What Makes the VIX Tick?

Warren Bailey, Lin Zheng, and Yinggang Zhou *

Cornell University, City College of New York, and Chinese University of Hong Kong

31st May 2012

Preliminary: please do not quote or distribute

Abstract

We study one-minute changes in VIX, an index of ex ante S&P 500 volatility, using measures of public information, trading conditions, and investor sentiment. Autocorrelation and leverage or volatility feedback have the most explanatory power. Some evidence on short term interest rates and liquidity suggests expected ineffective Fed monetary easing. Two surprises are, first, reversals in VIX reactions to macroeconomic news, short term interest rates, and credit default spreads, and, second, VIX and gold do not reflect hedging demand or fear similarly. Investor sentiment seems of secondary importance to VIX.

Keywords: VIX, implied volatility, volatility risk premium, investor sentiment

JEL classifications: G11, G12, G13

* Cornell University, Johnson Graduate School of Management, 387 Sage Hall, Ithaca NY 14850 U.S.A., (607) 2554627, wbb1@cornell.edu; NAC 7/113A, Department of Economics. City College of New York. New York, NY 10031 U.S.A., (212) 650-6142, lzheng@ccny.cuny.edu.; and Chinese University of Hong Kong, Faculty of Business Administration, Room 718, 7/F, No.12, Chak Cheung Street, Shatin, N.T., Hong Kong, P.R.C., (852) 2609 8780, ygzhou@baf.cuhk.edu.hk. We thank Murillo Campello, Mancang Dong, George Gao, Andrew Karolyi, Alok Kumar, Edith Liu, Pamela Moulton, David Ng, Gideon Saar, Andrei Ukhov, Fan Yu, Xiaoyan Zhang, and seminar participants at Cheung Kong Graduate School of Business, City College of New York, Peking University HSBC business school, Shanghai Advanced Institute of Finance, Shanghai University of Finance and Economics, and Sun Yat-Sen University for helpful discussions, comments on earlier drafts, and other assistance. We are particularly grateful to Peter Carr and Eric Jacquier for many detailed suggestions.

1. Introduction

Why does stock volatility change over time? Schwert (1989) examines this question but reports little evidence of causality from the volatility of macroeconomic fundamentals to stock market volatility. The only robust finding seems to be that the stage of the business cycle affects stock market volatility. A radically different stream of thought ascribes excess stock market volatility to popular opinion and psychology.[1] A potential constraint on any study that seeks to explain stock volatility with fundamentals is the low frequency of realized volatility dictated by the use of daily stock returns.

Our study takes a fresh look at the underlying causes of volatility using high frequency data from markets for index option derivatives, other equities, futures contracts, and credit default spreads. We identify three potential sources of volatility as a starting point for our empirical specifications: public information, private information, and investor sentiment.

Ross (1989) argues that stock return volatility is directly related to the flow of information. Ederington and Lee (1993) attribute intraday and day-of-the-week volatility patterns in interest rate and exchange rate futures to macroeconomic announcements. Andersen and Bollerslev (1998) and Anderson, Bollerslev, Diebold, and Vega (2006) examine the effect of public news shocks on high frequency return volatility. Other studies based on intraday data (Andersen et al, 2003, 2006) document the real-time impact of public information shocks on returns themselves, rather than on return volatility. Therefore, our first set of explanatory variables reflects the notion that public information, in the form of news arrival and changes in securities prices, is related to stock index volatility.

Second, not all information relevant for securities pricing is public. Private information features in much of the finance literature, ranging from early formulations of market efficiency (Fama, 1965) to models of informed and liquidity-motivated traders (Kyle, 1985; Glosten and

[1] See, for example, Shiller (2000) for an overview, Shiller (1981) for classic evidence, and Kleidon (1986) for a critique of the early "excess volatility" literature.

Milgrom, 1985; Admati and Pfleiderer, 1988). Empirical work demonstrates how the order flow imbalance reveals private information flow in markets for stocks (Hasbrouck, 1991; Berry and Howe, 1994), foreign exchange (Evans and Lyons, 2008), and Treasury bonds (Brandt and Kavajecz, 2004; Green, 2004; Pasquariello and Vega, 2007; Jiang and Lo, 2011). Other authors use microstructure models to measure explicitly the extent of informed trading in the record of orders and trades (for example, Easley, Kiefer, O'Hara, and Paperman, 1996). The potential for informed trading can also be reflected in the bid-ask spread, which can be a priced factor in stock returns (Amihud and Mendelson, 1986; Easley, Hvidkjaer, and O'Hara, 2002). Bid-ask spreads have also been used as control variables in studying associations between PIN measures and stock returns (Easley, Hvidkjaer, and O'Hara, 2002, page 2215). Thus, trading volume, order flow imbalances, liquidity, and other measures that can reflect trading on private information or differences of opinion serve as our second set of explanatory variables.

Third, beyond public and private information, another potential source of stock price volatility is investor sentiment.[2] The noise trader model of De Long et al (1990) motivates many papers that explore the effect of noise trader risks on returns (Lee, Shleifer and Thaler, 1991; Neal and Wheatley, 1998; Baker and Wurgler, 2006).[3] In particular, we exploit the idea of Lee, Shleifer, and Thaler (1991) that small investor sentiment is reflected in trading of

[2] John Maynard Keynes noted the significance of "animal spirits" for economic decision-makers. See Akerlof and Schiller (2009) for a comprehensive treatment.

[3] A few papers investigate the relationship between sentiment and volatility. Brown (1999) and Lee, Jiang, and Indro (2002) document weekly associations between sentiment proxies and equity price volatility. Han (2008) relates daily pricing of S&P 500 index options to daily and weekly measures of institutional investor sentiment. In his keynote address to the European Financial Management Association, Schwert (2011) suggests that perceptions of the link between readily-observed measures of stock market volatility and broader economic indicators can be biased.

closed end funds, though this interpretation is not without controversy.[4] Therefore, our third set of explanatory variables measures several dimensions of investor sentiment.

We apply these three sets of explanatory variables to stock index implied volatility, an increasingly popular indicator for both academic researchers and sophisticated practitioners. Implied volatility can be computed using either parametric or nonparametric methods. Parametric implied volatilities are inferred from market prices of options or other derivatives with a pricing model such as the Black and Scholes (1973) model. For example, the Chicago Board Option Exchange's first implied volatility index, VXO, was computed from S&P100 index option prices. The evidence on the information content of VXO is mixed (Harvey and Whaley, 1992; Canina and Figlewski, 1993; Blair, Poon, and Taylor, 2001), perhaps because VXO concentrates on near-the-money options. Nonparametric implied variances are equivalent to prices of variance swaps (derived by Carr and Madan, 1998; Demeterfi, Derman, Kamal, and Zou, 1999; Britten-Jones and Neuberger, 2000; Jiang and Tian, 2005; Carr and Wu, 2006, 2009; and others) and, therefore, rely on no-arbitrage conditions and all option strike prices traded at a particular time. The information content of nonparametric implied volatility is superior to that of its parametric counterparts (Jiang and Tian, 2005).

The Chicago Board Option Exchange replaced VXO with an S&P500 volatility index, VIX, which is the square root of a weighted average of mid-point prices of a wide range of options across different strikes, which equals the price of a portfolio of options that replicates the payoff on a variance swap. It parallels the square root of the model-free implied variance of Britten-Jones and Neuberger (2000) and the risk-neutral expected value of return variance of

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[4] Klibanoff, Lamont, and Wizman (1998) confirm the interpretation of the closed end fund discount as a sentiment indicator with their study of the reaction to news arrival. However, this interpretation remains controversial (Chen, Kan, and Miller, 1993). Other studies ascribe closed end fund discounts to market segmentation (Swaminathan, 1996), arbitrage costs (Gemmill and Thomas, 2002), and illiquidity of underlying assets (Cherkes, Sagi, and Stanton, 2009), rather than an irrational sentiment factor. See Baker and Wurgler (2006) for a detailed discussion.

Carr and Wu (2009) over a 30-day horizon (Chicago Board Options Exchange, 2009). VIX is widely reported by the financial press and financial web sites, and even appears on the ticker of the CNBC financial news cable television network during trading hours. It is also well-accepted in the academic literature as a measure of the market's price of future stock index volatility. VIX is particularly suitable for a high frequency study of equity volatility because the underlying stock index options are heavily traded and, as a consequence, VIX changes very frequently during trading hours.

The VIX index also allows us to study an interesting component, the volatility risk premium (VRP), defined as the difference between an implied volatility measure from option prices and the expected quadratic variation of the underlying return series. Carr and Wu (2009) shows that VRP for major U.S. stock indexes is consistent with a significant premium for exposure to stochastic variance risk. Bollerslev, Tauchen, and Zhou (2010) find that VRP explains a large fraction of the variation in quarterly stock returns from 1990 to 2005. The model of Drechsler and Yaron (2011) shows how aversion to long-run risks generates a VRP that can predict stock returns. Bollerslev and Todorov (2011) show that, on average, "disaster risk" drives most of the variation in VRP. Bali and Zhou (2011) shows that equity portfolios that mimic the variance risk premium earn a substantial monthly risk premium. For example, suppose institutional investors buy S&P500 options to hedge the risk of their positions. If risk averse, they offer a premium and, as a consequence, the spot VIX computed from those option prices exceeds expected realized volatility.[5] Put another way, the risk neutral probability puts more weight on the bad state and that induces additional risk neutral variance, that is, a positive variance risk premium. The higher is risk aversion, the higher is the variance premium.

We use data sampled at 1-minute intervals from January 2005 to June 2010 to assess associations among public news, proxies for private information, proxies for investor

[5] Carr and Wu (2009) study realized volatility minus risk neutral volatility, so their risk premiums are opposite in sign from ours. They find negative risk premiums for all stock indexes and for most stocks.

sentiment, and implied volatility measured with the VIX index. We also estimate the volatility risk premiums implicit in VIX. Our findings serve several purposes. First, we document the high frequency univariate behavior of VIX. Second, we measure in great detail the high-frequency linkages between volatility, economic and financial fundamentals, and investor sentiment that academics and practitioners have studied since the dawn of financial markets centuries ago. Our use of 1-minute intervals allows us to measure precisely associations between VIX and other variables. Given the rapid trading in financial markets that is enhanced by modern trading technologies, associations are likely to evolve very rapidly and can be obscured in less frequently observed data.[6] Third, our decomposition of VIX allows us to compute the variance risk premium, VRP, and increase our understanding by contrasting its behavior with that of the raw VIX. Fourth, we present evidence to explain serial correlation of changes in VIX. Our findings offer insights about this key market indicator that is followed by market participating ranging from ordinary investors to professional portfolio managers.

The balance of this paper is organized as follows. Section 2 describes our testable hypotheses, data, and empirical methodology. Section 3 discusses empirical results. Section 4 summarizes, concludes, and sketches additional work that is underway.

2. Empirical design

2.1 Testable hypotheses

To organize our exploration of the minute-by-minute evolution of the VIX index and the volatility risk premium, VRP, we present a few testable propositions. They are not mutually

[6] Pagan and Schwert (1990) discuss how non-stationarity can blur studies of volatility sampled at low frequency over very long time periods. Jacquier and Okou (2012) show how the effect of jumps on excess returns weakens at longer horizons.

exclusive, but serve to formalize predictions about the correlation of VIX with other variables rather than validating a particular complete theory of VIX fluctuations.

First, much previous work has documented associations between stock index volatility and the direction of the stock market. Although we are working with much higher frequency data than previous authors, we expect to find similar effects and therefore designate our null hypothesis as:

> H0: Leverage or volatility feedback explains associations between VIX and measures of equity market direction and corporate leverage.

By the leverage argument (Merton, 1974; Black, 1976; Christie, 1982), a decrease in stock index value increases corporate leverage and the expected volatility of the index. Risk premium (French, Schwert, and Stambaugh, 1987) or volatility feedback arguments (Bekaert and Wu, 2000) are slightly more complex.[7] If the expected stock market risk premium is positively correlated with expected stock index volatility, then realized market risk premiums are negatively correlated with index volatility surprises. Changes in VIX are negatively correlated with stock index returns and stock index buy-sell imbalances.[8] If corporate debt is not riskless, changes in VIX are positively correlated with changes in credit default swap spreads because they reflect both the probability of corporate default and a risk premium.

Second, the stock index is the present value of aggregate corporate cash flows which, in turn, depend on macroeconomic conditions. Thus, information about ex ante volatility embedded in index option prices reflects the expected volatility of macroeconomic conditions:

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[7] While our purpose is not to distinguish leverage and volatility feedback effects, French, Schwert, and Stambaugh (1987) reason that elasticity of volatility with respect to stock return less than minus one suggests volatility feedback rather than leverage.

[8] See Beber, Brandt, and Kavajecz (2011) on the predictive power of price-setting buy sell imbalances for broad market returns.

H1: Changes in VIX are positively correlated with changes in macroeconomic uncertainty.

Bekaert, Hoerova, and Lo Duca (2011) document significant monthly associations between VIX and measures of monetary policy and macroeconomic conditions. We specify several dimensions of H1 with macroeconomic announcements and associations between short term interest rates and monetary policy. News surprises of any sign can either increase or resolve uncertainty (Patell and Wolfson, 1979; Bailey, 1988):

H1a: Changes in VIX are positively correlated with surprises in macroeconomic announcements because such surprises increase uncertainty.

H1b: Changes in VIX are negatively correlated with surprises in macroeconomic announcements because such surprises resolve uncertainty.

Short-term interest rates reflect expectations of monetary policy actions and their consequences:

H1c: Changes in VIX are negatively correlated with short term interest rates if central bank stimulus using lower interest rates is expected to be ineffective.

H1d: Changes in VIX are positively correlated with short term interest rates if central bank stimulus using lower interest rates is expected to be effective.

Third, VIX is perceived by practitioners as both a price for portfolio insurance and a measure of fear (Whaley, 2000; 2008):

> H2: Risk aversion or fear governs associations between VIX and the prices and trading of assets that hedge risks or reflect small investor sentiment.

Several of our variables can reveal effects consistent with H2. If gold hedges turmoil in the stock market and economy generally,[9] its price increases with both the expected volatility and risk premium components of VIX.[10] Thus, changes in VIX are positively correlated with changes in the price of gold and buy-sell imbalances for gold.[11] H2 also implies a flight-to-quality effect: changes in VIX are negatively correlated with changes in short term interest rates.[12] Furthermore, credit default swap spreads are the price of protection against corporate distress and are positively correlated with changes in VIX. If small investors willingly trade closed end funds even when perfect substitutes are available, their markets reflect irrational sentiment or fear about the future course of asset prices (Lee, Shleifer, and Thaler; 1991). Thus, changes in VIX are negatively correlated with closed end equity fund price premiums and buy-sell imbalances and positively correlated with gold-related closed end fund price premiums and buy-sell imbalances.

There are overlaps and ambiguities among our predictions but our data can help resolve some of them. Securities market liquidity as measured with the SPY and CDX bid-ask

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[9] For a good summary of fundamental and sentiment influences on the gold market, see "Gilt-edged argument: The battle to explain the remorseless rise of the bullion price" from *The Economist* print edition 28th April 2011.

[10] See, for example, Bessembinder (1992), Bailey and Chan (1993), and Pukthuanthong and Roll (2011).

[11] This holds regardless of whether gold trading is driven by hedging or noise trading.

