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WHAT MAKES THE VIX TICK?

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Abstract

We seek the roots of one-minute changes in VIX, an index of S&P 500 option prices, to understand risk neutral volatility and its risk premium component. Beyond leverage and risk premium effects, macroeconomic influences and some proxies for noise trading in the S&P 500 ETF market are significant, though measures of small investor sentiment have little significance. VIX changes display negative serial correlation suggesting liquidity provision in the options market. Temporary price effects are observed around macroeconomic news releases. Though often viewed as an exogenous state variable, a significant portion of VIX variability relates to trader behavior and macroeconomic fundamentals.

Keywords: VIX, Implied Volatility, Volatility Risk Premium, Investor Sentiment

JEL Classification: G11, G12, G13

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1. Introduction

Why does stock volatility change over time? Classic studies find that the volatility of macroeconomic fundamentals explains only a fraction of stock index volatility.[1] 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.[2]

A potential limitation to explaining stock volatility with fundamentals is the low frequency of observations dictated by the use of daily stock returns to compute realized volatility and by the monthly frequency of typical macroeconomic series. Our study takes a fresh look at the underlying causes of volatility using high-frequency data from markets for index option derivatives, equities, futures contracts, and credit default spreads. Today's capital markets feature frequent or even automated trading, high liquidity, and rapid rebalancing across asset classes by participants ranging from hedge funds to proprietary trading desks of institutions. In this environment, high-frequency data allows us to uncover relationships between volatility and fundamentals that cannot be observed at lower frequencies. We construct intraday variables and use them to test hypotheses that relate minute-by-minute changes in volatility to measurable financial factors, macroeconomic conditions, and trader behavior that reflect underlying fundamentals like risk aversion and aggregate wealth or consumption.

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 (2003) 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.

Information relevant to financial markets goes beyond prices and news flow. Trading volume, order flow imbalances, liquidity, and other measures can reflect private information, information processing, liquidity, and other forces. While private information may not be very significant for the index-related securities that we study (Subrahmanyam, 1991), private information features in much finance literature, ranging from early formulations of market efficiency (Fama, 1965) to models of informed and liquidity-motivated traders (Kyle, 1985; Glosten and Milgrom, 1985; Admati and Pfleiderer, 1988). Order flow imbalances reveal private information for stocks (Hasbrouck, 1991; Berry and Howe, 1994), foreign exchange (Evans and Lyons, 2008), and Treasury bonds (Brandt and Kavajecz, 2004; Green,

1 See Schwert (1989). R-squared coefficients in his Table XII, for example, range from 2% to 20%.

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

2004; Pasquariello and Vega, 2007; Jiang and Lo, 2011). An even more basic element of financial markets is liquidity. Organized markets can add value by lowering the cost of rebalancing portfolios. In particular, market makers provide immediacy and absorb intertemporal imbalances in order flow. Volume, buy-sell imbalance, and the bid-ask spread allow us to study important aspects of trading activity such as the direction and scale of trade, the cost of trading, and the workings of the market's microstructure.

Beyond news, securities returns and trading activity, another potential contributor to stock price volatility is sentiment among market participants. Theoretical models in which investor utility does not depend only on future consumption can yield excessively volatile stock returns (Barberis, Huang, and Santos, 2001). The noise trader model of De Long et al (1990a) 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 two ideas from the finance literature to motivate highfrequency proxies for sentiment. First, the model of De Long, Shleifer, Summers, and Waldmann (1990b) includes noise traders who follow positive feedback trading strategies motivated by extrapolative expectations or trend-chasing.[4] Second, Lee, Shleifer, and Thaler (1991) suggest that small investor sentiment is reflected in trading of closed-end funds, though this interpretation is not without controversy.[5] Therefore, our third set of explanatory variables measures several dimensions of investor sentiment based on the ideas in these papers.

We organize explanatory variables and econometric specifications around several predictions, and then apply them 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 approximate 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

[3] 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.

[4] For an empirical application, see Choe, Kho, and Stulz, (1999).

[5] Klibanoff, Lamont, and Wizman (1998) interpret the closedend fund discount as a sentiment indicator with the reaction to news arrival, though this 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.

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 out-of-the-money put and call options and approximates 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 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 and is increasingly common in empirical work. 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, its volatility risk premium (VRP), defined as the difference between risk neutral volatility 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. 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 between public news, measures of securities returns and trading activity, proxies for noise trading, and risk neutral 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 minute-by-minute changes in VIX.

Our findings offer new insights into the forces reflected in minute-by-minute changes in this key market indicator. In particular, the evolution of VIX and its correlation with other variables suggests significant roots in both trading behavior and economic fundamentals, in addition to leverage and risk premium effects. Put another way, VIX is often thought of as a state variable in research and in financial news outlets, but our results remind us that changes in VIX reflect even more basic forces.

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 ideas for subsequent work.

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 several testable propositions. They are not mutually exclusive, but serve to formalize predictions about associations between VIX and 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

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.

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

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, the risk neutral volatility embedded in index option prices reflects the expected volatility of macroeconomic conditions. Bekaert, Hoerova, and Lo Duca (2011) document significant monthly associations between VIX and measures of monetary policy and macroeconomic conditions. We hypothesize that macroeconomic news surprises 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.

We make additional specific predictions about the Eurodollar futures rate of price change. Short-term interest rates reflect expectations of monetary policy actions and their consequences in addition to the business cycle, aggregate wealth and consumption, risk aversion, and other fundamentals:

> 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.

Put another way, the relationship between changes in VIX and changes in the price of Eurodollar futures depends on whether monetary easing signaled by lower short-term interest rates increases or reduces uncertainty.

Third, VIX is perceived by practitioners as both a price for portfolio insurance and a measure of fear (Whaley, 2000; 2009):

> H2: Changes in hedging demand and optimism or pessimism reflected in asset prices and trading are correlated with changes in VIX.

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

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. Thus, changes in VIX are positively correlated with changes in the price of gold and buy-sell imbalances for gold. H2 also implies a flight-to-quality effect: changes in VIX are negatively correlated with changes in short term interest rates.[10] Furthermore, credit default swap spreads are the price of protection against corporate distress and are positively correlated with changes in VIX. When optimistic (pessimistic) noise traders following positive feedback trading strategies dominate the stock market, positive (negative) index returns followed by heavy buying (selling) are associated with declines (increases) in VIX. If small investors pay premiums for closed-end funds even though perfect substitutes are available, their markets reflect irrational optimism 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.

Finally, VIX equals the weighted midpoint price of a portfolio of options. Therefore, the time-series behavior of VIX reflects the behavior of participants in the S&P500 options market. In particular, the market microstructure literature suggests how market maker behavior can affect prices:

> H3: Negative serial correlation in VIX changes reflects liquidity provision and rises with the costs, risks, and constraints faced by market makers.

In theoretical models such as those of Grossman and Miller (1988) and Nagel (2012), market makers respond to demand for immediacy, buying securities when other traders want to sell and selling when other traders want to buy. This induces negative serial correlation in price changes. Negative serial correlation is more severe if the costs, risks, and constraints of market making rise because of weaker liquidity provision in response to demand for immediacy.

There are overlaps and ambiguities among our predictions but our data can help to resolve some of them.[11] For example, expected ineffective monetary policy, H1c, appears identical to the flight-to-quality dimension of H2. However, the funding of traders affects securities market liquidity (Brunnermeier and Pedersen, 2009) and monetary easing, whether effective or ineffective in achieving its broader goals, can increase funding for securities market liquidity provision. Therefore, under expected ineffective (effective) monetary policy, H1c (H1d), changes in VIX are negatively (positively) correlated with changes in short-term interest rates and changes in bid-ask spreads. In

9 For a summary of fundamental and sentiment influences on gold, see "Gilt-edged argument: The battle to explain the remorseless rise of the bullion price", *The Economist* 28th April 2011. See also Bessembinder (1992), Bailey and Chan (1993), and Pukthuanthong and Roll (2011).

