk-neutral market skewness. Both *VIX-* and *SKEW-* are extracted from SP500 puts. The data sample ranges from January 2010 to December 2020. The numbers in parentheses are Newey and West (1987) robust t-statistics, significant at the 1%, 5%, and 10% levels, denoted respectively by ***, **, and *.

Figure 1. Time series of *VVIX*, $VVIX^{+}$, $VVIX^{-}$ and *VSKEW*



Note: We plot the time-series curves of $VVIX^{+}$, $VIXVIX^{-}$, *VVIX* and *VSKEW*, computed using all OTM VIX calls, OTM VIX puts and all OTM VIX options, presented in Panels A, B, C and D, respectively, at daily frequency. The sample period is from January 1, 2010, to December 31, 2020.