[12] In a simple general equilibrium model with a representative investor and a stochastic variance production technology, Bailey and Stulz (1989) demonstrate a negative association between stock index volatility and the interest rate. Stulz (1986) demonstrates a negative association between the nominal interest rate and another volatility-related state variable, monetary uncertainty.

spreads relates to some of our predictions about VIX. For example, if uncertainty affects bid-ask spreads, our bid-ask spread variables relate to H1a and H1b. Spreads can also help distinguish two of our other predictions. Expected ineffective monetary policy, H1c, appears identical to the flight-to-quality dimension of H2. However, changes in bid-ask spreads for the index basket and the credit default spread allow us to distinguish them. In the model of Brunnermeier and Pedersen (2009), the funding of traders affects securities market liquidity. They explicitly define flight-to-quality as risky securities becoming less liquid. Monetary easing, whether effective or ineffective in achieving its broader goals, increases potential funding for traders and, thus, tends to increase securities market liquidity. Therefore, under expected ineffective monetary policy, H1c, changes in VIX are negatively correlated with changes in the short term interest rate and changes in bid-ask spreads.[13] In contrast, under the flight-to-quality dimension of H2, changes in VIX are negatively correlated with changes in the short term interest rate but positively correlated with changes in bid-ask spreads.[14]

The estimated risk premium component, VRP, of VIX allows us to distinguish our testable hypotheses on another dimension. Under habit-based preferences, Bekaert, Engstrom, and Xing (2009) find that risk aversion plays a relatively larger role in equity-related risk premiums while fundamental uncertainty is more important for asset price volatility. Giesecke, Longstaff, Schaefer, and Strebulaev (2011) find that credit spreads primarily reflect risk premiums, rather than the probability of default, which suggests that variation in risk aversion will be particularly prominent in our measure of credit default swap spreads.[15] H0 and H1 are

[13] Under expected effective monetary policy, H1d, changes in VIX are positively correlated with changes in the short term interest rate and changes in bid-ask spreads

[14] Theory suggests many channels for positive correlation between volatility and securities liquidity such as market maker’s cost of holding inventory (Copeland and Galai, 1983) to the solvency of large traders (Brunnermeier and Pedersen, 2005; Carlin, Lobo, and Viswanathan, 2007).

[15] See Stanton and Wallace (2011) for broadly similar evidence on the relationship between mortgage-related credit spreads and the fundamentals of the underlying mortgages.

uncertainty stories, while H2 can be thought of as a risk aversion story. Thus, the relationships predicted by H2 for VIX should be even stronger for VRP, particularly with respect to a risk premium variable like the credit default swap spread.[16]

2.2 Data

The time period we study is January 2005 to the end of June 2010. Fifteen-second ticks of the VIX spot index are purchased from the Chicago Board Options Exchange's Market Data Express service.[17] They represent the spot value of the VIX, that is, the implied volatility average itself, rather than the VIX futures contracts traded on it. Note that the spot VIX measures the market's current risk-neutral expectation of future stock index volatility over the next 30 days. In contrast, VIX futures measure the expectation of 30-day volatility starting at the point in the future when the contract matures.

The first group of explanatory variables measure public information, and they include both continuous measures of market prices and macroeconomic news releases. We begin with four series constructed from financial market prices. They can be thought of as continuously-observed public information. As we discuss later, at least one of them can also reflect investor sentiment.

To measure the evolution of the price series underlying VIX, we use intraday trade returns on the SPDR S&P 500 exchange traded fund (SPY) from TAQ.[18] SPY returns represent broad movement in stock prices and, more broadly, the market's estimate of changes in future

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[16] Other overlaps and complexities across our predictions remain. An increase in the interest rate can reduce the value of debt and, therefore, decreases leverage and equity volatility (Christie, 1982). Trading volume can recede due to concerns about adverse selection, reducing liquidity and increasing expected volatility, or trading volume can have different implications if it reflects differences of opinion.

[17] Every 15 seconds, CBOE samples S&P500 index option quotes, computes the spot VIX as described in Chicago Board Options Exchange (2009), and disseminates the spot VIX publicly.

[18] TAQ trade records are filtered for condition codes and a tiny number of large immediate reversals.

economic growth. Given the structure of the SPY ETF which allows arbitrage by certain traders, SPY tracks the S&P 500 index very closely (Ackert and Tian, 2000).[19]

To measure the intraday evolution of information about interest rates and monetary policy we use the rate of change of short maturity Eurodollar futures contract prices at the Chicago Mercantile Exchange. The rate of change of the Eurodollar futures contract price (which is essentially 100 minus the annualized yield) represents short term interest rates, the state of the business cycle, actual and expected monetary policy, and bank credit risk.

Another measure of macroeconomic conditions, risks, and uncertainty is the rate of change of short maturity gold futures contract prices at COMEX. The rate of change of the price of gold futures reflects changes in the demand for gold due to inflation expectations, consumption demand, and hedging against economic and political uncertainty around the world.[20] Both futures series are purchased through www.tickdata.com.

Finally, given the importance of ongoing global credit crises, our fourth series is intraday changes of the Markit 5 year CDX NAIG index of credit default swap spreads of investment grade North American firms purchased from Markit.[21] Longstaff, Mithal, and Neis (2005) describe how credit default swap spreads reflect both corporate default risk and bond market liquidity. VIX is derived from prices of stock index options, which can be thought of as the price of stock portfolio insurance (Whaley, 2009), so it is plausible that VIX is correlated with

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[19] Drechsler and Yaron (2011) suggest that the volatility of the spot S&P500 provides forecasts that are inferior to those based on S&P500 futures. SPY, however, is extremely heavily traded. Each share is worth ten cents per S&P500 index point, and volume averages about 200 million shares per day. Dollar turnover is larger in E-mini S&P500 futures, which are worth $50 per S&P 500 index point and trade about two million contracts per day (CME Group, 2011). However, SPY offers the advantage of full trade and quote data to measure several dimensions of market activity.

[20] There is evidence of similar time-series patterns in VIX and the number of weekly google searches for "gold price" in 2011. See "2011 Revisited: Charting the Year", The Economist, 31st December 2011, page 60.

[21] The 5 year CDS is the most liquid market and has the most dense intraday data. However, it only starts from 30th September 2008. We use the mid-quote, that is, the average of bid and ask spreads.

the price of corporate bond portfolio insurance. Indeed, Bali and Zhou (2011) report that monthly VRP is strongly correlated with credit default swap spreads. Furthermore, given that our sample includes the crisis period, this variable can reveal associations between VIX and the evolution of the broader crisis.

Our announcement measures of public information consist of the surprise component of principal US macroeconomic announcements. The standardized announcement surprise (actual minus forecast, all divided by standard deviation of surprise) follows Andersen et al (2003; 2006) and is applied to the ten macroeconomic announcements from 9:30 to 16:00 used by Pasquariello and Vega (2007). Source is Bloomberg. Many previous authors have shown that such announcements contribute significantly to explaining the evolution of stock returns, presumably because changes in economic conditions affect expected corporate cash flows, risk exposures, and risk premiums that underlie stock prices.

Our second group of explanatory variables is inspired by the work of previous authors on private information and stock trading. They include SPY trading volume, the price-setting or aggressive buy-sell imbalance of SPY, and the new VPIN measure (Easley, Lopez de Prado, and O'Hara, 2010) of the extent of informed trading of SPY. These three series are computed from the trade and quote information on the TAQ database.[22] They reflect trading interest, buying or selling pressure, and, thus, the extent to which differentially-informed traders are present in the market. If these measures reflect the trading of informed investors, they can contribute to the volatility of stock returns perceived by uninformed traders who fear trading at a disadvantage. Given that a gold ETF (symbol: GLD) is also publicly-traded and has data recorded on TAQ that spans the time period we study, we also compute trading volume, buy-sell imbalance, and VPIN for gold, thereby allowing us to observe trading interest and

[22] For tests based on fixed-length intervals, we compute VPIN using 50 "buckets" per 1 or 5 minute interval.

direction for this key indicator, in addition to SPY.[23] Additional measures of market conditions are changes in the bid-ask spreads for SPY and for the CDX NAIG index.[24]

Our third set of explanatory variables measures dimensions of investor sentiment. The construction of proxies for investor sentiment is severely constrained by our need for high-frequency variables to match our VIX series and other data. For example, the discount or premium on closed end equity funds is a classic measure of the optimism or pessimism of small investors (Lee, Shleifer, and Thaler, 1991). However, intraday net asset values of closed-end funds are not available so that intraday discounts or premiums relative to trading prices cannot be computed. Thus, the low frequency series proposed by Baker and Wurgler (2006, 2007) are not feasible for our purposes.

For our first sentiment indicator, we construct a high frequency proxy for closed end equity fund premiums because we cannot observe closed-end fund NAVs intraday. We identify closed end equity funds with daily NAV that closely tracks SPY by regressing the daily rate of change of individual fund NAVs on daily SPY returns. We form a capitalization-weighted portfolio, CEF, of such funds,[25] then construct a common stock portfolio, CEF_NAV, with daily returns that mimic the rate of change of the daily cap-weighted NAV of the CEF portfolio.

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[23] Although our gold futures data extend back to January 2005, we only have trades so we cannot compute quote based measures like the buy-sell imbalance and VPIN.

[24] We also considered using the difference between bid-ask spreads of on-the-run versus off-the-run 10-year U.S. Treasury bonds (Asness, Moskowitz, and Pedersen, 2009) but found the data on the GovPX database is not frequent enough for our one minute intervals.

[25] We begin with all closed end funds classified online as "general equity funds" and are listed on the NYSE. We then collect daily NAVs from Bloomberg for each remaining fund for the period 2005 to June 2010, and regress each fund's rate of change of NAV on the rate of change of the price of SPY. We retain only those funds which display a reasonably high r-squared and slope reasonably close to one from those regressions. They are (slope and r-squared in parentheses): Adams Express (0.918, 94.2%), Denali Fund (1.302, 46.4%), Gabelli Equity Trust (1.259, 88.0%), General American Investors (1.108, 83.9%), Royce Micro Cap Trust (1.076, 79.3%), Royce Value Trust (1.172, 86.3%), and Tri Continental (1.047, 95.8%).

Given the mimicking portfolio weights, we compute the intraday returns of the portfolio.[26] Thus, our proxy for the intraday change in closed end fund premium is ln{CEF(t)/CEF(t-1)} – ln{CEF_NAV(t)/CEF_NAV(t-1)}. Our second sentiment indicator is the price-setting buy-sell imbalance for the previously-identified portfolio, CEF. It indicates whether closed end fund investors are optimistic or pessimistic.[27]

In addition to these two equity market sentiment indicators, we are aware of a closed-end fund devoted to gold, ASA Gold and Precious Metals Ltd (formerly known as American South African Fund). The fund's assets currently consist of a mix of gold mining stocks and gold bullion, so its NAV may not track the price of gold perfectly.[28] Nonetheless, we use it to compute two sentiment indicators for gold, a proxy for the change in gold-oriented closed end fund premium and price-setting buying minus selling of the gold-oriented closed end fund.[29] Their construction parallels what has been described previously for common stock closed end funds sentiment measures.

2.3 Methodology

2.3.1 Measuring the variance risk premium

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[26] We identify the 100 most heavily-traded CRSP common stocks during our sample period. Daily returns of each are regressed on an intercept, daily CRSP index excess return, and daily change of the CEF portfolio's NAV. We then construct a set of portfolio weights with minimum variance, zero intercept, zero market beta, and unit CEF NAV beta. These weights are then applied to intraday returns to generate CEF_NAV, the intraday mimicking portfolio return series.

[27] Our original intention was to express the CEF buy-sell imbalance in excess of the SPY buy-sell imbalance, but the two are virtually uncorrelated.

[28] See "The wacky world of gold: Why gold bugs no longer love gold miners" from *The Economist* print edition 2nd June 2011. A regression of the daily rate of change of ASA's NAV on the daily rate of change of the spot price of gold yields a slope coefficient of 1.202 and an r-squared of 17.1%.

[29] The mimicking portfolio for gold sentiment measures is computed with all CRSP stocks from SIC codes 1041 (gold ores), 1044 (silver ores). The abnormal buy-sell imbalance for ASA is computed relative to the buy-sell imbalance for the GLD ETF.

Because the variance risk premium, VRP, is not directly observable, we must infer it using the VIX index and other information. *ΔVRP* is the change in variance risk premium, that is, the difference between the squared VIX index (expressed in annualized terms) and expected annualized realized return variance [30] over the same 30-day horizon as VIX:

$$VRP_t = VIX_t^2 - E_t(RV_{t,t+NT}) \tag{1a}$$

Note that VIX can be interpreted as the price of a volatility swap (that is, a swap that pays based on the realized standard deviation of the underlying) while VIX squared can be interpreted as the price of a variance swap. Thus, VRP can be thought of as the variance swap rate risk premium.[31]

We estimate the expected annualized realized volatility in (1a) with a linear forecast of realized volatility with one lag of squared VIX and the most recent value of monthly realized volatility as follows:[32]

$$E_t(RV_{t,t+NT}) = \hat{\alpha} + \hat{\beta} VIX_t^2 + \hat{\gamma} RV_{t-NT,t} \tag{1b}$$

where the annualized realized variance at t over the past 30 days (typically 22 trading days) horizon to t is measured by:

[30] Realized returns include ex post risk premiums from the stock market, which is distinct from VRP, the ex ante premium for exposure to stochastic volatility risk paid by the derivatives market.

[31] Carr and Wu (2009) study realized volatility minus risk neutral volatility, so their risk premiums are opposite in sign from ours. They find negative risk premiums for all stock indexes and for most stocks.

[32] Table 2 in Drechsler and Yaron (2011) suggests that this method has good forecast power. See also discussion and footnote 6 on page 5 of Bollerslev, Marrone, Xu, and Zhou (2011).

$$RV_{t-NT,t} = \{\sum_{n=1}^{NT} f^2_{t-NT+n}\} \times 12 \qquad (1c)$$

t represents a particular date and interval in the sample. N times T is the number of intraday returns used to estimate realized volatility from t to 30 days beyond. N-1 is the number of intraday intervals from 9:30am to 16:15pm (Eastern Standard Time) in a trading day, the Nth interval is overnight, and T is the number of trading days in a month, which is typically 22. f^2 is the square of the log rate of change of the forward price of the underlying stock basket expressed in percent to parallel the scale of squared VIX. We follow Carr and Wu (2009) and estimate the forward price using the cost-of-carry model.[33] The multiplier 12 annualizes monthly realized volatility. Note that VRP is in terms of basis points while VIX is in terms of percentage. Equation (1b) is estimated in-sample with all available data points and yields an r-squared of 52.2% and strongly significant positive slopes on both terms.

Carr and Wu (2006) note that the "…VIX index squared …can be regarded…as an approximation of the variance swap rate up to the discretization error and the error induced by jumps." The realized volatility observed at time t, (1c), reflects both diffusion and jump components of the actual path taken by the forward price from t-NT to t. Thus, VIX squared equals the risk neutral ex ante variance plus additional risk neutral ex ante higher order cumulants due to jump risk (Martin, 2011, equation 16).