10 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.

11 Some overlaps are difficult to untangle (for example, Baker and Stein (2004) on sentiment and liquidity).

contrast, under the flight-to-quality dimension of H2, changes in VIX are negatively correlated with changes in short-term interest rates but positively correlated with changes in bid-ask spreads.[12]

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.[13] While H0 and H1 encompass both uncertainty and risk aversion, H2 is more focused on risk aversion. 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.[14]

2.2 Data

The time period we study is January 2005 to the end of June 2010. 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. We purchase these 15-second ticks from the Chicago Board Options Exchange's Market Data Express service. 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. We construct a minute-by-minute series by taking the closest 15-second value prior to the beginning of each minute.

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.[15] SPY returns represent broad movement in

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12 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) or the solvency of large traders (Brunnermeier and Pedersen, 2005; Carlin, Lobo, and Viswanathan, 2007).

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

14 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.

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

stock prices and, more broadly, the market's estimate of changes in future 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).[16]

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[17]) 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.[18] Both futures series are purchased through www.tickdata.com.

Finally, given the importance of the ongoing global credit crisis, 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.[19] 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 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 absolute value of the standardized announcement surprise (actual minus forecast, all divided by standard deviation of surprise; see Andersen et al 2003; 2006) is computed for 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

[16] 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.

[17] See http://www.cmegroup.com/trading/interest-rates/stir/eurodollar_contract_specifications.html.

[18] 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.

[19] The 5 year CDS is the most liquid 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.

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. We also control for days of heavy public news flow as follows. Baker, Bloom, and Davis (2012) construct a daily index of economic policy uncertainty news from ten major US newspapers. We download their series from www.policyuncertainty.com. Lucca and Moench (2012) note an apparently large equity market risk premium earned on days prior to Federal Open Market Committee announcements. We collect the dates of these announcements from their Table 1. Our FOMC dummy variable equals 1 for all one-minute periods in the day prior to an announcement and zero otherwise.

Our second group of explanatory variables is based on trade and quote information following the work of many previous authors. They include SPY trading volume, the price-setting or aggressive buy-sell imbalance of SPY, and the bid-ask spread of SPY. These series are computed from the trade and quote information on the TAQ database. 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 and buy-sell imbalance GLD, thereby allowing us to measure associations with this key indicator.[20] An additional measure of market conditions is changes in bid-ask spreads for the CDX NAIG index.[21]

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,) are not feasible for our purposes.

To proxy for stock market sentiment directly with returns and trading activity, we start with the positive feedback trader notion of De Long et al (1990b). If noise traders observe positive S&P500 returns and this induces optimism, they respond with heavy buying, and the product of the SPY buy-sell imbalance at interval t and the SPY return at interval t-1 is positive and large. This product is also positive and large if negative SPY returns induce pessimism and selling. Therefore, we construct two variables. Feedback+ is the product times a dummy variable equal to one if the lag of the SPY return is positive and zero otherwise, and Feedback- is a similar variable for cases when the lag of the SPY return is less than or equal to zero. Given shorting constraints (Antoniou, Doukas, and Subrahmanyam, 2012) and our predictions about sentiment and VIX (H2), the size and sign of the positive feedback trading effect can depend on the sign of the market return that precedes it.[22]

[20] 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.

[21] 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.

[22] These variables reflect both explicitly irrational trading and automated strategies like portfolio insurance.

Specifically, we expect optimistic positive feedback in a rising market to coincide with declines in VIX and pessimistic positive feedback in a declining market to coincide with increases in VIX.[23]

Our proxies for positive feedback trading reflect many types of noise trading including portfolio insurance, index futures arbitrage, and speculative trend-following. They also aggregate the behavior of all traders ranging from institutional professionals to behaviorally-biased individuals. To focus more specifically on small investor sentiment, 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,[24] 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. Given the mimicking portfolio weights, we compute the intraday returns of the portfolio.[25] 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)}. We also construct the price-setting buy-sell imbalance for the previously-identified portfolio, CEF. It indicates whether the small investors who typically trade closed-end equity funds investors are net buyers or sellers.[26]

In addition to 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.[27] 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.[28] Their construction parallels what has been described previously for common stock closed-end funds sentiment measures.

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23 We tested trading rules triggered by values of Feedback- and Feedback+ that exceed one or two standard deviations. Returns for holding periods of one to thirty minutes are tiny compared to bid-ask spreads, suggesting that following these rules is irrational, and market makers can profit from accommodating short horizon positive feedback traders. Results are available upon request.

24 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%).

25 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.

26 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.

27 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%.

28 The mimicking portfolio for gold sentiment measures is computed with all CRSP stocks from SIC codes 1041 (gold ores), 1044 (silver ores).

2.3 Methodology

2.3.1 Measuring the Variance Risk Premium

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 [29] 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 approximates the price of a variance swap (Carr and Wu, 2006, page 15). Thus, VRP can be thought of as the variance swap rate risk premium.[30]

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:[31]

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

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

$$RV_{t-NT,t} = \{\sum_{n=1}^{NT} f_{t-NT+n}^2\} \times 12 \tag{1c}$$

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

29 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.

30 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.

31 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).

of squared VIX. We follow Carr and Wu (2009) and estimate the forward price using the cost-of-carry model.[32] 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, 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:

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

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):

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

where:

[32] 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).

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

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:

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

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:

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

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:

$$OJ_t = \max\{ f_{t1\_last,t2\_first}^2 , 0\} \quad (2f)$$

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:

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

This, in turn, is subtracted from VIX squared as in (2a) to produce an estimate of the variance risk premium, VRP_Jump, which accounts for the effect of jumps on realized quadratic utility.[33] 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:

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

ΔVIX_t is the change in the VIX implied volatility index from the close of intraday interval t-1 to t.[34] 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 absolute value of the surprise 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. 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

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[33] 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).

[34] 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.

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 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. We exclude overnight intervals in computing the feedback measures, and overnight periods are not included in OLS or VAR regressions. 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, price changes of SPY, the Eurodollar futures price, gold, and the CDX index) are replaced with zero.[35]

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, Summed absolute news surprise, which sums 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 contains.

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

35 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.

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).

Table 5 presents the Pearson correlation matrix for 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). VIX and its risk premium decline as the gold price and gold ETF buy-sell imbalance increase, rejecting H2. The positive correlations of changes in VIX and VRP (but not VRP_Jump, which displays a negative correlation) with changes in the CDX credit spread suggests commonalities in equity and corporate debt pricing, while negative correlations with Summed absolute news surprise suggest that macro announcements resolve uncertainty (H1b). Positive correlations of VIX, VRP, and VRP_Jump with Feedback- and negative correlations with Feedback+ indicate VIX increases with pessimistic positive feedback trading and decreases with optimistic positive feedback trading (H2). Associations with the small investor 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 (Grinblatt and Keloharju, 2000). 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 between 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.

Table 6 presents results of varimax factor analysis applied to the independent variables the full 2005 to June 2010 sample. 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.

Given eigenvalues of principal components of one or greater, we present results for seven factors. We label the first factor “equity direction” given its large positive weight on SPY return, SPY buy-sell imbalance, and Feedback+. It explains almost 12% of total variance. The second factor explains almost 10% of total variance and has large positive weight on SPY and GLD volumes and the daily policy uncertainty news index. We refer to it as the “trading” factor. We refer to the third factor as “gold direction” given strong positive loadings on GLD return and buy-sell imbalance. The fourth 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 fifth factor is “macro conditions” given large negative weight on Eurodollar futures return and large positive weight on Summed news surprise. 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 sixth 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. The seventh factor has large positive weight on the SPY bid-ask spread change and the FOMC daily dummy. 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 first factor, "equity direction".