Jump risks are particularly important for the period we study because it includes the recent global credit crisis. Carr and Lee (2009) note "The cataclysm that hit almost all financial markets in 2008 had particularly pronounced effects on volatility derivatives.…In particular,

[33] f is estimated as the spot price of the SPY S&P500 ETF times one plus the Eurodollar yield divided by 1200, minus the expected dividend from t to (t+22N). SPY pays dividends quarterly, so we set the expected dividend to the actual dividend, if any, paid between (t-66N) and (t-44N).

sharp moves in the underlying highlighted exposures to cubed and higher-order daily returns...[T]he market for single-name variance swap[s] has evaporated in 2009." Jumps pose a challenge to empiricists attempting to decompose the VIX index into expectations and risk premium terms. The decomposition, (1a), requires a forecast of realized variation in the underlying asset, but, as under a peso problem, jumps are not always observed and their contribution to realized variation can be large (Todorov and Tauchen, 2011) and difficult to forecast (Bollerslev and Todorov, 2011).

To address this issue, we adapt the method for incorporating both diffusion and jump elements into forecasts of realized variation in Andersen, Bollerslev, and Diebold (2007). Begin with their equation (5) for realized daily intraday bi-power variation:

$$BV_t = BV_{t-N,t} = \mu^{-2}\{\sum_{n=2}^{N}|f_{t-N+n}||f_{t-N+(n-1)}|\} \tag{2a}$$

where μ is defined as the square root of (2/π). The expression converges to the estimated diffusion component of total variation with intraday data for one day. Therefore, the realized intraday jump component over one day equals total realized variation minus BV, with a correction for estimation errors in BV that could yield a negative estimated jump component (Andersen, Bollerslev, and Diebold, 2007, equation 8):

$$J_t = \max\{(DRV_t - BV_t),0\} \tag{2b}$$

where:

$$DRV_t = DRV_{t-N,t} = \sum_{n=1}^{N} f_{t-N+n}^2 \tag{2c}$$

This computes total intraday variation for the day prior to day t as in equation 3 of Andersen, Bollerslev, and Diebold (2007). Next, define realized variation over arbitrary intervals:

$$ARV_{t,t+KN} = (1/K)\{\sum_{k=1}^{K} DRV_{t+(k-1)N,t+kN}\} \tag{2d}$$

This measure sums the daily realized intraday variation, (2c), over K, days following equation 9 in Andersen, Bollerslev, and Diebold (2007). To compute realized variation over a month, set K equal to T. While our goal is a variance forecast that extends out one month, the forecast procedure to be described presently also requires realized intraday variation over other numbers of days.

To implement the HAR-RV-J model (equation 11 of Andersen, Bollerslev, and Diebold, 2007), realized intraday variation over the month is regressed on lags of realized volatility and the estimated jump term:

$$ARV_{t,t+22N} = \beta_0 + \beta_D DRV_{t-N,t} + \beta_W ARV_{t-5N,t} + \beta_M ARV_{t-22N,t} + \beta_J J_t + \beta_o OJ_t + \varepsilon_{t,t+N} \tag{2e}$$

The average monthly intraday variation is regressed on the most recent lag of the daily intraday variation, the average weekly intraday variation over the previous week, the average monthly intraday variation over the previous month, the most recent lag of the daily intraday jump, and a term to pick up the overnight close-to-open jump:

$$OJ_t = \max\{f^2_{t1\_last,t2\_first}, 0\} \tag{2f}$$

where t1_last is the last interval of day t and t2_first is the first interval of the next trading day. Equation (2e) is estimated in-sample with all available data points and yields results that are broadly similar to those reported by Andersen, Bollerslev, and Diebold (2007) for lower frequency data: an r-squared of 60.8%, strongly significant positive slopes on RV terms, and significantly negative slope on contemporaneous jump term, plus an insignificant coefficient on the overnight jump term. The negative sign indicates that the forecast removes any very recent jump from realized quadratic variance since jumps are unusual.

Expected variation is the fitted value from the estimated regression coefficients from (2e), which is then annualized and adjusted from average volatility over the month to total volatility over the month:

$$E_t(RV_{t,t+22N}) = 22 * \hat{ARV}_{t,t+22N} * 12 \tag{2g}$$

This, in turn, is subtracted from VIX squared as in (2a) to produce a more sophisticated estimate of the variance risk premium, VRP_Jump.[34] We present two sets of results on the variance risk premium, one for VRP_Jump and one from the simple VRP defined by equations (2a), (2b), and (2c).

2.3.2 Explaining the high frequency evolution of VIX and VRP

Our basic empirical specification estimates associations between changes in the VIX index (or changes in VRP) and proxies for the three categories of factors previously described:

$$\begin{aligned} \Delta VIX_t = a + \sum_{i=1}^{I} b_i \Delta VIX_{t-i} + \sum_{j=0}^{J}\sum_{k=1}^{K} c_{kj} r_{k,t-j} + \sum_{p=1}^{P} d_p \sum_{l=1}^{L} NEWS_{l,t-p} + \sum_{m=1}^{M}\sum_{q=1}^{Q} e_{mq} TRADE_{m,t-q} + \\ \sum_{n=1}^{N}\sum_{s=1}^{S} f_{ns} SENTIMENT_{n,t-s} + \varepsilon_t \end{aligned} \tag{3}$$

[34] Bollerslev, Tauchen, and Zhou (2010) find (footnote 30) that a simpler HAR-RV forecast produces a monthly expected variance risk premium which has a correlation of 85% with the monthly realized variance risk premium (the swap rate minus the realized volatility).

ΔVIX_t is the change in the VIX implied volatility index from the close of intraday interval t-1 to t.[35] As we document later, the 1-minute VIX series is highly serially correlated and, therefore, we work with first-differences in VIX, VRP, and VRP_Jump rather than their levels. The b coefficients represent serial correlation in the dependent variable. The notation indicates the sources of volatility we use to explain ΔVIX. $r_{k,t}$ is the kth financial market return, price, or spread change including the S&P 500 index, the short maturity gold futures contract price, the short maturity Eurodollar deposit futures contract price, and a CDX spread index. $NEWS_{l,t}$ is the surprise of component of macroeconomic announcements at time t. $TRADE_{m,t}$ is the mth measure of trading activity at time t. $SENTIMENT_{n,t}$ is the nth measure of investor sentiment at time t. If the lags of independent variables are kept identical, then I, J, P, Q and S are equal. For the variance risk premium, we estimate a specification similar to (3) but with ΔVRP as the dependent variable and lags of ΔVRP, rather than lags of VIX, among the explanatory variables.

3. Preliminary empirical results and discussion

3.1 An overview of the data

Figure 1 shows 1-minute ticks of VIX, VRP, and VRP_Jump during our sample period 9:30 to 16:00 of each trading day from the beginning of 2005 to the end of June 2010. Note that VIX is expressed in standard deviation terms while VRP is in variance terms so that the levels of the two series cannot be directly compared. It is clear that the VIX peaked during the 2008 financial crisis. Also notably, the VIX typically remained below 20 before August 2007 near

[35] Interval length is set at 1 minute, though some results in this draft also use 5 minutes. While the high frequency of trades in these markets suggests working in transactions time, Engle and Lunde (2003) and others find that working with more than one series in transactions time is difficult or intractable.

the start of the crisis, and increased well above 20 afterward. Similarly, VRP has fluctuated a lot since the summer of 2007.

Table 1 reports the numbers of available and missing observations for principal intraday data series at 1-minute intervals. Statistics for 5-minute intervals are also included to suggest how dependent the extent of missing data is on interval length.[36] We exclude overnight intervals. There are 530,124 1-minute and 106,509 5-minute VIX observations respectively. Among the explanatory variables, the series of CEF and ASA return spreads and imbalances have many missing observations, due to the relatively thin trading of the closed end fund components of those two series, CEF and ASA. The CDX spread change (only available from September 30, 2008) has many missing observations. The Eurodollar and gold futures price rates of change also have substantial missing observations. To make best use of our intraday data, missing values of explanatory variables (that is, volumes, imbalances, VPINs, price changes of SPY, the Eurodollar futures price, gold, and the CDX index) are replaced with zero.[37]

Table 2 summarizes the macro news announcements. They are broadly consistent with Anderson et al (2007). Because news surprises have values only at announcement times and zeros at other times, , we reduce NEWS to a simple series that sums across all the different NEWS variables. This creates a simple indicator of whether any macro news arrives during that particular interval and how large a surprise that news is.

Table 3 reports summary statistics for dependent variables at 1-minute intervals. The

[36] An early draft of this paper (available on request) includes 5 minute results and finds they are very similar to, though somewhat weaker than, 1 minute results.

[37] See Hotchkiss and Ronen (2002) and Downing, Underwood, and Xing (2009). Other authors suggest interpolation schemes for filling in missing values. See, for example, the brief discussion (bottom of page 703) in Andersen, Bollerslev, and Diebold (2007). Filling missing trade indicator observations with zeros is not problematic because zero represents precisely the trading activity in an interval with no trades.

average VIX is 21.70, which means that the annualized standard deviation expected over the coming 30 calendar days is about 22%. To state this number in variance terms, square 0.2170 and multiply by 100 to yield 4.71%. The average VRP is 30.65 basis points, meaning that the expected annualized variance risk premium over the coming 30 calendar days is 0.3065%. The average VRP_Jump is larger, 38.03 basis points. On average, the risk premium is only a small component of the certainty equivalent ex ante volatility expressed in squared terms, 4.71%, regardless of whether or not jumps are considered. Also, levels of VIX, VRP, and VRP_Jump exhibit very large and significant serial correlation approaching one, strongly suggesting a unit root. While levels of these variables are quite persistent, their first-differences are not. Thus, we conduct subsequent analysis with first-differences, rather than levels, of VIX, VRP, and VRP_Jump as dependent variables.

Table 3 also presents statistics for three subsamples, "Pre Crisis" from January 2005 to January 2007, "Crisis" from February 2007 to March 2009, and "Post Crisis" from April 2009 to June 2010. VIX more than doubles and becomes many times more volatile after the Pre Crisis period. The average VRP and VRP_Jump switch from negative to positive after the Pre Crisis period, suggesting relatively greater demand to hedge long volatility and less speculative buying of volatility. VRP_Jump is, on average, larger in absolute value than VRP in all three sub periods, perhaps because it accounts for both diffusion and jump risks. High values of VIX and its risk premiums after the Crisis period suggests continuing high uncertainty in financial markets, perhaps due to the emerging crisis in the euro area.

Table 4 presents summary statistics on the VIX index broken down by day of the week and time of day. Day-of-the-week and time-of-day return seasonals can result from patterns in information flow during trading and non trading hours, inventory management by traders, and heightened uncertainty when trading commences. Panel A shows that VIX is typically slightly higher on Mondays, averaging 22.14% versus under 22% on other days of the week. A test of the hypothesis that the averages on each day are jointly equal is strongly rejected. Serial correlation of VIX is very high, approaching one. Panel B shows that, during the first half hour of the trading day, there is evidence of a very small "smirk", with average VIX of 21.77% versus less than 21.70% during other intervals. This parallels the finding in Panel A of heightened volatility on Mondays, perhaps due to information arrival and pent-up demand for immediacy after the weekend. However, the hypothesis that the averages in each period are equal cannot be rejected. Standard deviation is also higher during the opening half hour, while serial correlation of VIX is lower in the first and, particularly, last half hours of the day. During the 15 minute period after the NYSE has ceased trading, the standard deviation of VIX is only a third or quarter of its value when the NYSE is open. This suggests that much of the variability in VIX is supported by trading activity in the underlying S&P 500.

Panel B also summarizes close-to-open changes in VIX. The average close-to-open change is about five times higher over weekends than over weeknights. In contrast, the average overnight change in VIX spanning the "roll" period (third Friday of each month when the S&P500 options used to compute VIX change) is negative, and more than double the absolute size of the typical average weekday close-to-open change. This suggests a downward sloping implied volatility curve looking out 30 days.

Figure 2 plots the average value of VIX by 1 minute intervals averaged across all days in the sample. The plot suggests a smirk, that is, VIX is typically highest at the start of the trading day. However, the range of average values across the day is small, less than 21.9% at its peak in the morning and above 21.6% later in the day. This is consistent with the summary statistics on mean VIX presented in Table 4. The smirk at open is echoed in other measures of the intraday behavior of the S&P 500 such as the bid-ask spread for the SPY ETF (plot is available on request).

Prior to running regressions, it is important to understand the degree of correlation among the explanatory variables. Table 5 presents the Pearson correlation matrix at the one-minute interval among regression variables, with zeros inserted for missing observations.

Some highlights of the cross correlations of changes in VIX and VRP with other variables are as follows. The substantial negative correlation of SPY return (and buy-sell imbalance) with VIX, VRP, and VRP_Jump is consistent with the leverage or volatility feedback story (H0). VIX and its risk premium measures rise with Eurodollar futures returns, that is, as Eurodollar yields decline (H1c, H2). VIX and its risk premium decline as the gold price (and gold ETF buy-sell imbalance) increases, rejecting H2. The positive correlations of changes in VIX and VRP (but not VRP_Jump, which displays a negative correlaation) with changes in the CDX credit spread suggests a common risk premium, while negative correlations with the NEWS measures suggest that macro announcements resolve uncertainty (H1b). Associations with the sentiment measures are sometimes significant. VIX, VRP, and VRP_Jump are positively contemporaneously correlated with increases in premiums above net asset value and buying pressure for common stock closed end funds, rejecting H2 and instead suggesting contrarian trading by small investors at times of high volatility.. However, the positive coefficients for the gold-related closed end fund premium and buying pressure suggest that interest in gold increases at times of high uncertainty in the stock market, which is consistent with H2.

Table 5 also presents interesting correlations among the explanatory variables. SPY and gold futures returns are positively correlated, which is not consistent with gold as a safe haven from declining equity markets. SPY returns decline when Eurodollar futures prices rise (that is, when Eurodollar yields decline), suggesting flight-to-quality or expectations of monetary easing when stock performance is poor. The SPY return goes up with SPY buying pressure and the gold return goes up with GLD buying pressure, which makes sense. The SPY return and buying pressure decline as the equity closed end fund premium rises, suggesting that small investors are contrarians (Grinblatt and Keloharju, 2000). For both SPY and GLD, trading volume and VPIN are negatively correlated, perhaps because VPIN is derived from trading volume.

Table 6 presents results of varimax factor analysis applied to the independent variables. This serves both to identify common forces among the variables and to mute potential multi-colinearity with alternative more parsimonious set of explanatory variables to explain first-differences of VIX, VRP, and VRP_Jump.

Panel A of Table 6 presents factor analysis for the full 2005 to June 2010 sample. Given eigenvalues of principal components of one or greater, we present results for 7 factors. The first factor explains almost 12% of total variance and has large negative weight on SPY and GLD volumes and large positive weight on SPY and GLD VPINs. We refer to it as the "trading" factor. We label the second factor "equity direction" given its large positive weight on SPY return and buy-sell imbalance. It explains almost 10% of total variance. Similarly, the third factor is "gold direction" given strong positive loadings on GLD return and buy-sell imbalance. The fourth factor is "macro conditions" given large negative weight on Eurodollar futures return and large positive weight on macro surprises. Recall that Eurodollar futures rise when the Eurodollar yield drops. Thus, low interest rates and relatively small macro surprises coincide in this factor. We refer to the fifth factor as "gold sentiment" since it has large positive weight on both the price premium and buy-sell imbalance of the ASA gold-related closed end fund. Similarly, the sixth factor is "equity sentiment" given large positive weight on both the price premium and buy-sell imbalance measures of the CEF portfolio of closed end equity funds. The seventh factor is dominated by the SPY bid-ask spread change and we refer to it as "equity liquidity". The last three rows of Panel A indicate correlations between each factor and VIX and its risk premiums. Most prominent is a substantial negative correlation between the volatility measures and the second factor, "equity direction", followed by negative correlations with "macro conditions" and "gold direction".

Panel B presents factor analysis for the sub-sample which includes the CDX NAIG credit swap spread series and bid-ask spread change series. Given the eigenvalues, we also compute seven factors for the sub period. The first, third, fourth, fifth, sixth, and seventh factors parallel the “trading”, “equity direction”, “gold direction”, “gold sentiment”, “equity sentiment”, and “equity liquidity” factors identified for the full sample. The second factor has large weight on the CDX-related measures so we refer to it as “credit risk”. As was the case for the full sample reported in the previous panel, there is a particularly substantial negative correlation between the volatility measures and “equity direction”.

3.2 Single-equation regression estimates

We report results first for VIX and VRP for 1 minute intervals for the entire January 2005 to June 2010 sample, which means we must exclude the CDX credit spread variable. We then report sub-period results to make use of the CDX spread variable and to isolate relationships during the height of the financial crisis.

3.2.1 Full sample results

Table 7 shows regression results for 1-minute changes in VIX for the entire time period. The regression has an adjusted r-squared of 18.33%. The change in VIX displays statistically significant, decaying negative autoregressive terms that range from -0.3086 at the first lag to -0.0400 at the fifth lag. Slopes on the SPY return are significantly negative and sum to -1.8673 from contemporaneous to fifth lag..Based on typical corporate leverage, French, Schwert, and Stambaugh (1987) informally argue that elasticity of volatility with respect to stock return less than minus one is not consistent with the leverage effect and, thus, suggests a risk premium related story like volatility feedback . . The contemporaneous slope on the Eurodollar futures price is strongly positive. An increase of one percent in the Eurodollar futures price is associated with a contemporaneous increase of 0.1395 percent in VIX, though negative slopes on lags indicate that this more than fully reverses within several minutes.[38] The Eurodollar

[38] Since Eurodollar futures prices roughly equal 100 minus the annualized Eurodollar yield, a one percent increase in the futures prices is associated with a substantial change (approximately 100 basis points) in yield.

futures price rises as the Eurodollar yield declines. Thus, VIX rises when the short term interest rate declines, then reverses quickly.[39] The reversal effect is not predicted by any of our hypotheses.

Table 7 also shows that the slope on the contemporaneous gold futures return is relatively small, -0.0197, but statistically significant. The negative sign is not consistent with the hypothesis, H2, that gold is a hedge or fear indicator that is positively correlated with VIX. Among the coefficients on the summed NEWS variable, the contemporaneous effect is negative (suggesting resolution of uncertainty, H1b) while the first lag is significantly positive (suggesting increased uncertainty, H1a). This reversal parallels what was found for the Eurodollar yield.

The coefficients on TRADE indicators are not easy to interpret. Contemporaneous associations are sometimes statistically significant but reverse sign at lags. Among the SENTIMENT indicators, some small but significant negative coefficients on the CEF premium and buy-sell imbalance suggest weaker small investor sentiment when VIX is high, H2. Small significantly positive coefficients on the ASA premium suggest small investor sentiment towards gold increases with VIX, H2. However, this effect is tiny: a one percent increase in the ASA price-to-NAV premium is associated with a few hundredths of a basis point increase in VIX. Coefficients for the SPY bid-ask spread cannot help us distinguish H1c from H2 because they are insignificant.

Table 8 shows regression results for changes in the simple 1-minute volatility risk premium, VRP. On some dimensions, the results for VRP are qualitatively similar to those for VIX in Table 7. The adjusted r-squared is 18.24%, and we note strong but diminishing negative

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[39] Using monthly data from 1990 to 2007, Bekaert, Hoerova, and Lo Duca (2011) find substantially different patterns in lower frequency data. Monthly VIX and real interest rate show persistently positively correlation, becoming negative after 13 months.

autocorrelation, significant negative slopes for the SPY return and the gold futures price change, and a significant reversal pattern in the coefficients on NEWS. However, in contrast to what is found for VIX, there is a significant and persistently negative association between VRP and the Eurodollar futures price rate of change. That is, the risk premium consistently declines when the short term Eurodollar yield declines. If the Eurodollar yield includes a credit risk component (Knez, Litterman, and Scheinkman, 1994), its correlation with VRP is consistent with H2.

As was found for VIX, associations between TRADE variables and VRP can be insignificant or change sign across lags. The only consistent pattern is positive coefficients on SPY and GLD buy-sell imbalances that indicate increased buying when VRP increases. Changes in VRP around times of increased SPY buying seem economically significant: a one percent increase in the SPY buy-sell imbalance is associated with an immediate increase of 0.13 in VRP and subsequent increases of 0.86 at one minute and 0.35 at two minutes. Among SENTIMENT indicators, the clearest pattern is that VRP increases are associated with decreased premiums and buy-sell imbalances for the equity fund portfolio. While this is consistent with H2, the effects are economically small.

Table 9 presents similar regression results for the more complex VRP_Jump risk premium. In comparing the results of Tables 8 and 9, note that summary statistics (Table 3) show that VRP_Jump is typically larger than VRP. Relative to VRP in Table 8, changes in VRP_Jump exhibit much larger associations with Eurodollar futures returns. This suggests that hedging and fear effects, H2, relate to stock market jump risk. There are also much larger associations with gold futures returns and SPY volume for VRP_Jump relative to VRP, suggesting an association between gold and aversion to the jump component of stock market risk in particular.

To this point, Tables 7, 8, and 9 display the predicted leverage or volatility feedback effect, and responses to public macroeconomic news and short term interest rates that reverse. Some differences between the behavior of VIX and the behavior of its risk premium component emerge. We also see that the relationship between VIX and gold is not what we expected (H2): the gold return is negatively correlated with changes in VIX, although premiums on a gold-related closed-end fund are positively correlated with changes in VIX.

3.2.2 Sub period results including CDX corporate credit spread

This subsection summarizes regression results for 30th September 2008 to June 2010, the period for which we have data on the CDX NAIG credit spread and its bid-ask spread. As previously discussed, the CDX variable is a barometer of credit risk, particularly during a period of market turbulence, and it can contribute to our understanding of forces that move the VIX, and VRP, from minute to minute.

Tables 10, 11, and 12 report sub-period regressions for VIX, VRP, and VRP_Jump. First, compare sub period results for VIX in Table 10 to the full sample results in Table 7. The sub period coefficients for Eurodollar futures return and NEWS are larger, but the reversal pattern remains. The signs of coefficients on the CDX spread suggest that an increase in the cost of credit risk protection is associated with an immediate drop in VIX that is more than reversed within a few minutes. Negative signs on change in bid-ask spread of CDX indicate that VIX declines around times when CDX illiquidity widens, which can be consistent with expected ineffective monetary policy, H1c.

Second, compare sub period results for VRP in Table 11 to full sample results in Table 8. The sign reversal in coefficients on Eurodollar futures return vanishes, though remains for NEWS. Reversing signs of coefficients on change in CDX spread and change in CDX bid-ask spread are difficult to interpret. Finally, we note that the results for VRP_Jump in Table 12 include sign reversals for coefficients on Eurodollar futures and the two CDX measures that are difficult to interpret.

To check robustness, we re-estimated the specifications reported in Tables 7 through 12 with the residual modeled as an EGARCH. Specifically, the noise term (such as ε_t in Equation 1) is heteroskedastic, with its volatility depending exponentially on white noise and lagged volatility. The results (available upon request) are very similar to the single-equation results already presented. Slope coefficients on some of the sentiment variables become more statistically significant, although they remain economically small.

3.3 Multiple-equation regression estimates

Our previous simple regression specifications treat VIX and VRP as endogenous and all other explanatory variables as exogenous. Given, however, the likelihood that many conditions across markets are jointly determined, we next present estimates of systems of equations to accommodate the associations among the variables. Specifically, we estimate VAR models to measure associations among variables more exhaustively.

Table 13 summarizes results for VIX over 1-minute intervals over the full sample period. Echoing previous tables, we find diminishing negative autoregressive effects for VIX, and significant, persistent negative association of VIX with lagged SPY price changes and Eurodollar futures price changes, and large positive lagged associations with NEWS.

The two columns on the right-hand side of the table summarize selected Cholesky decomposition coefficients and their standard errors. Given that the VAR does not produce coefficients for contemporary associations among the variables, Cholesky decomposition can reflect contemporaneous associations among the variables. Most of the Cholesky coefficients are many standard deviations away from zero. The signs and standard errors suggest particularly significant negative contemporaneous associations between changes in VIX and SPY returns (H0), gold futures returns (rejects H2), NEWS surprises (H1b), and buy-sell imbalances for SPY, GLD, the closed end equity fund portfolio CEF (rejects H2), and the gold fund ASA (H2). Other coefficients suggest particularly significantly positive contemporaneous associations for changes in VIX with Eurodollar futures prices and the CEF price premium.

Table 14 reports similar tests for the sub period starting 30th September 2011 for which the CDX variables are available. Results are qualitatively similar to what is reported for the full sample in Table 14 except for the following. There is a significantly positive effect of the CDX spread change that extends to several lags. That is, VIX increases occur when CDX spreads have been rising (H0, H2), though the Cholesky coefficient suggests the contemporaneous relationship is not significant. This is consistent with a common uncertainty or risk premium element in both VIX and CDX prices.

Table 15 reports results of VARs that relate VIX and its risk premium component to the factors derived from factor analysis, rather than the full set of explanatory variables. Highlights are as follows. For changes in VIX (Panel A), coefficients on “equity direction” make sense (H0) but, as before, negative coefficients on “gold direction” are not the sign we expected (reject H2). Lags of “macro conditions” are negative (H1b). Some significantly positive slopes for “gold sentiment” make sense, while positive signs on “equity sentiment” suggest contrarian trading. “Equity liquidity” (H2) is not significant. The results for changes in VRP (Panel B) parallel results for VIX except for negative coefficients on lags of “equity liquidity”. While greater liquidity at times of greater uncertainty is consistent with expected ineffective monetary policy (H1c), it can be due to the heightened trading activity in SPY during the height of the financial crisis when VIX was high. Finally, the results for changes in VRP_Jump (Panel C) are similar to the results for changes in VRP.

Table 15 also includes selected Cholesky decomposition coefficients. Negative coefficients for Factor 2 equity direction, which has positive weight on SPY return and SPY buy-sell imbalance (Table 6), is consistent with earlier findings of a leverage effect (H1). There are negative coefficients for Factor 4 macro conditions, which has negative weight on Eurodollar futures return. Therefore, VIX goes up if the eurodollar yield goes down. This is consistent with "expected ineffective monetary policy" (H1c) or flight-to-quality (H2). Combining this with the finding that equity liquidity (the SPY bid-ask spread) goes down when VIX goes up points to H1c rather than H2. Figure 3 presents impulse response functions related to the VARs of Table 15. The dominance of the autoregressive and equity direction factors is evident, paralleling the strength of the autoregressive and equity return effects in earlier single equation regressions.

3.4 Explaining the negative serial correlation of VIX

Previous results show that autocorrelation that rapidly decays is the most prominent feature of the high frequency behavior of changes in the VIX index. Persistence or clustering of volatility can be caused by gradual incorporation of information or dispersion in beliefs of traders. This idea has been used to explain clustering in longer-horizon return volatility, though its power weakens in intraday data (Andersen and Bollerslev, 1997). With this in mind, Table 16 presents several tests intended to characterize what drives this serial correlation and, in particular, what causes it to vary during the trading day. The first test is non-linear regression in which the slope on the first lag of the change in VIX depends on a constant and our public information, trade, and sentiment indicators, or the factors (Table 6) derived from them.

$$\Delta VIX_t = a + (\alpha + \sum_{j=1}^{J} \beta_j r_{j,t-1} + \sum_{p=1}^{P} \gamma_p \sum_{l=1}^{L} NEWS_{l,t-1} + \sum_{m=1}^{M} \delta_m TRADE_{m,t-1} + \sum_{n=1}^{N} \varphi_n SENTIMENT_{n,t-s}) \Delta VIX_{t-1} + \varepsilon_t \qquad (4)$$

Estimates of this specification reveal whether the sign and size of autocorrelation varies systematically with our explanatory variables. The second test consists of summary statistics on half-hour serial correlation sorted individually on our explanatory variables and factors constructed from them. If the average serial correlation of VIX changes for the high quintile portfolio minus that for the low quintile portfolio for a particular variable is significant, it suggests an association between that characteristic and the evolution of VIX autocorrelation. Both tests are exploratory in that we are not aware of any theory of serial correlation in index volatility with which to interpret our findings.

Panel A presents results based on our set of public information, private information and sentiment indicators. Highlights of the regression are as follows. The constant component of the slope on changes in VIX, -0.07128 (t=-6.70) indicates the baseline of significant negative serial correlation, which indicates a tendency of VIX changes of one sign to be followed by VIX changes of the other sign. The significantly positive slope on the term for first lag of SPY return times first lag of VIX change indicates that positive market returns can reduce or even reverse the negative serial correlation, as can positive return spreads and buy-sell imbalances for the closed-end equity fund portfolio. In contrast, macro news in the form of Eurodollar futures price increases (that is, declines in Eurodollar yields) or surprises in macroeconomic announcements tend to heighten negative serial correlation in VIX. The impact of gold-related variables on the serial correlation of VIX is less consistent: serial correlation declines with increases in gold futures prices or the gold closed-end fund premium but rises with gold ETF buy-sell imbalances. Also in Panel B, sorts of half-hour autocorrelation produce a few statistically significant differences between high-quintile versus low-quintile autocorrelation. For example, serial correlation is higher (that is, less negative) for higher values of SPY and GLD trading activity and SPY bid-ask spread. Previous tables, however, show that the serial correlation of changes in VIX decays after a few one-minute intervals.

Panel B presents results based on the seven factors derived from our variables as detailed in Table 6. Regression results suggest a much larger baseline level of serial correlation, -0.22628, than what is reported for the regression in Panel A. Other coefficients show that serial correlation is more negative with larger values of the trading and gold sentiment factors and is less negative with larger values of the equity direction, equity sentiment, and equity liquidity factors. Given the composition of the factors (Table 6), the regression findings of

Panel B for factors closely parallel the findings of Panel A for the variables. Sorts of half-hour autocorrelation on factors show that autocorrelation of VIX changes is related to the first factor, trading, but little else.

3.5 For the next revision

For the next draft, we will augment or change our experimental design in several dimensions. First, we believe that our efforts to include investor sentiment in the analysis of VIX are important, novel, and worthy of additional effort. Previous authors report evidence that retail stock traders contribute to stock return volatility (Brandt, Brav, Graham, and Kumar, 2010; Foucault, Sraer, and Thesmar, 2011). Therefore, we will look for additional effects of investor sentiment on the VIX index with the buy-sell imbalance for “lottery type” stocks known to attract behaviorally-biased individual investors (Kumar, 2009).

Second, we will consider methods for sorting macroeconomic news surprises as “good” or “bad”, perhaps with an event study of the SPY response to each type of macroeconomic announcement. Although the impact of positive and negative surprises can differ or can depend on the stage of the business cycle (Boyd, Hu, and Jagannathan, 2005), we may uncover further insights on the validity of our testable hypotheses and on the apparent overreaction of changes in VIX to macroeconomic news.