We also compute factor analysis for the sub-sample which includes the CDX NAIG credit swap spread series and bid-ask spread change series. Results are available upon request. The first, third, fourth, seventh, and eighth factors parallel the "equity direction", "trading", "gold direction", "gold sentiment", and "equity sentiment" 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". The fifth factor has particularly high weight on summed absolute news surprise, daily policy uncertainty index, and daily FOMC dummy so we label it "News". The sixth factor is complicated but its largest loading is on the Eurodollar futures rate of change so we label it "interest rate". As was the case for the full sample, 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 discuss sub-period results that 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 19.06%. The change in VIX displays statistically significance, decaying negative autoregressive terms that range from -0.2765 at the first lag to -0.0328 at the fifth lag. The coefficients sum to -0.7154, thus, more than two-thirds of a change in VIX is reversed within five minutes. Slopes on the SPY return are significantly negative and sum to about -1.60 from the contemporaneous to the fifth lag. Based on typical corporate leverage, French, Schwert, and Stambaugh (1987) informally argue that an elasticity of volatility with respect to stock return of less than minus one is not consistent with the leverage effect and, thus, suggests a risk premium 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 0.1554 percent in VIX, though negative slopes on lags indicate that this more than fully reverses within several minutes (the sum of coefficients is -0.7243 which an unreported exclusion test indicates is significantly different from zero).[36] The Eurodollar futures price rises as the Eurodollar yield declines. Thus, VIX rises when short-term interest rates decline, but reverses quickly and, on net, declines.[37] This suggests that expected monetary easing reflected in lower euro-deposit rates leads (almost immediately) to declines in risk neutral volatility, H1d.

Among the coefficients on Summed absolute news surprise, the contemporaneous effect is negative (suggesting resolution of uncertainty, H1b) but the first lag is significantly positive (suggesting increased uncertainty, H1a) and the coefficients from lags 0 to 5 sum to 0.0064, which an unreported exclusion test indicates is not significantly different from zero. Given that this sum is economically and statistically insignificant, VIX changes around macroeconomic news releases can be thought of as temporary price effects (see, for example, Holthausen, Leftwich, and Mayers; 1990) .

Table 7 also shows that the slope on the contemporaneous gold futures return is relatively small, -0.0209, but statistically significant and, in contrast to findings for Eurodollar and Summed news surprise, does not reverse sign over the course of five minutes. The negative sign is not consistent with the hypothesis, H2, that gold is a hedge or fear indicator that is positively correlated with VIX. The signs and sizes of coefficients on SPY and GLD trading volume indicators are not easy to interpret. Coefficients on Feedback- are uniformly positive except for insignificance at lag 4. Coefficients on Feedback+ are significantly negative except for lag 3. This suggests that positive feedback trading heightens risk neutral volatility when the S&P500 has declined and dampens risk neutral volatility when the S&P500 has risen.[38] Under H2, this suggests that this form of noise trading is associated with optimism in a risking market and pessimism or fear in a declining market.

Coefficients for the equity and gold small investor sentiment proxies are typically insignificant, although 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. SPY bid-ask spread coefficients are insignificant.

Table 8 shows regression results for changes in the simple 1-minute volatility risk premium, VRP. On many dimensions, the results for VRP are qualitatively similar to those for VIX in Table 7. The adjusted r-squared is 20.72%, and we note strong but diminishing negative autocorrelation, significant negative slopes for the SPY return, the gold futures price change, and Feedback+, a significant

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36 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 decrease (approximately 100 basis points) in yield. Therefore, the sum, -0.7243, of slopes on the Eurodollar futures price change implies VIX declines by about 0.7243% within five minutes of a 100 basis point decline in the Eurodollar yield .

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

38 Using an early sample of program trades, Harris, Sofianos, and Shapiro (1994) find that these trades have only a very small impact on intraday volatility, which suggests that our feedback variables are measuring something more than automated trading strategies.

positive slope on Feedback-, and significant reversal patterns in coefficients for Eurodollar futures returns and Summed absolute news surprise. Thus, a decrease in the Eurodollar yield is, after a minute, associated with a statistically signification cumulative decline in VRP which is consistent with H1d. As was found for VIX, the sum of coefficients on Summed absolute news surprise is not significantly different from zero.

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 buy-sell imbalances that indicate increased VRP when SPY buying pressure 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 0.6895 in VRP and subsequent increases of 0.6764 at one minute and 0.3863 at two minutes. Among small investor sentiment proxies, a few coefficients are statistically significant though economically small.

Table 9 presents similar regression results for the VRP_Jump risk premium. Recall that this measure of the volatility risk premium controls for the possibility that forecast volatility is overestimated due to infrequent jumps and, therefore, the risk premium is underestimated. 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 most variables. There are also much larger associations with gold futures returns and SPY volume for component of stock market risk in particular. Thus, variance risk premium effects are stronger when jumps are more carefully factored into the calculation of VRP.

3.2.2 Robustness Checks

We also estimated single-equation regressions 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. The CDX related variables are interesting because they reflect the uncertainty and risk premium of potential corporate default, and trading is dominated by institutional investors rather than small investors. Results are available on request. 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. Comparing sub period results for VIX to the full sample results in Table 7, coefficients for Eurodollar futures return and summed absolute news surprise are larger, but the reversal pattern remains. The coefficients on the CDX spread suggest that an increase in the cost of credit risk protection is associated with an eventual increase in VIX two to five minutes later. Comparing sub period results for VRP to full sample results in Table 8, the sign reversal in coefficients for Eurodollar futures return and Summed absolute news surprise remains. Increases in CDX spread precede increases in VIX (H2). Furthermore, unlike findings for VIX itself, VRP rises within a minute of increases in the CDX bid-ask spread. Finally, sub period results for VRP_Jump include sign reversals for coefficients on Eurodollar futures, CDX spread rises preceding

VIX increases, and, unlike findings for VRP, insignificant coefficients for CDX bid-ask spread changes and negative slopes on second and third lags of SPY bid-ask spreads.

To further check robustness, we re-estimated the specifications reported in Tables 7 through 9 and unreported tables 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

To this point, Tables 7, 8, and 9 display the predicted leverage or volatility feedback effect, additional patterns we attribute to positive feedback trading, responses to Eurodollar yields consistent with monetary easing, temporary price effects at times of macroeconomic news releases, and strong negative serial correlation in VIX changes that suggests liquidity provision. Our previous OLS regression specifications treat VIX or VRP as endogenous and all other explanatory variables as exogenous. Given, however, the likelihood that many conditions across markets are jointly determined and the time-series properties of the variables are complex, we next present estimates of systems of equations to accommodate the associations between the variables. Specifically, we estimate VAR models to measure associations between variables more exhaustively.

Table 10 summarizes results for VIX over 1-minute intervals over the full sample period. Echoing previous tables, we find diminishing negative autoregressive effects for VIX, significant, persistent negative association of VIX with lagged SPY price changes and Eurodollar futures price changes, and large positive lagged associations with Summed absolute news surprise.

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, the Cholesky decomposition offers a view of contemporaneous associations among the variables. Most of the Cholesky coefficients are at least several 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), Summed absolute news surprise (H1b), and buy-sell imbalances for SPY, GLD, the closed-end equity fund portfolio CEF (rejects H2), the gold fund ASA (H2), and Feedback+. Other coefficients suggest particularly significantly positive contemporaneous associations for changes in VIX with Eurodollar futures prices, the CEF price premium, and Feedback-. When we compare the sign of the Cholesky coefficient to the signs of the VAR slope coefficients, the reversal patterns for Eurodollar returns and Summed absolute news surprise as uncovered in single equation regressions is evident, as is reversal in VIX changes related to SPY and GLD buy-sell imbalances, Feedback-, and Feedback+.