Third, we will estimate a few of our specifications using daily observations. This will highlight anything that is lost in using lower frequency data, thereby validating the importance of minute-by-minute data. Finally, we will consider a slight reduction in the number of explanatory variables we use in our tests. In particular, there is strong correlation between the trading volume and VPIN measures for SPY and GLD, which is unsurprising given how VPIN is constructed. Therefore, we may exclude the VPIN measures.

4. Summary and conclusions

This paper uses proxies for public information, private information, and investor sentiment to study the evolution of the widely followed VIX implied volatility index in light of several testable hypotheses. The negative association between VIX returns suggests leverage or volatility feedback. Associations between VIX, short term interest rates, and liquidity may reflect expectations of Fed monetary easing and its consequences. Several of our variables lead the autocorrelation of changes in VIX, thereby explaining an additional dimension of the tick-by-tick variation of VIX.

Our results contain several surprises. First, gold is not synonymous with VIX as a hedge or fear indicator: its price is not positively correlated with VIX,[40] although some other gold-related indicators suggest that some investors flee to gold when ex ante stock volatility is high. Second, reversals in associations between VIX and macroeconomic news, short term interest rates, and credit default spreads are unexpected. Third, some associations between VIX and pricing in the equity closed end fund market suggest that some investors use these investments for contrarian purposes, eagerly buying such funds when the market as a whole signals higher risk with heightened values for VIX. Finally, the contribution of the proxies for small investor sentiment to explanatory power seems small relative to the financial market factors. It is tempting to conclude that investor sentiment, psychology, or "animal spirits" are minor contributors to aggregate stock market volatility relative to rational explanations. We will explain more of the behavior of the VIX index in our next draft.

[40] For a discussion of the complexity of the price of gold, see "Mood swings", *The Economist* 1st October 2011.

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Table 1. Frequency of principal intraday data series

This table summarizes the numbers of available and missing observations for principal intraday data series at 1- minute and 5-minute frequencies. All series are 9:30am to 16:00 from January 2005 to June 2010, except for CDX spread, which is only available from September 30, 2008.

	One minute intervals		Five minute intervals	
Series	**Number of available observations**	**Number of missing observations**	**Number of available observations**	**Number of missing observations**
VIX index	530,124	13,317	106,509	2,479
SPY price rate of change	537,815	5,599	107,623	1,365
Eurodollar futures price rate of change	269,902	275,539	53,579	55,409
Gold futures price rate of change	425,275	118,116	89,071	19,917
CDX NAIG spread change	26,028	147,917	20,811	14,058
SPY trading volume	537,988	5,453	107,688	1,300
SPY price-setting buy-sell imbalance	537,985	5,456	107,688	1,300
SPY VPIN	537,988	5,453	107,688	1,300
GLD trading volume	518,621	24,820	107,513	1,475
GLD price-setting buy-sell imbalance	518,621	24,820	107,513	1,475
GLD VPIN	518,621	24,820	107,513	1,475
CEF – NAV return spread	445,774	98,351	107,326	1,662
ASA – NAV return spread	156,099	388,026	15,329	33,659
CEF price-setting buy-sell imbalance	446816	97113	107312	1676
ASA price-setting buy-sell imbalance	158553	385572	76625	32363

Table 2. Frequency, Source, Timing, and Volatility of Macroeconomic News Announcements

Abbreviations are: Bureau of the Census (BC), Federal Reserve Board (FRB), National Association of Purchasing Managers (NAPM), Conference Board (CB), Financial Management Office (FMO).In February 200, business inventory announcement was moved from 8:30 A.M. to 10:00 A.M. Consumer credit and trade balance are rescaled by dividing 10^9. New home sales are rescaled by dividing 10^3 and housing start is rescaled by dividing 10^6. All announcements are monthly unless noted.

Announcement	Observations	Source	Time	Standard deviation
Consumer Credit	66	FRB	3:00 PM	6.506
New Home Sales	66	BC	10:00 AM	67.964
Durable Goods Orders	66	BC	10:00 AM	0.025
Factory Orders	66	BC	10:00 AM	0.781
Construction Spending	66	BC	10:00 AM	0.778
Business Inventories	66	BC	8:30/10:00 AM	0.002
Government Budget deficit	66	FMS	2:00 PM	11.435
Consumer Confidence Index	66	CB	10:00 AM	5.157
NAPM Index	66	NAPM	10:00 AM	2.102
FOMC Target Federal Funds Rate (6 week)	46	FRB	2:15 PM	0.056

Table 3. Summary statistics for 1-minute intervals

VIX is intraday ticks of the Chicago Board Option Exchange (CBOE) S&P500 volatility spot index from the CBOE's Market Data Express service, which is annualized standard deviation in terms of percentage. VRP is intraday ticks of the variance risk premiums defined as the difference between the squared VIX and expected annualized realized variance, which is in terms of basis points. VRP_Jump is a variation of VRP that accounts more explicitly for the impact of jumps. "Δ" prefix indicates first differenced series "Lag x" denotes autocorrelation at x period lag. LB Q(60) is the Ljung-Box Q (60) statistic with *, **, and *** denoting significance at 10%, 5%, and 1%, respectively.

Variable	Mean	Std	Min	Max	Skew	Kurt	Lag1	Lag60	LB Q (60)
Whole sample									
VIX	21.70	12.11	9.39	96.40	1.87	3.89	0.999	0.998	32558528.784***
VRP	30.65	150.91	-1368.05	2542.95	1.58	19.23	0.999	0.974	31342339.723***
VRP_Jump	38.03	328.83	-6117.78	5335.79	-1.44	27.67	0.999	0.960	30930605.661***
ΔVIX	0.00	0.16	-28.19	27.99	19.34	13871.17	-0.175	0.003	20877.559***
ΔVRP	0.00	7.39	-2090.02	2102.95	34.63	37924.62	-0.202	0.004	28652.929***
ΔVRP_Jump	0.00	17.06	-4580.39	4605.58	25.68	30752.16	-0.193	0.003	25748.515***
Pre Crisis (1/2005 to 1/2007)									
VIX	12.74	1.84	9.39	41.60	1.51	3.94	0.997	0.975	11859272.795***
VRP	-33.05	17.62	-61.73	680.52	3.13	34.69	0.985	0.931	10903629.657***
VRP_Jump	-73.47	32.05	-164.67	1482.47	3.65	62.66	0.977	0.893	10284303.314***
ΔVIX	-0.00	0.14	-28.19	27.99	19.58	18345.52	-0.267	-0.0002	10284303.314***
ΔVRP	-0.00	3.11	-707.63	705.17	15.15	30193.61	-0.327	-0.000	25262.786***
ΔVRP_Jump	-0.00	6.82	-1550.73	1545.28	15.07	30052.27	-0.326	-0.000	25087.581***
Crisis (2/2007 to 3/2009)									
VIX	27.91	14.90	9.71	96.40	1.32	1.03	0.999	0.997	12864787.949***
VRP	62.02	217.94	-1368.05	2542.94	0.83	9.25	0.999	0.973	12327145.696***
VRP_Jump	64.75	472.11	-6117.77	5335.79	-1.38	15.11	0.999	0.958	12168419.113***
ΔVIX	0.00	0.19	-27.75	27.96	19.67	9759.82	-0.139	0.004	12168419.113***

ΔVRP	0.00	11.16	-2090.01	2102.94	25.32	18291.97	-0.199	0.005	11688.028***
ΔVRP_Jump	0.01	25.71	-4580.38	4605.58	19.01	14957.56	-0.198	0.004	11160.755***
Post Crisis (4/2009 to 6/2010)									
VIX	25.68	6.07	15.25	48.20	0.63	0.02	0.999	0.989	7371507.452***
VRP	82.15	78.94	-219.54	626.35	0.74	2.20	0.999	0.956	6997520.342***
VRP_Jump	176.91	213.21	-1920.72	1145.37	-2.34	18.32	0.999	0.941	6893728.697***
ΔVIX	-0.00	0.09	-12.45	6.23	-11.72	3277.08	-0.051	0.999	1912.476***
ΔVRP	0.00	2.84	-396.50	216.40	-15.00	4255.22	-0.024	0.008	2395.863***
ΔVRP_Jump	0.00	7.52	-907.37	481.64	-17.54	3086.76	0.083	-0.002	4729.640***

Table 4. Weekly and daily patterns in level of VIX index

This table presents summary statistics on day-of-the-week and time-of-day averages of the VIX index. "Roll" indicates overnight period (from open of third Friday of the month to previous close) when the VIX calculation moves to a new longer maturity options. . Mean, standard deviation and auto-correlation are equally-weighted averages of statistics computed once a day for each day.

Panel A: Summary statistics on 1 minute VIX within each day of the week, 9:30am to 4:00PM, 2005 to June 2010					
	Monday	Tuesday	Wednesday	Thursday	Friday
Mean	22.144	21.749	21.459	21.424	21.640
Standard deviation	0.423	0.447	0.425	0.456	0.435
Autocorrelation	0.968	0.972	0.972	0.978	0.974
F statistic (p-value)	72.79*** (<0.001)	-	-	-	-

Panel B: Summary statistics on VIX around the clock, 2005 to June 2010											
	1 minute intervals								Overnight close-to-open change in VIX		
	9:30 to 10	10 to 11	11 to 12	12 to 1	1 to 2	2 to 3	3 to 4	4 to 4:15	Weekdays	Weekends	Roll
Mean	21.775	21.695	21.668	21.656	21.674	21.674	21.656	21.658	0.123	0.679	-0.268
Standard deviation	0.202	0.182	0.139	0.117	0.124	0.149	0.185	0.056	-	-	-
Autocorrelation	0.753	0.873	0.879	0.865	0.871	0.874	0.881	0.534	-	-	-
F statistic (p-value)	0.84 (0.554)	-	-	-	-	-	-	-	-	-	-

Table 5. Correlation matrix for regression variables

This table presents contemporaneous Pearson correlations at the one minute interval. "ret" indicates percentage rate of price change, "vol" volume in terms of million, "imb" price setting buy sell imbalance, and "sp" spread between two return series. *, **, and *** denote significance at 10%, 5%, and 1%, respectively. The CDX spread change is only available starting 30th September 2008, unlike other series which start January 2005.

Panel A:

Variable	ΔVRP	ΔVRP_ Jump	SPY return	Eurodollar return	Gold futures return	CDX spread change	Sum of NEWS	SPY volume	SPY imbalance	SPY VPIN
ΔVIX	0.882***	0.835***	-0.167***	0.023***	-0.024***	0.024***	-0.017***	0.001	-0.086***	-0.003*
ΔVRP		0.954***	-0.142***	0.018***	-0.023***	0.014***	-0.011***	-0.006***	-0.051***	0.000
ΔVRP_Jump			-0.127***	0.014***	-0.029***	-0.005**	-0.011***	-0.027***	-0.049***	0.006***
SPY return				-0.064***	0.087***	-0.183***	0.024***	0.006***	0.361***	0.000
Eurodollar ret					0.004***	0.002	-0.017***	0.005***	-0.037***	-0.001
Gold return						-0.001	-0.005***	-0.002	0.050***	0.002*
ΔCDX spread							-0.002	-0.001	-0.006**	-0.001
Sum of NEWS								0.002*	0.007***	-0.002
SPY volume									0.009***	-0.474***
SPY imbalance										-0.008***

Panel B:

Variable	GLD Volume	GLD imbalance	GLD VPIN	CEF-NAV spread	ASA-NAV spread	CEF imbalance	ASA imbalance	SPY bid-ask change	CDX bid-ask change
ΔVIX	0.003**	-0.010***	-0.002*	0.021***	0.003**	0.038***	0.003**	0.001	-0.031***
ΔVRP	-0.003**	-0.008***	-0.001	0.017***	0.002	0.021***	0.002	0.002	-0.027***
ΔVRP_Jump	-0.019***	-0.008***	0.001	0.014***	0.002	0.021***	0.003*	0.003**	-0.029***
SPY return	-0.004***	0.036***	0.001	-0.063***	0.001	-0.186***	-0.016***	0.002*	0.085***
Eurodollar ret	0.000	-0.002	0.000	0.015***	0.002	0.018***	0.000	-0.001	-0.007***
Gold return	-0.015***	0.253***	0.006***	0.012***	0.057***	-0.026***	-0.180***	0.000	0.003
ΔCDX spread	0.002	-0.002	0.001	-0.010***	0.003	0.000	-0.001	0.002	-0.493***
Sum of NEWS	0.002	0.000	0.001	-0.010***	-0.001	-0.004***	-0.001	-0.002	0.006**
SPY volume	0.272***	-0.029***	-0.064***	0.002	0.002	-0.018***	0.013***	0.001	-0.002
SPY imbalance	0.004***	0.037***	0.003**	-0.027***	0.002*	-0.549***	-0.020***	-0.002	0.003

Table 5 continued.

Panel C:

Variable	GLD volume	GLD imbalance	GLD VPIN	CEF-NAV spread	ASA-NAV spread	CEF imbalance	ASA imblanace	SPY bid-ask change	CDX bid-ask change
SPY VPIN	-0.225***	0.039***	0.318***	-0.002	-0.001	0.028***	-0.019***	0.001	0.001
GLD volume		-0.032***	-0.124***	0.002	0.001	-0.020***	0.019***	-0.001	0.002
GLD imbalance			0.036***	0.008***	0.022***	-0.020***	-0.726***	-0.001	0.005**
GLD VPIN				0.000	-0.002	0.015***	-0.025***	0.001	0.000
CEF-NAV sp					0.004***	0.025***	-0.006***	-0.001	0.009***
ASA–NAV sp						-0.002	-0.008***	0.003**	-0.001
CEF imbalance							0.012***	0.001	0.001
ASA imbalance								0.000	-0.001
SPY bid-ask change									-0.002

Table 6. Factor analysis of explanatory variables

This table reports results of varimax factor analysis applied to the set of explanatory variables at 1-minute frequency.

Panel A: Full Sample January 2005 – June 2010							
	Factor						
	1	2	3	4	5	6	7
Factor characteristics:							
Eigenvalue (principal component)	1.787	1.445	1.215	1.012	1.004	1.003	1.000
Variance explained	0.119	0.096	0.081	0.068	0.067	0.067	0.067
Cumulative variance explained	0.119	0.216	0.297	0.364	0.431	0.498	0.565
Loadings on:							
SPY return	0.001	0.807	0.063	0.081	0.001	-0.044	0.005
Eurodollar return	-0.008	-0.127	0.044	-0.519	-0.051	0.041	-0.037
Gold return	-0.010	0.083	0.776	-0.024	0.075	0.018	0.004
Sum of NEWS	-0.009	-0.094	0.042	0.849	-0.037	0.011	-0.047
SPY volume	-0.739	0.017	0.022	0.009	-0.057	0.069	0.0211
SPY imbalance	-0.009	0.807	0.026	-0.003	-0.012	-0.000	-0.008
SPY VPIN	0.815	-0.005	-0.002	0.001	0.007	0.004	-0.000
GLD volume	-0.572	-0.001	-0.022	0.010	-0.024	0.022	0.006
GLD imbalance	0.064	0.004	0.779	0.003	-0.006	0.005	-0.014
GLD VPIN	0.485	0.011	0.045	0.020	-0.086	0.099	0.027
SPY bid-ask spread change	0.006	-0.001	-0.015	0.003	0.030	-0.006	0.978
CEF-NAV return spread	-0.024	-0.149	0.076	-0.117	0.013	0.588	-0.036
ASA –NAV return spread	-0.026	-0.053	0.141	0.046	0.564	-0.009	0.142
CEF imbalance	0.057	0.122	-0.066	0.088	-0.004	0.805	0.035
ASA imbalance	0.020	0.053	-0.087	-0.021	0.8218	0.022	-0.132
Correlation with:							
ΔVIX	-0.004***	-0.152***	-0.016***	-0.030***	-0.002**	0.006***	0.002**
ΔVRP	0.003**	-0.115***	-0.016***	-0.023***	-0.002**	0.005***	0.001**
ΔVRP_Jump	0.020***	-0.106***	-0.021***	-0.020***	-0.001**	0.002**	0.002**

Table 6 continued.