We also estimate (results available upon request) 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 except for the following. First, there is a significantly positive effect of the CDX spread change that extends to several lags. That is, VIX rises 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. Second, there is a negative slope on the CDX bid-ask spread at lag 1, indicating that VIX tends to rise a minute after CDX illiquidity declines.

Table 11 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), VAR coefficients and the Cholesky for "equity direction" make sense (H0). As with earlier results, negative coefficients on "gold direction" are not the sign we expected (reject H2). Some significantly positive slopes for lags of "gold sentiment" make sense (H2), while positive signs on "equity sentiment" suggest contrarian trading. "Equity liquidity" appears negatively correlated with VIX changes at lags 0 and 1 but switches sign at lag 4. This factor is dominated by positive weight on the SPY bid-ask spread so the negative correlation of "Equity Liquidity" with VIX changes at lags 0 and 1 means VIX rises when SPY trading is more liquid. "Trading" switches sign twice across the five lags. The reversal effect for the Eurodollar and news surprises seen in earlier results is also evident in the Cholesky and lagged VAR coefficients for "macro conditions". The results for changes in VRP (Panel B) and VRP_Jump (Panel C) are qualitatively similar to those for VIX.

Figure 3 presents impulse response functions related to the VARs of Table 11. 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. The shapes of some of the lines in the plot also echo the finding of reversals in VIX responses indicated in the OLS and VAR parameter estimates.

3.4 Further Analysis of the Negative Serial Correlation of VIX

Previous results show that negative autocorrelation that rapidly decays is a prominent feature of the high-frequency behavior of changes in the VIX index. Our testable hypothesis, H3, indicates that negative serial correlation reflects liquidity provision and is more severe when liquidity provision is relatively costly.[39] With this in mind, Table 12 explores what drives this serial correlation and, in particular, whether there is any evidence consistent with a liquidity provision theory for negative serial correlation. We estimate non-linear regressions 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:

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[39] Persistence or clustering of volatility can also be caused by gradual incorporation of information or dispersion in beliefs of traders, though this appears to weaken in intraday data (Andersen and Bollerslev, 1997).

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

Estimates of this specification reveal how VIX's time-varying autocorrelation relates to our explanatory variables. H3 suggests a particular interpretation for such associations: the variables proxy for the underlying forces affecting the willingness of index option market makers to provide liquidity.

The left side of the table presents results using the news, returns, trading, and sentiment variables. The constant component of the slope on changes in VIX, -0.20828 (t=-92.66) indicates the baseline of very significant negative serial correlation, that is, a tendency of VIX changes of one sign to be followed by VIX changes of the other sign. It is roughly the same size as the first-order serial correlation in the OLS regression in Table 7, -0.2765.

The significantly positive slope (0.12453, t=15.38) on the term for the first lag of SPY return times the first lag of VIX change indicates that positive S&P500 index returns are associated with reduced negative serial correlation of VIX, as is also the case for increases in SPY volume (0.07062, t=47.82). Under H3, these findings are consistent with liquidity provision in the S&P 500 options market rising as returns and trading volume rise in the SPY basket market.

The significant positive slope on SPY bid-ask spread (1.68194, t=75.82) indicates that negative serial correlation of VIX weakens when SPY becomes less liquid, which is consistent with liquidity provision rising in the option market when trading costs rise in the SPY basket market. Increases in the SPY buy-sell imbalance are associated with heightened (-0.0519, t=13.66) negative serial correlation of VIX changes. This is consistent with liquidity provision declining in the options market when there is heavy buying pressure in the SPY market. While a comprehensive explanation for these last two findings is beyond the scope of this paper, they do suggest that trading activity (including liquidity provision) can cross between markets, at times increasing in one while decreasing in the other.

The negative slope on the Eurodollar futures price change indicates that a decline in the Eurodollar yield is associated with deepening negative serial correlation of VIX changes. The relationship between VIX changes and the Eurodollar deposit rate documented in Table 7 and other earlier tables and viewed with H1d suggests that expected monetary easing permanently lowers risk neutral volatility within several minutes. However, this monetary easing does not appear to enhance the ability of market makers to provide liquidity, as indicated by more severe negative serial correlation.

Increases in gold futures prices or Summed absolute news surprise are also associated with heightened negative serial correlation of VIX changes. If higher demand for a hedge, gold, and the arrival of macroeconomic news surprises are associated with increased risk and raise the cost of market making, H3 interprets these findings as reflecting weaker liquidity provision.

Among noise trading indicators, positive slopes on Feedback+ and Feedback- indicate greater positive feedback trading of SPY is associated with reduced negative serial correlation in VIX. Under H3, this implies that market makers provide more liquidity provision to the index options market when positive feedback trading in SPY is heavy, possibly to hedge their positions in the SPY market or because liquidity provision at times of significant positive feedback trading of SPY is profitable. The findings for some of the small investor noise trading variables can also be interpreted in light of liquidity provision. Negative serial correlation in VIX changes deepens with increases in the gold closed-end fund premium (increased fear, H2, impedes liquidity provision, H3) but lessens with small investor sentiment towards equities (CEF-NAV return spread and buy-sell imbalance).

The right side of the table presents results based on the seven factors detailed in Table 6. Regression results suggest a comparable baseline level of serial correlation, -0.21639, relative to what is reported for the regression with variables not factors. Other coefficients show that serial correlation is more negative (and, under H3, liquidity provision is lessened) with larger values of the gold direction, gold sentiment, and equity liquidity factors, and is less negative (suggesting more liquidity provision) with larger values of the equity direction, trading, equity sentiment, and macro conditions factors. Given the composition of the factors (Table 6), the regression findings of Panel B for factors are broadly similar to the findings of Panel A for the variables.

4. Summary and Conclusions

While stock index volatility is an important factor for capital markets and the economy generally, there is still much to be learned and explained. Zhou and Zhu (2012) note that how "volatility and volatility risk premiums…are determined by institutional trading and by the real economy and how to incorporate them into a general equilibrium model are all open questions". Our paper describes and interprets associations between economically-intuitive factors and risk neutral expected variance and its components. Our high-frequency approach reveals new facets of the relationship between stock volatility and more basic trading conditions and economic forces. While it is increasingly common to see VIX used as an explanatory variable in empirical studies, our work reminds researchers, practitioners, and anyone who follows the VIX that this popular indicator has roots in more fundamental forces.

Beyond confirming that leverage or volatility feedback effects appear in high frequency data, associations between VIX and price, trading, and sentiment indicators suggest a variety of influences. Like any financial market price, VIX combines fundamental factors and by-products of the trading process. Macroeconomic conditions are important to VIX, as is liquidity provision suggested by negative serial correlation of VIX changes and temporary price effects at times of macroeconomic news announcements. A surprising finding is that not all indicators of hedging demand or "fear" are identical: changes in VIX are negatively correlated with changes in the price of gold,[40] although some

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

other gold-related indicators suggest that some investors flee to gold when ex ante stock volatility is high.

The power of proxies for small investor sentiment to explain changes in VIX is very small. Therefore, it is tempting to conclude that investor sentiment, psychology, or “animal spirits” are only minor contributors to minute-by-minute aggregate stock market volatility. However, the explanatory power of the Feedback- and Feedback+ variables is substantial. If invoking De Long et al (1990b) to motivate these variables as proxies for noise trading is appropriate, the results for the feedback variables suggest a significant psychological component to VIX changes.