Panel B: Subsample from 30th September 2008 – June 2010							
	Factor						
	1	2	3	4	5	6	7
Factor characteristics:							
Eigenvalue (principal component)	1.907	1.739	1.491	1.184	1.011	1.007	1.004
Variance explained	0.112	0.102	0.088	0.070	0.060	0.059	0.059
Cumulative variance explained	0.112	0.215	0.302	0.372	0.431	0.491	0.5506
Loadings on:							
SPY return	0.001	-0.170	0.808	0.074	0.005	-0.067	0.061
Eurodollar return	0.000	-0.011	-0.123	0.038	0.002	0.018	-0.566
Gold return	0.006	0.008	0.149	0.806	0.076	0.029	-0.016
Sum of NEWS	-0.014	-0.006	0.068	-0.046	0.214	-0.377	-0.172
SPY volume	-0.619	0.004	0.016	0.001	0.000	0.008	-0.007
SPY imbalance	-0.0051	0.065	0.806	0.1294	-0.035	-0.029	0.033
SPY VPIN	0.842	-0.003	-0.002	-0.007	-0.004	-0.0416	-0.007
GLD volume	-0.464	-0.001	-0.005	-0.024	-0.006	-0.060	-0.007
GLD imbalance	0.027	0.002	0.047	0.821	0.023	0.026	-0.032
GLD VPIN	0.771	0.004	0.0106	0.005	-0.006	-0.025	-0.007
SPY bid-ask spread change	0.005	-0.005	-0.066	0.004	0.060	0.0550	0.786
CEF-NAV return spread	0.001	-0.059	-0.190	0.117	-0.044	0.546	0.012
ASA –NAV return spread	-0.007	-0.006	-0.063	0.182	0.555	0.008	0.112
CEF imbalance	0.005	0.049	0.229	-0.155	0.188	0.744	-0.144
ASA imbalance	0.010	-0.002	0.033	-0.079	0.787	-0.054	-0.049
ΔCDX spread	-0.001	0.861	-0.088	0.014	-0.001	-0.012	0.004
CDX bid-ask spread change	0.000	-0.856	-0.002	0.005	0.008	0.012	-0.007
Correlation with:							
ΔVIX	-0.005**	0.031***	-0.165***	-0.021***	-0.009***	0.019***	-0.009***
ΔVRP	0.003**	0.024***	-0.127***	-0.014***	-0.007***	0.013***	-0.010***
ΔVRP_Jump	0.020***	0.013***	-0.114***	-0.017***	-0.006**	0.011***	-0.007***

Table 7. Regression of changes in 1-minute S&P 500 Volatility Index (VIX) on its lags and explanatory variables

This table summarizes regressions for 1-minute intervals and ΔVIX as dependent variable expressed in percentage. SPY, Eurodollar, Gold futures price rates of change, CDX spread change, CEF-SPY and ASA-GLD return spreads are in terms of percentage. SPY and GLD volume are in millions. Buy-sell imbalances and VPINs are between 0 and 1. The numbers in the table are regression coefficients with p-values in the parenthesis. The adjusted R-squared is in the last row. *, **, and *** denote significance at 10%, 5%, and 1%, respectively.

Slope coefficients on:	Contemporaneous	Lag 1	Lag 2	Lag 3	Lag 4	Lag 5
ΔVIX		-0.309***(0.000)	-0.191***(0.000)	-0.136***(0.000)	-0.089***(0.000)	-0.040***(0.000)
SPY price rate of change	-0.353***(0.000)	-0.684***(0.000)	-0.325***(0.000)	-0.210***(0.000)	-0.155***(0.000)	-0.142***(0.000)
Eurodollar futures price rate of change	0.140**(0.038)	-0.469***(0.000)	-0.327***(0.000)	-0.150**(0.029)	-0.286***(0.000)	-0.095(0.160)
Gold futures price rate of change	-0.020***(0.000)	0.002(0.523)	0.004(0.297)	-0.005(0.235)	0.004(0.368)	0.001(0.905)
Sum of NEWS Surprises	-0.059***(0.000)	0.040***(0.000)	0.005(0.482)	-0.000(0.985)	-0.003(0.637)	-0.003(0.694)
SPY volume	-0.002***(0.003)	-0.002***(0.000)	0.001(0.247)	0.007***(0.000)	0.001**(0.014)	-0.002***(0.003)
SPY price-setting buy-sell imbalance	-0.006**(0.000)	0.015***(0.000)	0.005***(0.000)	0.002***(0.000)	0.000(0.385)	0.002***(0.000)
SPY VPIN	0.004(0.126)	0.000(0.964)	-0.001(0.679)	0.002(0.380)	0.003(0.217)	-0.002(0.575)
SPY bid-ask spread change	0.003(0.582)	-0.003(0.692)	0.002(0.777)	-0.004(0.537)	-0.001(0.908)	-0.003(0.571)
GLD volume	-0.010**(0.033)	0.049***(0.000)	0.017***(0.001)	-0.026***(0.000)	-0.011**(0.027)	-0.009*(0.050)
GLD price-setting buy-sell imbalance	0.000(0.513)	0.001**(0.036)	0.000(0.272)	0.000(0.696)	0.000(0.919)	-0.000(0.748)
GLD VPIN	0.000(0.889)	0.001(0.260)	-0.002(0.113)	-0.001(0.380)	-0.002**(0.028)	-0.002*(0.052)
CEF – NAV return spread	0.000(0.297)	-0.000***(0.000)	-0.000***(0.003)	0.0000(0.610)	-0.000***(0.000)	-0.000***(0.000)
ASA – NAV return spread	0.000***(0.009)	0.001***(0.000)	0.000(0.216)	0.000*(0.057)	0.000***(0.000)	0.000***(0.000)
CEF price-setting buy-sell imbalance	-0.001***(0.002)	0.000(0.644)	0.000(0.420)	-0.000(0.301)	-0.000(0.694)	-0.000(0.142)
ASA price -setting buy-sell imbalance	-0.001(0.192)	0.001(0.162)	-0.000(0.283)	-0.000(0.762)	-0.000(0.653)	0.001(0.150)
Adjusted R-squared	18.33%					

Table 8. Regression of changes in 1-minute Volatility Risk Premium (VRP) on its lags and explanatory variables

This table summarizes regressions for 1-minute intervals and ΔVRP as dependent variable expressed in basis points. SPY, Eurodollar, Gold futures price rates of change, CDX spread change, CEF-SPY and ASA-GLD return spreads are in terms of percentage. SPY and GLD volume are in million. Buy-sell imbalances and VPINs are between 0 and 1. The numbers in the table are regression coefficients with p-values in the parenthesis The adjusted R-squared is in the last row. *, **, and *** denote significance at 10%, 5%, and 1%, respectively.

Slope coefficients on:	Contemporaneous	Lag 1	Lag 2	Lag 3	Lag 4	Lag 5
ΔVRP	-	-0.345***(0.000)	-0.252***(0.000)	-0.164***(0.000)	-0.103***(0.000)	-0.053***(0.000)
SPY price rate of change	-15.043***(0.000)	-28.296***(0.000)	-15.620***(0.000)	-10.340***(0.000)	-7.344***(0.000)	-6.871***(0.000)
Eurodollar futures price rate of change	-1.878(0.565)	-28.252***(0.000)	-22.444***(0.000)	-8.997***(0.007)	-17.989***(0.000)	-5.426*(0.096)
Gold futures price rate of change	-1.317***(0.000)	-0.667***(0.000)	0.346*(0.056)	-0.494***(0.006)	0.218(0.228)	0.085(0.639)
Sum of NEWS Surprises	-1.546***(0.000)	1.470***(0.000)	0.217(0.470)	0.067(0.823)	-0.169(0.574)	-0.050(0.867)
SPY volume	-0.158***(0.000)	-0.301***(0.000)	-0.046*(0.072)	0.413***(0.000)	0.100***(0.000)	-0.053**(0.031)
SPY price-setting buy-sell imbalance	0.133***(0.000)	0.860***(0.000)	0.356***(0.000)	0.187***(0.000)	0.110***(0.000)	0.138***(0.000)
SPY VPIN	-0.245*(0.058)	-0.524***(0.000)	0.084(0.532)	0.265**(0.048)	0.348***(0.009)	0.179(0.167)
SPY bid-ask spread change	0.294(0.217)	0.179(0.557)	0.052(0.877)	-0.241(0.469)	-0.041(0.893)	-0.162(0.497)
GLD volume	-1.164***(0.000)	1.435***(0.000)	0.587**(0.013)	-0.637***(0.007)	-0.252(0.282)	0.267(0.241)
GLD price-setting buy-sell imbalance	0.031**(0.046)	0.039**(0.013)	0.016(0.309)	-0.001(0.928)	-0.001(0.962)	-0.002(0.881)
GLD VPIN	-0.010(0.842)	0.014(0.795)	-0.010(0.846)	0.065(0.215)	0.029(0.572)	0.042(0.417)
CEF – NAV return spread	-0.004(0.181)	-0.020***(0.000)	-0.012***(0.000)	0.000(0.928)	-0.018***(0.000)	-0.014***(0.000)
ASA – NAV return spread	-0.002(0.467)	0.000(0.948)	-0.015***(0.000)	-0.002(0.485)	0.007**(0.022)	0.008***(0.007)
CEF imbalance	-0.034***(0.009)	0.014(0.277)	0.011(0.405)	-0.014(0.272)	-0.013(0.333)	-0.024*(0.068)
ASA imbalance	-0.011(0.551)	0.029(0.109)	-0.002(0.927)	-0.015(0.425)	0.007(0.715)	0.013(0.488)
Adjusted R-squared	18.24%					

Table 9. Subsample regression of changes in Volatility Risk Premium with Jumps (VIX_Jump) on its lags and explanatory variables including corporate credit spread variable

This table summarizes regressions for 1-minute intervals from September 30, 2008 and ΔVRP_Jump as dependent variable expressed in percentage. SPY, Eurodollar, Gold futures price rates of change, CDX spread change, CEF-SPY and ASA-GLD return spreads are in terms of percentage. SPY and GLD volume are in millions. Buy-sell imbalances and VPINs are between 0 and 1. The numbers in the table are regression coefficients with p-values in the parenthesis. The adjusted R-squared is in the last row. *, **, and *** denote significance at 10%, 5%, and 1%, respectively.

Slope coefficients on:	Contemporaneous	Lag 1	Lag 2	Lag 3	Lag 4	Lag 5
ΔVIX_Jump	-	-0.303***(0.000)	-0.204***(0.000)	-0.118***(0.000)	-0.065***(0.000)	-0.033***(0.000)
SPY price rate of change	-30.825***(0.000)	-60.325***(0.000)	-29.906***(0.000)	-17.221***(0.000)	-10.641***(0.000)	-11.280***(0.000)
Eurodollar futures price rate of change	-17.619**(0.018)	-72.151***(0.000)	-49.223***(0.000)	-6.806(0.372)	-20.537***(0.007)	2.062(0.782)
Gold futures price rate of change	-6.036***(0.000)	-2.807***(0.000)	0.072(0.866)	-2.080***(0.000)	-0.256(0.547)	-0.540(0.203)
Sum of NEWS Surprises	-3.755***(0.000)	3.290***(0.000)	0.268(0.704)	-0.014(0.984)	-0.469(0.506)	-0.125(0.859)
SPY volume	-0.665***(0.000)	-1.431***(0.000)	-0.515***(0.000)	0.671***(0.000)	-0.023(0.701)	-0.276***(0.000)
SPY price-setting buy-sell imbalance	0.156***(0.001)	1.871***(0.000)	0.653***(0.000)	0.263***(0.000)	0.090*(0.063)	0.205***(0.000)
SPY VPIN	-0.113(0.694)	-0.910***(0.002)	-0.787***(0.009)	-0.488(0.104)	-0.388(0.194)	-0.764***(0.008)
SPY bid-ask spread change	1.045*(0.061)	0.700(0.326)	-0.434(0.577)	-1.517*(0.051)	-0.920(0.197)	-0.755(0.175)
GLD volume	-7.781***(0.000)	4.212***(0.000)	1.551***(0.005)	-0.401(0.466)	1.315**(0.016)	2.939***(0.000)
GLD price-setting buy-sell imbalance	0.073**(0.046)	0.086**(0.021)	0.025(0.507)	-0.015(0.689)	-0.022(0.553)	-0.028(0.448)
GLD VPIN	0.247**(0.039)	0.302**(0.012)	0.124(0.304)	0.283**(0.019)	0.204*(0.091)	0.200*(0.095)
CEF – NAV return spread	-0.011(0.121)	-0.053***(0.000)	-0.035***(0.000)	-0.007(0.347)	-0.040**(0.000)	-0.030***(0.000)
ASA – NAV return spread	-0.008(0.229)	-0.010(0.171)	-0.032***(0.000)	-0.004(0.623)	0.021***(0.002)	0.019***(0.007)
CEF imbalance	-0.067**(0.028)	0.032(0.281)	0.033(0.271)	-0.036(0.239)	-0.025(0.404)	-0.054*(0.073)
ASA imbalance	-0.053(0.215)	0.083*(0.053)	0.002(0.964)	-0.038(0.377)	0.034(0.426)	0.024(0.583)
Adjusted R-squared	15.14%					

Table 10. Subsample regression of changes in 1-minute S&P 500 Volatility Index (VIX) on its lags and explanatory variables

This table summarizes regressions for 1-minute intervals and ΔVIX as dependent variable expressed in percentage. SPY, Eurodollar, Gold futures price rates of change, CDX spread change, CEF-SPY and ASA-GLD return spreads are in terms of percentage. SPY and GLD volume are in millions. Buy-sell imbalances and VPINs are between 0 and 1. The numbers in the table are regression coefficients with p-values in the parenthesis. The adjusted R-squared is in the last row. *, **, and *** denote significance at 10%, 5%, and 1%, respectively.