By taking the question of what drives volatility to minute-by-minute data, we highlight elements of the trading process such as volume and direction, noise trading, small investor sentiment, and market making. This suggests a number of directions for further research on VIX. First, more attention can be paid to untangling fundamental forces, such as how sentiment is related to liquidity (Baker and Stein, 2004) or to under-reaction or over-reaction to news (Barberis, Shleifer, and Vishny, 1998). Second, retail stock traders contribute to stock return volatility (Brandt, Brav, Graham, and Kumar, 2010; Foucault, Sraer, and Thesmar, 2011). Therefore, an additional approach to small investor sentiment and VIX is implied by Kumar (2009), who finds that “lottery type” stocks tend to attract behaviorally-biased individual investors. The pricing and trading of these stocks can correlate with VIX changes in ways that reveal more of a small investor sentiment effect than we report. Finally, given trades and quotes for S&P500 options trading, future research can more thoroughly document the associations between trading conditions and changes in the VIX index.

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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. FOMC{-1,0} and Policy have maximum observations because a value is generated for each interval in each day. Feedback- and Feedback+ have slightly more observations than components SPY price rate of change and SPY price-setting buy-sell imbalances because missing values are filled with zeros. Observations are also lost due to early NYSE closing prior to several holidays and excluding the overnight period from computations of certain variables.

	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
Summed absolute news surprise				
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
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
Feedback-	542899	1419	108,715	148
Feedback+	542899	1419	108,715	148
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
SPY bid ask change	537,815	5,599	107.623	1,365
CDX bid ask change	26,028	147,917	20,811	14,508
FOMC{-1,0}	544318	0	108863	0
Policy	544318	0	108863	0

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, “sp” spread between two return series, “feedback” positive feedback trading proxied by SPY return(t-1) times SPY imb(t), and “feedback+” is feedback times dummy for SPY return(t-1)>0. *, **, 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	Summed absolute news surprise	SPY volume	SPY imbalance	GLD Volume
ΔVIX	0.882***	0.835***	-0.167***	0.023***	-0.024***	0.024***	-0.005***	0.001	-0.086***	0.003**
ΔVRP		0.954***	-0.142***	0.018***	-0.023***	0.014***	-0.003**	-0.006***	-0.051***	-0.003**
ΔVRP_Jump			-0.127***	0.014***	-0.029***	-0.005**	-0.004***	-0.027***	-0.049***	-0.019***
SPY return				-0.064***	0.087***	-0.183***	0.005	0.006***	0.361***	-0.004***
Eurodollar ret					0.004***	0.002	-0.002	0.005***	-0.037***	0.000
Gold return						-0.001	-0.003**	-0.002	0.050***	-0.015***
ΔCDX spread							0.0001	-0.001	-0.006**	0.002
Summed absolute news_surprise								0.039***	0.001	0.014***
SPY volume									0.009***	0.272***
SPY imbalance										0.004***

Panel B:

Variable	GLD imbalance	Feedback-	Feedback+	CEF-NAV spread	ASA-NAV spread	CEF imbalance	ASA imbalance	SPY bid-ask change	CDX bid-ask change	Policy	FOMC
ΔVIX	-0.010***	0.093***	-0.094***	0.021***	0.003**	0.038***	0.003**	0.001	-0.031***	-0.0003	0.0006
ΔVRP	-0.008***	0.088***	-0.080***	0.017***	0.002	0.021***	0.002	0.002	-0.027***	-0.00005	0.001
ΔVRP_Jump	-0.008***	0.0848***	-0.084***	0.014***	0.002	0.021***	0.003*	0.003**	-0.029***	-0.001	0.0005
SPY return	0.036***	-0.304***	0.343***	-0.063***	0.001	-0.186***	-0.016***	0.002*	0.085***	-0.001	-0.001
Eurodollar ret	-0.002	0.027***	-0.027***	0.015***	0.002	0.018***	0.000	-0.001	-0.007***	-0.0008	-0.0008
Gold return	0.253***	-0.031***	0.034***	0.012***	0.057***	-0.026***	-0.180***	0.000	0.003	-0.0016	-0.0019
ΔCDX spread	-0.002	0.007	-0.010***	-0.010***	0.003	0.000	-0.001	0.002	-0.493***	0.003	-0.001
Summed absolute news_surprise	-0.001	0.001	0.002	0.0004	-0.0001	0.0008	-0.001	0.001	0.004	-0.001	-0.002
SPY volume	-0.029***	0.035***	0.062***	0.002	0.002	-0.018***	0.013***	0.001	-0.002	0.378***	0.006***
SPY imbalance	0.037***	-0.375***	0.383***	-0.027***	0.002*	-0.549***	-0.020***	-0.002	0.003	0.003	-0.002

Panel C:

Variable	GLD imbalance	Feedback-	Feedback+	CEF-NAV spread	ASA-NAV spread	CEF imbalance	ASA imbalance	SPY bid-ask change	CDX bid-ask change	Policy	FOMC
GLD volume	-0.032***	0.006***	0.011***	0.002	0.001	-0.020***	0.019***	-0.001	0.002	0.222***	0.007***
GLD imbalance		-0.018***	0.015449707	0.008***	0.022***	-0.020***	-0.726***	-0.001	0.005**	-0.031***	-0.001
Feedback-			-0.001	0.202***	0.008***	-0.010***	-0.009***	0.003	-0.019***	0.008***	0.001
Feedback+				-0.206***	-0.007***	0.010***	0.007	-0.0027	0.008	0.016***	-0.001
CEF-NAV sp					0.004***	0.025***	-0.006***	-0.001	0.009***	-0.045***	0.002
ASA–NAV sp						-0.002	-0.008***	0.003**	-0.001	0.013***	-0.0001
CEF imbalance							0.012***	0.001	0.001	-0.052***	0.001
ASA imbalance								0.000	-0.001	-0.015***	-0.002
SPY bid-ask change									-0.002	0.00002	6.34E-6
CDX bid-ask change										-0.001	0.003
Policy											0.023***

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 for the January 2005 – June 2010 period.

	Factor						
	1	2	3	4	5	6	7
Factor characteristics:							
Eigenvalue (principal component)	1.9951872	1.6052237	1.2515026	1.0147823	1.00639805	1.00415483	1.0006417
Variance explained	0.1174	0.0944	0.0736	0.0597	0.0592	0.0591	0.0589
Cumulative variance explained	0.1174	0.2118	0.2854	0.3451	0.4043	0.4634	0.5222
Loadings on:							
SPY return	0.77496	-0.01044	-0.04938	-0.01247	0.01153	0.00418	0.00807
Eurodollar return	-0.11979	0.00631	0.05681	0.30957	-0.31038	0.05811	-0.17557
Gold return	0.18451	-0.09383	0.75396	-0.03484	0.00196	-0.09539	0.0043
Summed absolute news surprise	0.00386	0.06536	0.00421	0.17991	0.61308	-0.03721	0.10526
SPY volume	0.03295	0.76898	0.1022	0.06408	0.04868	-0.0134	-0.00889
SPY imbalance	0.79666	-0.0009	-0.10589	0.06539	-0.06175	0.00867	-0.01677
GLD volume	0.01025	0.63252	0.04737	0.01909	-0.02457	0.05965	0.01289
GLD imbalance	0.12879	-0.15443	0.73327	-0.07066	0.01802	-0.18375	0.00055
Feedback-	-0.57249	0.0795	0.11142	0.12354	0.30235	-0.2042	-0.09531
Feedback+	0.5918	0.0917	-0.06826	0.1987	0.21939	-0.18767	-0.11912
SPY bid-ask spread change	-0.00261	0.00563	0.00311	-0.06205	0.21384	0.07249	0.79385
CEF-NAV return spread	-0.10986	-0.00403	0.122	0.60499	-0.2766	0.0617	0.00824
ASA –NAV return spread	0.02372	-0.00674	0.25594	0.03664	0.02335	0.5443	0.06353
CEF imbalance	0.03933	-0.10328	-0.02945	0.66396	0.09825	-0.04439	0.19871
ASA imbalance	0.03668	-0.05227	0.08445	0.01282	0.15002	0.75081	-0.10415
Policy	0.01596	0.73929	0.10142	-0.05906	-0.08694	0.01618	0.00117
FOMC	-0.00261	0.00563	0.00311	-0.06205	0.21384	0.07249	0.79385
Correlation with:							
ΔVIX	-0.16895	0.00395	-0.01647	0.02091	-0.00238	-0.00926	-0.0047
ΔVRP	-0.13831	0.0011	-0.01413	0.01768	-0.00477	-0.00458	-0.00446
ΔVRP_Jump	-0.13847	-0.00476	-0.01551	0.01581	-0.00513	-0.00797	-0.00427

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		-0.2765***(0.000)	-0.1963***(0.000)	-0.1392** (0.000)	-0.0706***(0.000)	-0.0328***(0.000)
SPY price rate of change	-0.5050***(0.000)	-0.4419***(0.000)	-0.2542***(0.000)	-0.1892***(0.000)	-0.1279***(0.000)	-0.0761***(0.000)
Eurodollar futures price rate of change	0.1554***(0.003)	-0.2651***(0.000)	-0.2113***(0.000)	-0.1073 **(0.043)	-0.2593***(0.000)	-0.0367(0.474)
Gold futures price rate of change	-0.0209***(0.000)	-0.0180***(0.000)	-0.0025(0.379)	-0.0066 **(0.023)	0.0010(0.726)	0.0006(0.833)
Summed absolute news surprise	-0.0244***(0.000)	0.0180***(0.000)	-0.0003(0.945)	0.0059(0.160)	0.0015(0.727)	0.0057(0.177)
SPY volume	-0.0009 **(0.017)	-0.0031***(0.000)	-0.0000588	0.0069***(0.000)	0.0007(0.104)	-0.0012***(0.002)
SPY price-setting buy-sell imbalance	0.0036***(0.000)	0.0050***(0.000)	0.0028***(0.000)	0.0001(0.850)	0.0022***(0.000)	0.0000(0.930)
SPY bid-ask spread change	0.0010(0.778)	-0.0011(0.814)	0.0026(0.611)	-0.0011(0.825)	0.0010(0.836)	-0.0018(0.620)
GLD volume	0.0049(0.178)	0.0135***(0.000)	0.0027(0.476)	-0.0102***(0.007)	-0.0021(0.574)	-0.0082 **(0.024)
GLD price-setting buy-sell imbalance	0.0005*(0.058)	0.0003(0.297)	0.0000(0.992)	0.0000(0.941)	-0.0001(0.578)	-0.0000268
Feedback-	0.0730***(0.000)	0.1257***(0.000)	0.0472***(0.000)	-0.0163(0.117)	0.0689***(0.000)	0.0253***(0.004)
Feedback+	-0.0607***(0.000)	-0.0643***(0.000)	-0.0366***(0.001)	0.0281***(0.007)	-0.1051***(0.000)	-0.0246***(0.007)
CEF – NAV return spread	0.0003***(0.000)	0.0000(0.577)	0.0000(0.850)	0.0000(0.897)	-0.0001(0.193)	0.0000(0.725)
ASA – NAV return spread	0.0000(0.774)	0.0002***(0.002)	0.0000(0.738)	0.0002***(0.000)	0.0002***(0.000)	0.0002***(0.002)
CEF price-setting buy-sell imbalance	-0.0008***(0.000)	0.0000(0.855)	0.0003(0.137)	-0.0000294	-0.0000316	-0.0004 **(0.032)
ASA price -setting buy-sell imbalance	-0.0005(0.103)	0.0004(0.200)	0.0000(0.952)	0.0000(0.904)	0.0001(0.832)	-0.0001(0.775)
FOMC {-1,0} daily dummy	0.0006(0.421)					
Daily policy uncertainty news index	0.0000***(0.001)					
Adjusted R-squared	19.06%					

Table 8. Regression of Changes in 1-Minute S&P 500 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	-	-0.3605***(0.000)	-0.2756***(0.000)	-0.1770***(0.000)	-0.1039***(0.000)	-0.0481***(0.000)
SPY price rate of change	-21.1500***(0.000)	-20.3707***(0.000)	-13.5004***(0.000)	-9.7474***(0.000)	-6.6692***(0.000)	-4.1136***(0.000)
Eurodollar futures price rate of change	0.4520(0.870)	-16.6638***(0.000)	-12.4962***(0.000)	-6.2860 **(0.027)	-15.5560***(0.000)	-1.2805(0.641)
Gold futures price rate of change	-1.3810***(0.000)	-1.4307***(0.000)	-0.1522(0.322)	-0.5846***(0.000)	-0.0898(0.557)	-0.0762(0.616)
Summed absolute news surprise	-0.5068 **(0.024)	0.5044 **(0.024)	0.0561(0.802)	0.1381(0.537)	0.1506(0.501)	0.1974(0.378)
SPY volume	-0.1390***(0.000)	-0.2513***(0.000)	-0.0805***(0.000)	0.3672***(0.000)	0.0584***(0.006)	-0.0551***(0.007)
SPY price-setting buy-sell imbalance	0.6895***(0.000)	0.6764***(0.000)	0.3863***(0.000)	0.1582***(0.000)	0.2239***(0.000)	0.0538***(0.005)
SPY bid-ask spread change	0.0616(0.755)	-0.0594(0.815)	-0.0572(0.836)	-0.2043(0.459)	-0.0002(0.999)	-0.0791(0.689)
GLD volume	-0.0249(0.898)	0.7346***(0.000)	0.1424(0.479)	-0.4103 **(0.041)	-0.2126(0.287)	-0.4207 **(0.030)
GLD price-setting buy-sell imbalance	0.0461***(0.000)	0.0290 **(0.027)	0.0124(0.342)	0.0024(0.854)	-0.0002(0.987)	-0.0067(0.606)
Feedback-	8.5637***(0.000)	11.9527***(0.000)	4.6413***(0.000)	1.0532*(0.058)	3.9408***(0.000)	0.9058*(0.054)
Feedback+	-8.0687***(0.000)	-8.8930***(0.000)	-5.8722***(0.000)	-0.0908(0.871)	-7.5983***(0.000)	-2.3154***(0.000)
CEF – NAV return spread	0.0070***(0.006)	-0.0021(0.419)	0.0002(0.938)	-0.0011(0.661)	-0.0073***(0.004)	-0.0033(0.184)
ASA – NAV return spread	-0.0078***(0.005)	0.0043(0.122)	-0.0056 **(0.046)	0.0106***(0.000)	0.0088***(0.001)	0.0088***(0.001)
CEF imbalance	-0.0344***(0.001)	0.0038(0.725)	0.0142(0.185)	-0.0173(0.105)	-0.0213 **(0.046)	-0.0249**(0.020)
ASA imbalance	-0.0048(0.752)	0.0178(0.241)	0.0064(0.676)	-0.0012(0.940)	0.0039(0.796)	-0.0104(0.494)
FOMC {-1,0} daily dummy	0.0394(0.358)					
Daily policy uncertainty news index	0.0001(0.187)					
Adjusted R-squared	20.72%					