Slope coefficients on:	Contemporaneous	Lag 1	Lag 2	Lag 3	Lag 4	Lag 5
ΔVIX	-	-0.294***(0.000)	-0.231***(0.000)	-0.145***(0.000)	-0.087***(0.000)	-0.039***(0.000)
SPY price rate of change	-0.357***(0.000)	-0.696***(0.000)	-0.352***(0.000)	-0.228***(0.000)	-0.161***(0.000)	-0.145***(0.000)
Eurodollar futures price rate of change	0.548***(0.001)	-0.837***(0.000)	-0.564***(0.000)	-0.133(0.405)	-0.656***(0.000)	-0.113(0.472)
Gold futures price rate of change	-0.032***(0.000)	0.001(0.888)	0.024***(0.003)	-0.007(0.371)	0.006(0.467)	0.010(0.247)
CDX spread change	-2.917***(0.000)	5.902***(0.000)	1.174***(0.000)	0.893***(0.000)	1.307***(0.000)	1.268***(0.000)
Sum of NEWS Surprises	-0.109***(0.000)	0.077***(0.000)	0.003(0.807)	0.005(0.697)	-0.002(0.861)	-0.005(0.688)
SPY volume	-0.003***(0.000)	-0.005***(0.000)	-0.000(0.896)	0.015***(0.000)	0.002**(0.020)	-0.001(0.128)
SPY price-setting buy-sell imbalance	-0.007***(0.000)	0.027***(0.000)	0.007***(0.000)	0.002*(0.080)	0.002(0.147)	0.003***(0.003)
SPY VPIN	-0.008(0.169)	-0.015**(0.011)	0.010*(0.092)	0.012**(0.040)	0.013**(0.023)	0.010*(0.076)
SPY bid-ask spread change	0.014(0.326)	0.004(0.821)	-0.001(0.977)	-0.019(0.352)	0.007(0.725)	-0.004(0.796)
CDX bid-ask spread change	-1.485***(0.000)	-0.828***(0.005)	-0.430(0.144)	-0.225(0.445)	-0.289(0.325)	0.119(0.681)
GLD volume	-0.010(0.225)	0.052***(0.000)	0.010(0.200)	-0.020**(0.012)	-0.016**(0.047)	-0.006(0.434)
GLD price-setting buy-sell imbalance	0.001(0.510)	0.001(0.588)	0.000(0.994)	-0.001(0.404)	-0.000(0.863)	0.000(0.998)
GLD VPIN	0.001(0.828)	0.019***(0.003)	-0.017***(0.008)	-0.001(0.903)	-0.008(0.213)	-0.017***(0.007)
CEF – NAV return spread	0.000(0.597)	-0.001***(0.000)	-0.000*(0.073)	-0.000(0.422)	-0.001***(0.000)	-0.000***(0.001)
ASA – NAV return spread	0.000(0.641)	-0.000(0.627)	-0.001***(0.000)	-0.000(0.156)	0.000*(0.098)	0.000***(0.001)
CEF price-setting buy-sell imbalance	-0.001(0.137)	0.001(0.211)	0.001(0.123)	-0.001(0.432)	-0.000(0.627)	-0.001(0.173)
ASA price –setting buy-sell imbalance	-0.001(0.210)	0.001(0.444)	0.001(0.245)	-0.001(0.280)	0.001(0.376)	0.000(0.767)
Adjusted R-squared	22.2%					

Table 11. Subsample regression of changes in 1-minute Volatility Risk Premium (VRP) on its lags and explanatory variables

This table summarizes regressions for 1-minute intervals and ΔVRP as dependent variable expressed in basis points. SPY, Eurodollar, Gold futures price rates of change, CDX spread change, CEF-SPY and ASA-GLD return spreads are in terms of percentage. SPY and GLD volume are in million. Buy-sell imbalances and VPINs are between 0 and 1. The numbers in the table are regression coefficients with p-values in the parenthesis The adjusted R-squared is in the last row. *, **, and *** denote significance at 10%, 5%, and 1%, respectively.

Slope coefficients on:	Contemporaneous	Lag 1	Lag 2	Lag 3	Lag 4	Lag 5
ΔVRP		-0.358***(0.000)	-0.276***(0.000)	-0.180***(0.000)	-0.112***(0.000)	-0.058***(0.000)
SPY price rate of change	-18.515***(0.000)	-34.737***(0.000)	-20.480***(0.000)	-13.099***(0.000)	-9.483***(0.000)	-8.878***(0.000)
Eurodollar futures price rate of change	53.835***(0.000)	-14.602(0.134)	-16.195*(0.097)	10.244(0.294)	-27.846***(0.004)	-1.604(0.867)
Gold futures price rate of change	-1.827***(0.000)	-1.064**(0.034)	1.684***(0.001)	-0.719(0.153)	0.546(0.277)	0.623(0.215)
CDX spread change	-176.59***(0.000)	283.00***(0.000)	77.49***(0.000)	73.89***(0.000)	88.39***(0.000)	84.02***(0.000)
Sum of NEWS Surprises	-2.854***(0.000)	3.195***(0.000)	0.796(0.282)	0.640(0.387)	0.053(0.943)	0.033(0.965)
SPY volume	-0.301***(0.000)	-0.612***(0.000)	-0.150**(0.013)	0.836***(0.000)	0.195***(0.001)	-0.037(0.518)
SPY price-setting buy-sell imbalance	0.184***(0.008)	1.727***(0.000)	0.717***(0.000)	0.329***(0.000)	0.266***(0.000)	0.337***(0.000)
SPY VPIN	-0.994***(0.005)	-1.550***(0.000)	0.421(0.242)	0.714**(0.047)	0.784**(0.029)	0.546(0.118)
SPY bid-ask spread change	1.108(0.202)	0.578(0.605)	-0.483(0.693)	-1.362(0.265)	-0.012(0.991)	-0.500(0.565)
CDX bid-ask spread change	-70.165***(0.000)	145.925***(0.000)	71.054***(0.000)	64.757***(0.000)	41.373**(0.021)	41.822**(0.018)
GLD volume	-1.257***(0.010)	2.066***(0.000)	0.704(0.157)	-0.355(0.475)	0.045(0.928)	1.126**(0.021)
GLD price-setting buy-sell imbalance	0.092(0.131)	0.078(0.197)	-0.008(0.896)	-0.043(0.481)	-0.013(0.825)	-0.025(0.678)
GLD VPIN	-0.333(0.403)	0.278(0.497)	-0.504(0.221)	0.996**(0.016)	0.744*(0.070)	0.588(0.139)
CEF – NAV return spread	0.001(0.883)	-0.021***(0.005)	-0.011(0.164)	0.003(0.738)	-0.034***(0.000)	-0.027***(0.000)
ASA – NAV return spread	-0.007(0.380)	-0.014*(0.079)	-0.048***(0.000)	-0.013*(0.094)	0.008(0.291)	0.017**(0.026)
CEF price-setting buy-sell imbalance	-0.085**(0.030)	0.026(0.504)	0.041(0.302)	-0.036(0.358)	-0.037(0.346)	-0.061(0.117)
ASA price –setting buy-sell imbalance	-0.090(0.114)	0.031(0.595)	0.043(0.451)	-0.065(0.258)	0.053(0.358)	0.006(0.918)
Adjusted R-squared	20.72%					

Table 12. Subsample regression of changes in Volatility Risk Premium with Jumps (VIX_Jump) on its lags and explanatory variables including corporate credit spread variable

This table summarizes regressions for 1-minute intervals from September 30, 2008 and ΔVRP_Jump as dependent variable expressed in percentage. SPY, Eurodollar, Gold futures price rates of change, CDX spread change, CEF-SPY and ASA-GLD return spreads are in terms of percentage. SPY and GLD volume are in millions. Buy-sell imbalances and VPINs are between 0 and 1. The numbers in the table are regression coefficients with p-values in the parenthesis. The adjusted R-squared in the last row. *, **, and *** denote significance at 10%, 5%, and 1%, respectively.

Slope coefficients on:	Contemporaneous	Lag 1	Lag 2	Lag 3	Lag 4	Lag 5
ΔVRP_jump		-0.318***(0.000)	-0.228***(0.000)	-0.133***(0.000)	-0.074***(0.000)	-0.038***(0.000)
SPY price rate of change	-37.045***(0.000)	-72.972***(0.000)	-39.337***(0.000)	-21.336***(0.000)	-13.646***(0.000)	-14.696***(0.000)
Eurodollar futures price rate of change	95.938***(0.000)	-75.942***(0.001)	-53.483**(0.018)	48.537**(0.033)	-29.378(0.194)	11.839(0.595)
Gold futures price rate of change	-6.627***(0.000)	-3.631***(0.002)	2.698**(0.021)	-3.411***(0.004)	-0.374(0.750)	-0.151(0.897)
CDX spread change	-597.57***(0.000)	575.12***(0.000)	127.62***(0.000)	155.62***(0.000)	132.86***(0.000)	123.84***(0.000)
Sum of NEWS Surprises	-7.000***(0.000)	7.016***(0.000)	1.200(0.488)	0.930(0.591)	-0.273(0.875)	-0.103(0.953)
SPY volume	-1.076***(0.000)	-2.641***(0.000)	-1.103***(0.000)	1.415***(0.000)	-0.085(0.541)	-0.446***(0.001)
SPY price-setting buy-sell imbalance	-0.038(0.814)	3.626***(0.000)	1.238***(0.000)	0.329**(0.042)	0.221(0.173)	0.492***(0.002)
SPY VPIN	-2.001**(0.011)	-3.645***(0.000)	-1.022(0.207)	-0.237(0.769)	-0.335(0.677)	-0.836(0.284)
SPY bid-ask spread change	4.264**(0.035)	2.661(0.306)	-3.816(0.178)	-7.391***(0.009)	-3.532(0.174)	-2.803(0.165)
CDX bid-ask spread change	-398.174***(0.000)	183.134***(0.000)	39.291(0.346)	64.714(0.121)	10.315(0.804)	41.869(0.309)
GLD volume	-8.487***(0.000)	5.922***(0.000)	1.920*(0.092)	0.238(0.834)	1.883*(0.097)	4.332***(0.000)
GLD price-setting buy-sell imbalance	0.145(0.306)	0.165(0.242)	-0.042(0.768)	-0.107(0.449)	-0.074(0.600)	-0.098(0.489)
GLD VPIN	0.526(0.549)	1.716*(0.060)	-1.345(0.143)	2.094**(0.023)	1.604*(0.078)	0.841(0.337)
CEF – NAV return spread	-0.021(0.219)	-0.082***(0.000)	-0.054***(0.002)	-0.017(0.339)	-0.075***(0.000)	-0.054***(0.002)
ASA – NAV return spread	-0.010(0.587)	-0.039**(0.030)	-0.094***(0.000)	-0.020(0.279)	0.041**(0.025)	0.043**(0.017)
CEF price-setting buy-sell imbalance	-0.154*(0.092)	0.072(0.435)	0.120(0.192)	-0.096(0.297)	-0.068(0.457)	-0.140(0.125)
ASA price –setting buy-sell imbalance	-0.240*(0.073)	0.119(0.374)	0.119(0.376)	-0.155(0.248)	0.156(0.244)	-0.046(0.733)
Adjusted R-squared	17.63%					

Table 13. Coefficients from 1-minute VAR regression estimation

The table presents selected coefficients from a VAR in which ΔVIX and all other variables are endogenous. To conserve space, only coefficients for the equation in which VIX is the dependent variable are reported. *, **, and *** denote significance at 10%, 5%, and 1%, respectively. Standard errors for Cholesky coefficients are generated with 60 replications of a Monte Carlo simulation.

Slope coefficients on:	Lag 1	Lag 2	Lag 3	Lag4	Lag 5	Cholesky	Standard error
ΔVIX	-0.308***(0.000)	-0.191***(0.000)	-0.136***(0.000)	-0.091***(0.000)	-0.040***(0.000)	0.1437	0.001
SPY price rate of change	-0.678***(0.000)	-0.325***(0.000)	-0.207***(0.000)	-0.147***(0.000)	-0.141***(0.000)	-0.014	0.000
Eurodollar futures price rate of change	-0.561***(0.000)	-0.343***(0.000)	-0.169**(0.016)	-0.292***(0.000)	-0.111(0.105)	0.000	0.000
Gold futures price rate of change	0.003(0.476)	0.003(0.410)	-0.003(0.462)	0.005(0.181)	-0.001(0.841)	-0.001	0.000
Sum of NEWS Surprises	0.039***(0.000)	0.003(0.663)	0.001(0.932)	-0.004(0.580)	-0.005(0.418)	-0.001	0.000
SPY volume	-0.003***(0.000)	0.000(0.470)	0.007***(0.000)	0.001**(0.015)	-0.002***(0.001)	-0.002	0.000
SPY price-setting buy-sell imbalance	0.015***(0.000)	0.005***(0.000)	0.002***(0.000)	0.000(0.504)	0.002***(0.000)	-0.041	0.000
SPY VPIN	0.002(0.478)	-0.000(0.975)	0.002(0.554)	0.003(0.218)	0.000(0.939)	0.000	0.000
SPY bid-ask spread change	-0.003(0.537)	0.001(0.935)	-0.005(0.416)	-0.002(0.738)	-0.004(0.483)	0.000	0.963
GLD volume	0.047***(0.000)	0.014***(0.006)	-0.027***(0.000)	-0.009*(0.067)	-0.013***(0.010)	-0.000	0.000
GLD price-setting buy-sell imbalance	0.001*(0.052)	0.000(0.234)	0.000(0.779)	-0.000(0.717)	-0.000(0.844)	-0.005	0.000
GLD VPIN	0.001(0.299)	-0.002(0.131)	-0.001(0.358)	-0.003**(0.021)	-0.002**(0.041)	0.000	0.000
CEF – NAV return spread	-0.000**(0.013)	0.000(0.624)	0.000(0.416)	-0.000(0.309)	-0.000(0.700)	0.042	0.001
ASA – NAV return spread	0.000**(0.017)	-0.000(0.563)	0.000(0.352)	0.000**(0.042)	0.000*(0.098)	0.001	0.001
CEF imbalance	0.000(0.991)	0.000(0.434)	-0.000(0.218)	-0.000(0.697)	-0.000(0.169)	-0.006	0.000
ASA imbalance	0.000(0.312)	-0.000(0.278)	-0.000(0.684)	-0.000(0.863)	0.001(0.110)	-0.002	0.000

Table 14. Coefficients from 1-minute VAR sub period regression estimation

The table presents selected coefficients from a VAR in which ΔVIX and all other variablesare endogenous. It is estimated for the sub period (starting 30 September 2008) when the CDX spread variable is available. To conserve space, only coefficients for the equation in which VIX is the dependent variable are reported. *, **, and *** denote significance at 10%, 5%, and 1%, respectively. This table covers Standard errors for Cholesky coefficients are generated with 60 replications of a Monte Carlo simulation.