Table 9. Regression of Changes in Volatility Risk Premium with Jumps (VRP_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	-	-0.2972***(0.000)	-0.2109***(0.000)	-0.1169***(0.000)	-0.0577***(0.000)	-0.0219***(0.000)
SPY price rate of change	-47.9629***(0.000)	-42.3125***(0.000)	-25.2076***(0.000)	-16.0706***(0.000)	-9.0965***(0.000)	-4.9045***(0.000)
Eurodollar futures price rate of change	-9.8953(0.123)	-47.8840***(0.000)	-19.4941***(0.003)	-0.0604(0.993)	-22.0741***(0.001)	7.1510(0.261)
Gold futures price rate of change	-3.3855***(0.000)	-3.1231***(0.000)	-0.0974(0.786)	-1.4321***(0.000)	-0.5802(0.103)	-0.7662**(0.030)
Summed absolute news surprise	-1.4851***(0.004)	0.9636*(0.065)	-0.0664(0.899)	0.1210(0.817)	0.2116(0.685)	0.3511(0.501)
SPY volume	-0.7731***(0.000)	-0.7540***(0.000)	-0.1850***(0.000)	0.8300***(0.000)	0.0554(0.266)	-0.1366***(0.004)
SPY price-setting buy-sell imbalance	1.6017***(0.000)	1.4074***(0.000)	0.6667***(0.000)	0.1195 **(0.010)	0.2893***(0.000)	0.0519(0.247)
SPY bid-ask spread change	0.1237(0.788)	-0.1525(0.795)	-0.8762(0.172)	-1.4471**(0.024)	-0.6954(0.236)	-0.6010(0.190)
GLD volume	0.2618(0.564)	2.0728***(0.000)	0.5625(0.231)	-0.7187(0.125)	0.0692(0.882)	-0.3572(0.429)
GLD price-setting buy-sell imbalance	0.0891***(0.003)	0.0454(0.137)	0.0053(0.863)	-0.0110(0.718)	-0.0255(0.403)	-0.0337(0.268)
Feedback-	16.6344***(0.000)	21.0987***(0.000)	1.4506(0.262)	-6.2405***(0.000)	3.0542 **(0.018)	1.3892(0.204)
Feedback+	-20.8786***(0.000)	-21.8596***(0.000)	-15.1379***(0.000)	-0.3132(0.810)	-17.3811***(0.000)	-6.9541***(0.000)
CEF – NAV return spread	0.0234***(0.000)	-0.0005(0.933)	0.0067(0.266)	0.0003(0.960)	-0.0132 **(0.026)	-0.0021(0.727)
ASA – NAV return spread	-0.0316***(0.000)	-0.0062(0.342)	-0.0188***(0.004)	0.0193***(0.003)	0.0194***(0.002)	0.0164***(0.008)
CEF imbalance	-0.0671***(0.007)	0.0213(0.393)	0.0508 **(0.042)	-0.0321(0.198)	-0.0296(0.235)	-0.0444*(0.075)
ASA imbalance	-0.0237(0.500)	0.0539(0.127)	0.0220(0.535)	0.0068(0.849)	0.0207(0.559)	-0.0249(0.482)
FOMC	-0.0556(0.578)					
Policy	0.0029***(0.000)					
Adjusted R-squared	16.13%					

Table 10. 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)	-0.090***(0.000)	-0.040***(0.000)	0.1856	0.01143
SPY price rate of change	-0.689***(0.000)	-0.334***(0.000)	-0.214***(0.000)	-0.159***(0.000)	-0.145***(0.000)	-0.0218	0.000859
Eurodollar futures price rate of change	-0.53 7***(0.000)	-0.332***(0.000)	-0.164**(0.019)	-0.281***(0.000)	-0.096(0.163)	0.0001	8.57E-06
Gold futures price rate of change	0.002	0.002(0.553)	-0.003(0.402)	0.005(0.201)	-0.001(0.796)	-0.0026	0.000219
Summed absolute news surprise	0.015***(0.009)	0.000(0.831)	0.008(0.162)	-0.003(0.649)	0.005(0.361)	-0.0005	0.000118
SPY volume	-0.003***(0.000)	0.004(0.454)	0.007***(0.000)	0.002***(0.004)	-0.002***(0.000)	-0.0051	0.001939
SPY price-setting buy-sell imbalance	0.011***(0.000)	0.004***(0.000)	0.000(0.384)	-0.002***(0.000)	0.002***(0.002)	-0.0447	0.002858
GLD volume	0.048***(0.000)	0.014***(0.007)	-0.026***(0.000)	-0.008(0.129)	-0.010**(0.033)	-0.0001	9.33E-05
GLD price-setting buy-sell imbalance	0.001**(0.039)	0.000 (0.218)	0.000(0.806)	-0.000(0.680)	-0.000(0.776)	-0.0094	0.000718
Feedback-	-0.092***(0.000)	-0.044***(0.000)	-0.057***(0.000)	-0.20396**(0.000)	-0.022*** (0.070)	0.0016	0.000169
Feedback+	0.190***(0.000)	0.057***(0.000)	0.062***(0.000)	0.014 (0.258)	0.015 (0.231)	-0.0013	0.000273
CEF – NAV return spread	-0.000***(0.000)	-0.00017 (0.007)	0.000(0.371)	-0.000***(0.000)	-0.000***(0.001)	0.0558	0.011058
ASA – NAV return spread	0.000***(0.000)	0.000 (0.053)	0.000**(0.020)	0.000***(0.000)	0.000***(0.000)	-0.0163	0.010541
CEF imbalance	-0.000(0.869)	0.000 (0.586)	-0.000(0.116)	-0.000(0.580)	-0.000(0.106)	-0.0063	0.00099
ASA imbalance	0.000(0.361)	-0.000(0.252)	-0.000(0.604)	-0.000(0.847)	0.000(0.118)	-0.0035	0.000396
SPY bid-ask spread change	-0.003(0.593)	0.001(0.875)	-0.005(0.485)	-0.001(0.859)	-0.003(0.525)	0.0001	7.43E-05
Policy	-0.002***(0.000)	0.002***(0.000)	0.000***(0.000)	-0.000(0.016)	-0.000(0.016)	-0.0007	0.026065
FOMC	-0.247***(0.000)	0.272***(0.000)	-0.027(0.211)	-0.007(0.761)	0.011(0.491)	0.00004	7.54E-05