Slope coefficients on:	Lag 1	Lag 2	Lag 3	Lag4	Lag 5	Cholesky	Standard error
ΔVIX	-0.292***(0.000)	-0.231***(0.000)	-0.146***(0.000)	-0.090***(0.000)	-0.040***(0.000)	0.186	0.002
SPY price rate of change	-0.688***(0.000)	-0.349***(0.000)	-0.22162***(0.000)	-0.152***(0.000)	-0.144***(0.000)	-0.022	0.000
Eurodollar futures price rate of change	-1.005***(0.0001)	-0.506***(0.002)	-0.072(0.658)	-0.691***(0.000)	-0.216(0.180)	0.000	0.000
Gold futures price rate of change	-0.004(0.633)	0.018**(0.030)	-0.010(0.240)	0.0071(0.434)	0.006(0.461)	-0.003	0.000
CDX spread change	6.056***(0.000)	1.211***(0.000)	0.996***(0.000)	1.341***(0.000)	1.207***(0.000)	0.000	0.000
Sum of NEWS Surprises	0.074***(0.000)	-0.004*(0.756)	0.003(0.806)	-0.002(0.899)	-0.010(0.416)	-0.001	0.000
SPY volume	-0.006***(0.000)	-0.001(0.621)	0.015***(0.000)	0.0025(0.036)	-0.002(0.042)	-0.004	0.000
SPY price-setting buy-sell imbalance	0.027***(0.000)	0.007***(0.000)	0.002**(0.064)	0.002(0.118)	0.004***(0.002)	-0.047	0.000
SPY VPIN	-0.015***(0.008)	0.010*(0.070)	0.009(0.115)	0.011(0.058)	0.009(0.103)	-0.000	0.000
SPY bid-ask spread change	-0.002(0.887)	-0.013(0.461)	-0.027(0.157)	-0.002(0.920)	-0.011(0.449)	0.000	0.000
CDX bid-ask spread change	-0.662*(0.026)	-0.282(0.347)	-0.059(0.844)	-0.166(0.579)	0.138(0.642)	-0.0009	0.000
GLD volume	0.050***(0.000)	0.006(0.428)	-0.022***(0.008)	-0.015*(0.070)	-0.012(0.146)	-0.000	0.000
GLD price-setting buy-sell imbalance	0.000(0.710)	0.000(0.802)	-0.001(0.371)	-0.000(0.724)	0.000(0.931)	-0.010	0.000
GLD VPIN	0.019**(0.0022)	-0.018(0.007)	-0.020(0.765)	-0.008(0.244)	-0.017***(0.007)	0.000	0.000
CEF – NAV return spread	-0.001***(0.000)	-0.000(0.091)	-0.000(0.972)	-0.000(0.017)	-0.000*(0.073)	0.059	0.00
ASA – NAV return spread	0.000**(0.029)	-0.000**(0.012)	0.000(0.140)	0.000(0.187)	0.000**(0.016)	-0.011	0.001
CEF imbalance	0.001(0.299)	0.001(0.155)	-0.001(0.437)	-0.000(0.654)	-0.001(0.214)	-0.006	0.000
ASA imbalance	0.000(0.938)	0.001(0.285)	-0.001(0.448)	0.001(0.398)	0.000(0.81)	-0.003	0.000

Table 15. VARs of 1-minute volatility measures and factors

The table presents selected coefficients from a VAR in which ΔVIX and factors constructed from other variables (see Table 6) are endogenous. To conserve space, only coefficients for the equation in which VIX is the dependent variable are reported. *, **, and *** denote significance at 10%, 5%, and 1%, respectively. Standard errors for Cholesky coefficients are generated with 60 replications of a Monte Carlo simulation.

	Slope coefficients on:	Lag 1	Lag 2	Lag 3	Lag4	Lag5	Cholesky	Standard error
A.	ΔVIX	-0.257***(0.000)	-0.149***(0.000)	-0.104***(0.000)	-0.065***(0.000)	-0.030***(0.000)	0.148	0.001
	Factor 1 trading	-0.001(0.162)	-0.001***(0.003)	-0.002***(0.000)	0.000(0.802)	0.001***(0.000)	0.002	0.000
	Factor 2 equity direction	-0.033***(0.000)	-0.012***(0.000)	-0.008***(0.000)	-0.005***(0.000)	-0.005***(0.000)	-0.153	0.001
	Factor 3 gold direction	-0.002***(0.000)	-0.001***(0.000)	-0.001***(0.001)	-0.000(0.185)	-0.001***(0.009)	-0.015	0.000
	Factor 4 macro conditions	-0.002***(0.000)	-0.002***(0.000)	-0.001***(0.000)	-0.001***(0.002)	-0.001***(0.000)	-0.032	0.000
	Factor 5 gold sentiment	0.001***(0.000)	-0.000(0.351)	-0.000(0.624)	0.000(0.117)	0.001***(0.000)	0.001	0.000
	Factor 6 equity sentiment	0.001***(0.000)	0.001***(0.000)	0.001***(0.000)	0.000(0.186)	0.000(0.458)	0.011	0.000
	Factor 7 equity liquidity	-0.000(0.533)	0.000(0.474)	0.000(0.995)	0.000(0.520)	0.000(0.921)	0.002	0.000
B.	ΔVRP	-0.289***(0.000)	-0.203***(0.000)	-0.124***(0.000)	-0.075***(0.000)	-0.040***(0.000)	6.932	0.109
	Factor 1 trading	0.053***(0.001)	0.004(0.816)	-0.115***(0.000)	0.001(0.965)	0.053***(0.001)	0.004	0.000
	Factor 2 equity direction	-1.266***(0.000)	-0.564***(0.000)	-0.355***(0.000)	-0.216***(0.000)	-0.228***(0.000)	-0.116	0.002
	Factor 3 gold direction	-0.131***(0.000)	-0.039***(0.000)	-0.047***(0.000)	-0.010(0.290)	-0.020**(0.032)	-0.01501	0.001
	Factor 4 macro conditions	-0.097***(0.000)	-0.075***(0.000)	-0.067***(0.000)	-0.028***(0.003)	-0.040***(0.000)	-0.024	0.000
	Factor 5 gold sentiment	0.008(0.421)	-0.024**(0.012)	-0.016*(0.084)	0.017*(0.079)	0.022(0.019)	-0.001	0.000
	Factor 6 equity sentiment	0.066***(0.000)	0.062***(0.000)	0.057***(0.000)	0.003(0.752)	-0.002(0.853)	0.007	0.000
	Factor 7 equity liquidity	-0.026**(0.023)	-0.032**(0.024)	-0.033**(0.024)	-0.015(0.302)	-0.012（0.316）	-0.000	0.000
C.	ΔVRP_Jump	-0.262***(0.000)	-0.172***(0.000)	-0.093***(0.000)	-0.048***(0.000)	-0.026***(0.000)	16.170	2.031
	Factor 1 equity trading	0.568***(0.000)	0.129***(0.002)	-0.262***(0.000)	-0.064(0.127)	-0.029(0.452)	0.010	0.001
	Factor 2 equity direction	-2.677***(0.000)	-1.104***(0.000)	-0.608***(0.000)	-0.310***(0.000)	-0.398***(0.000)	-0.107	-0.010
	Factor 3 gold direction	-0.350***(0.000)	-0.112***(0.000)	-0.129***(0.000)	-0.042*(0.055)	-0.075***(0.000)	-0.021	-0.002
	Factor 4 macro conditions	-0.182***(0.000)	-0.133***(0.000)	-0.132***(0.000)	-0.053**(0.015)	-0.085***(0.000)	-0.021	-0.002
	Factor 5 gold sentiment	0.0341(0.121)	-0.034(0.126)	-0.032(0.144)	0.058***(0.009)	0.048**(0.028)	-0.001	0.000

Factor 6 equity sentiment	0.086***(0.000)	0.081***(0.000)	0.070***(0.001)	-0.028(0.194)	-0.031(0.152)	0.004	0.000
Factor 7 equity liquidity	-0.076***(0.004)	-0.127***(0.000)	-0.144***(0.000)	-0.087***(0.007)	-0.058**(0.031)	-0.000	0.000

Table 16. Regressions and sorts to explain conditional autocorrelation of changes in VIX index

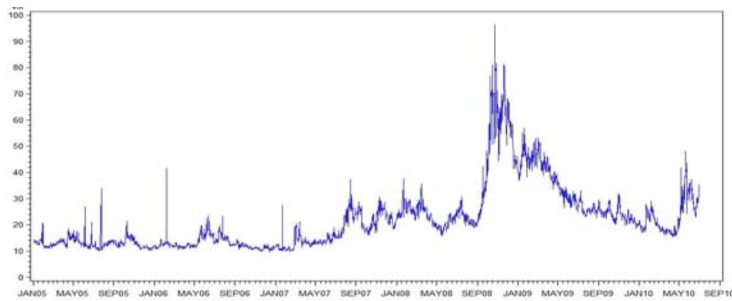
This table reports non-linear regressions of VIX changes on its first lag with a slope coefficient that depends on lags of either our explanatory variables or the factors constructed from those variables. The table also reports sorts of the 30-minute serial correlation on lags of the variables or factors.

Panel A: Conditioned on variables					Panel B: Conditioned on factors				
Variable	Non-linear regression slope (t-statistic)		Difference in serial correlation high quintile - low quintile (p-value)		Factor	Non-linear regression slope (t-statistic)		Difference in serial correlation high quintile - low quintile (p-value)	
Intercept	0.000	0.31	-	-	Intercept	0.001	2.58	-	-
ΔVIX	-0.071	-6.71	0.001	0.913	ΔVIX	-0.226	-128.54	0.001	0.913
SPY price rate of change	0.195	21.61	0.002	0.799	1 trading	-0.045	-51.27	-0.138	0.000
Eurodollar futures rate of change	-0.611	-2.7	0.011	0.109	2 equity direction	0.025	30.04	0.009	0.167
Gold futures rate of change	-0.180	-17.44	0.000	0.961	3 gold direction	-0.000	-0.58	0.004	0.515
NEWS surprises	-0.330	-26.08	-0.032	0.198	4 macro conditions	0.000	0.42	-0.009	0.193
SPY volume	0.031	19.64	0.143	0.000	5 gold sentiment	-0.034	-31.00	-0.006	0.393
SPY imbalance	-0.084	-19.56	0.014	0.043	6 equity sentiment	0.048	60.92	0.003	0.711
SPY VPIN	-0.232	-23.23	-0.159	0.000	7 equity liquidity	0.100	83.74	-0.002	0.767
SPY bid-ask spread change	1.832	74.45	-0.020	0.003	-	-	-	-	-
GLD volume	-0.017	-0.67	0.098	0.000	-	-	-	-	-
GLD imbalance	0.075	24.11	-0.012	0.068	-	-	-	-	-
GLD VPIN	0.012	1.07	-0.075	0.000	-	-	-	-	-
CEF – NAV return spread	0.003	18.67	0.008	0.229	-	-	-	-	-
ASA – NAV return spread	-0.003	-13.98	-0.009	0.182	-	-	-	-	-
CEF imbalance	0.166	79.69	-0.009	0.023	-	-	-	-	-
ASA imbalance	0.006	1.41	0.002	0.759	-	-	-	-	-
Adjusted r-squared	6.83%		-	-	Adjusted r-squared	5.78%	-	-	-

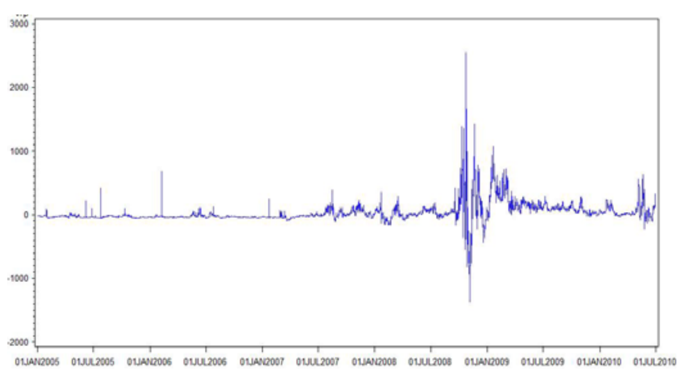
Figure 1. Intraday VIX and VRP at 1-minute intervals

VIX and VRP are expressed in different units but can be compared as follows. Suppose VIX is 21.70. Square 0.2170 and multiply by 100 to yield 4.71%. Suppose VRP is 220.34. Divide by 100 to yield 2.20%. Thus, VRP comprises slightly less than half of VIX.

Panel A: VIX (in percentage)



Panel B: VRP (in basis points) NEW



Panel C: VRP_Jump (in basis points) NEW

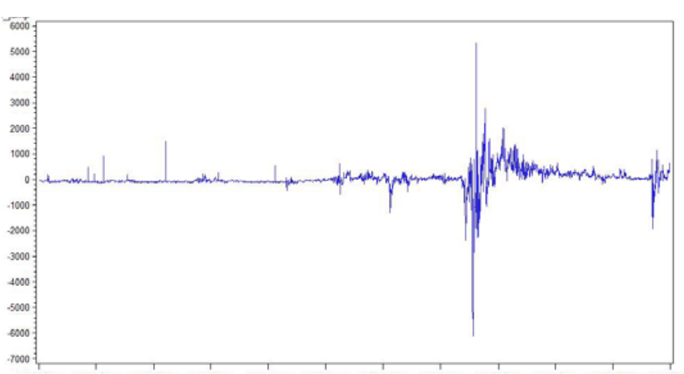


Figure 2. Average VIX Index at end of each 1-minute interval during trading day

The plot shows the average VIX minute-by-minute across each day from January 2005 to June 2010,

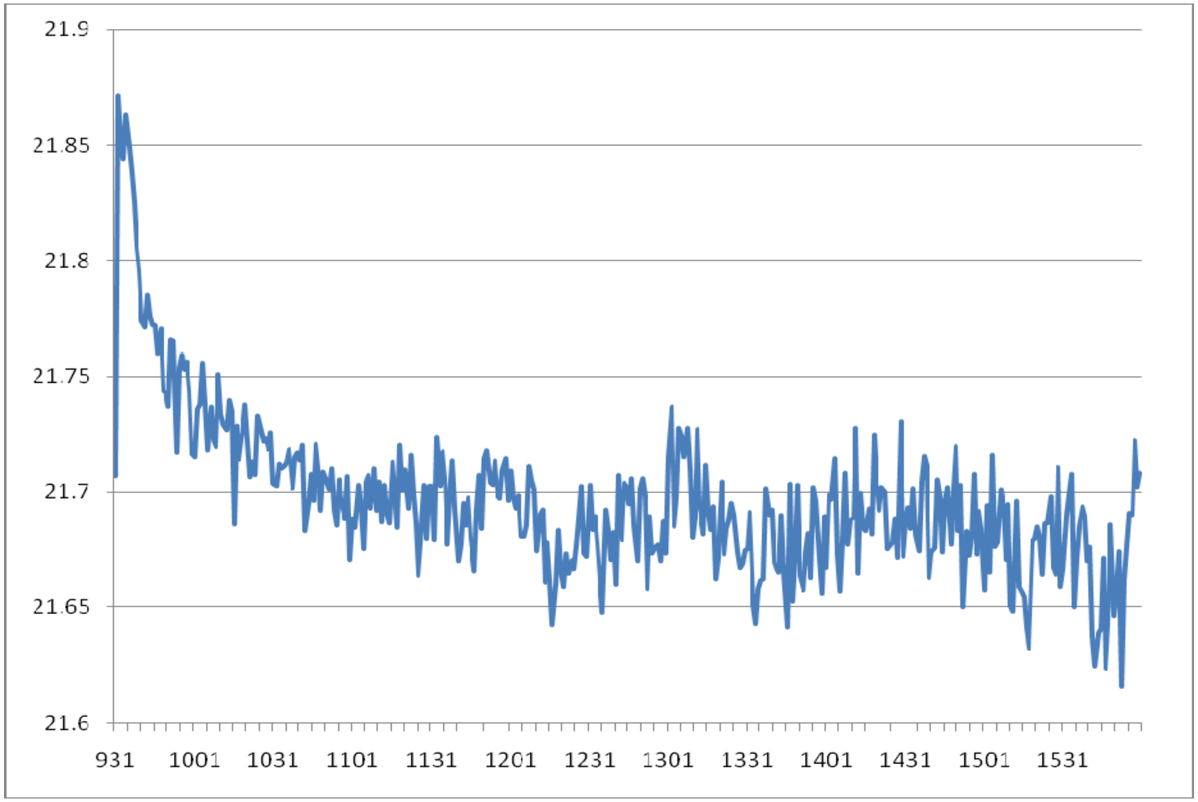


Figure 3. Impulse response plot for changes in 1 minute VIX (NEW)