Table 11. 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	-0.231***(0.000)	-0.130***(0.000)	-0.090***(0.000)	-0.054***(0.000)	-0.024***(0.000)	0.151	0.011433
	Factor 1 equity direction	-0.020*** (0.000)	-0.008***(0.000)	-0.005***(0.000)	-0.003***(0.000)	-0.002***(0.000)	-0.169	0.012892
	Factor 2 trading	-0.001***(0.000)	0.001(0.199)	0.003*** (0.000)	0.000***(0.445)	-0.002***(0.000)	0.002	0.002125
	Factor 3 gold direction	-0.002***(0.004)	-0.001***(0.000)	-0.001***(0.001)	-0.000*(0.079)	-0.000(0.223)	-0.015	0.00357
	Factor 4 equity sentiment	0.002***(0.000)	0.001***(0.000)	0.001*** (0.000)	-0.000(0.509)	0.000(0.299)	0.021	0.00284
	Factor 5 macro conditions	0.001***(0.000)	-0.000**(0.014)	0.000 (0.627)	0.001***(0.002)	0.001***(0.001)	-0.002	0.002834
	Factor 6 gold sentiment	0.001***(0.000)	0.001* (0.058)	-0.000 (0.352)	-0.002***(0.000)	0.000*(0.080)	-0.007	0.005591
	Factor 7 equity liquidity	-0.001***(0.003)	-0.0004(0.078)	0.000 (0.650)	0.001***(0.001)	-0.000(0.133)	-0.007	0.002369
B.	ΔVRP	-0.272***(0.000)	-0.189***(0.000)	-0.113***(0.000)	-0.075***(0.000)	-0.040***(0.000)	7.0203	0.789509
	Factor 1 equity direction	-0.803***(0.000)	-0.381***(0.000)	-0.226***(0.000)	-0.065***(0.000)	-0.035***(0.000)	-0.139	0.016385
	Factor 2 trading	-0.137***(0.000)	-0.028(0.143)	0.217***(0.000)	0.032*(0.08)	-0.101***(0.000)	0.003	0.002386
	Factor 3 gold direction	-0.108***(0.000)	-0.035***(0.000)	-0.048***(0.000)	-0.017* (0.072)	-0.005(0.563)	-0.014	0.005209
	Factor 4equity sentiment	0.074***(0.000)	0.053***(0.000)	0.064***(0.000)	-0.016*(0.09)	0.007(0.487)	0.017	0.00336
	Factor 5macro conditions	0.017***(0.085)	-0.029***(0.000)	-0.003(0.782)	0.043***(0.000)	0.481(0.001)	-0.004	0.003287
	Factor 6 gold sentiment	0.026**(0.018)	0.062***(0.000)	-0.016(0.139)	-0.101***(0.000)	0.008(0.481)	-0.003	0.008255
	Factor 7 equity liquidity	--0.045**(0.001)	-0.003(0.801)	-0.010(0.369)	0.0428***(0.000)	-0.018(0.099）	-0.008	0.002884
C.	ΔVRP_Jump	-0.250***(0.000)	-0.162***(0.000)	-0.086***(0.000)	-0.042***(0.000)	-0.024***(0.000)	16.326	1.733499
	Factor 1 equity direction	-1.727***(0.000)	-0.162***(0.000)	-0.379***(0.000)	-0.116***(0.000)	-0.186***(0.000)	-0.136	0.014099
	Factor 2 trading	-0.584***(0.000)	-0.217***(0.000)	0.464***(0.000)	0.104**(0.019)	-0.121***(0.001)	0.006	0.002811
	Factor 3 gold direction	-0.262***(0.000)	-0.093***(0.000)	-0.133***(0.000)	-0.061***(0.006)	-0.045**(0.039)	-0.016	0.005025
	Factor 4 equity sentiment	0.097***(0.000)	0.049**(0.028)	0.087***(0.000)	-0.064***(0.004)	-0.007(0.731)	0.013	0.002926
	Factor 5 macro conditions	0.057**(0.012)	-0.0221(0.325)	0.026(0.249)	0.139***(0.000)	0.077***(0.001)	-0.004	0.003212
	Factor 6 gold sentiment	-0.017(0.485)	-0.165***(0.000)	-0.116***(0.000)	-0.278***(0.000)	-0.025(0.319)	-0.007	0.006993
	Factor 7 equity liquidity	-0.085***(0.001)	-0.01450(0.596)	-0.053**(0.045)	0.054**(0.047)	-0.071***(0.007)	-0.008	0.002708

Table 12. Regressions to Explain Conditional Autocorrelation of Changes in VIX Index

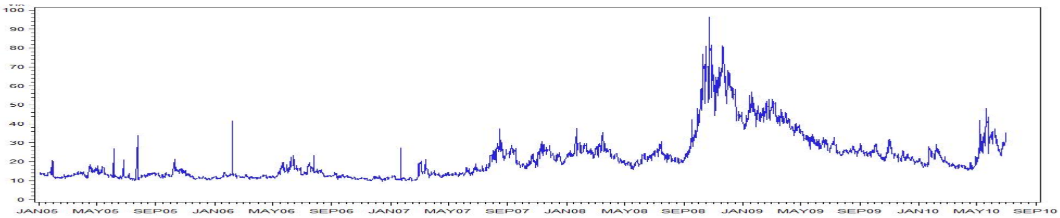
This table reports non-linear regressions of VIX changes on its first lag with a slope coefficient that depends on lags of either our explanatory variables or the factors constructed from those variables.

Conditioned on variables			Conditioned on factors		
Variable	Non-linear regression slope (t-statistic)		Factor	Non-linear regression slope (t-statistic)	
Intercept	-2.7283 E-4	-1.49	Intercept	-0.934 E-6	-0.05
ΔVIX	-0.20828	-92.66	ΔVIX	-0.21639	-132.89
SPY price rate of change	0.12453	15.38	1 equity direction	0.01075	16.38
Eurodollar futures rate of change	-1.45614	-7.03	2 trading	0.02618	40.04
Gold futures rate of change	-0.30955	-23.65	3 gold direction	-0.02584	-25.11
Summed absolute news surprise	-0.33586	-29.96	4 equity sentiment	0.01853	27.18
SPY volume	0.07062	47.82	5 macro conditions	0.00509	6.04
SPY imbalance	-0.0519	-13.66	6 gold sentiment	-0.04048	-35.73
SPY bid-ask spread change	1.68194	75.82	7 equity liquidity	-0.05216	-41.83
GLD volume	0.02847	1.30	-	-	-
GLD imbalance	0.06346	23.00	-	-	-
Feedback-	0.12326	15.44	-	-	-
Feedback+	0.0714	5.98	-	-	-
CEF – NAV return spread	0.00236	15.5	-	-	-
ASA – NAV return spread	-0.00423	-21.51	-	-	-
CEF imbalance	0.17811	96.17	-	-	-
ASA imbalance	0.0146	3.92	-	-	--
FOMC	0.10157	22.87	-	-	-
Policy	-0.0001907	-16.57	-	-	-
Adjusted r-squared	8.63%		Adjusted r-squared	4.50%	

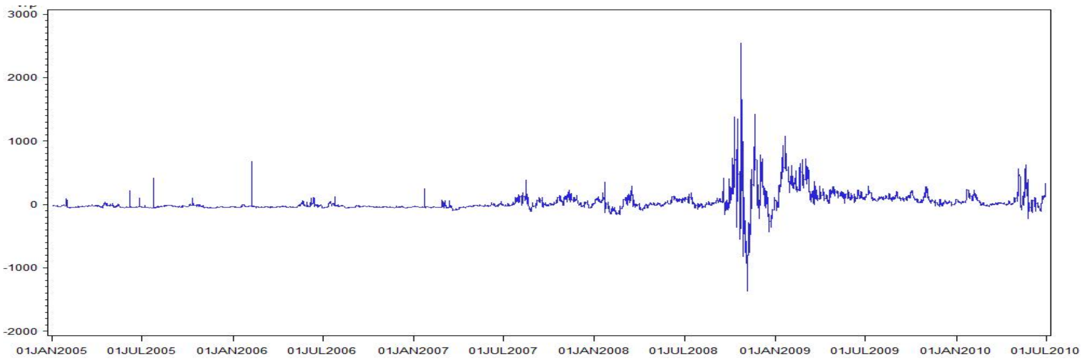
Figure 1. Intraday VIX and VRP at 1-Minute Intervals

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)



Panel C: VRP_Jump (in basis points)

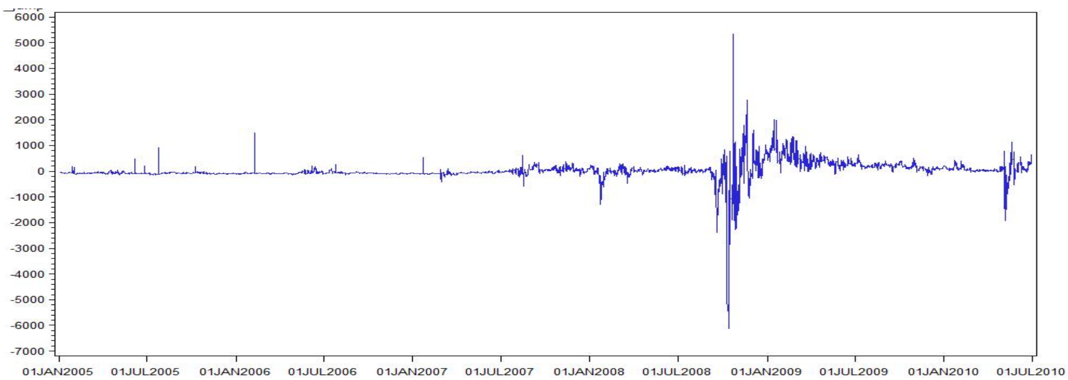


Figure 2. Average VIX Index at End of Each 1-Minute Interval during Trading Day

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

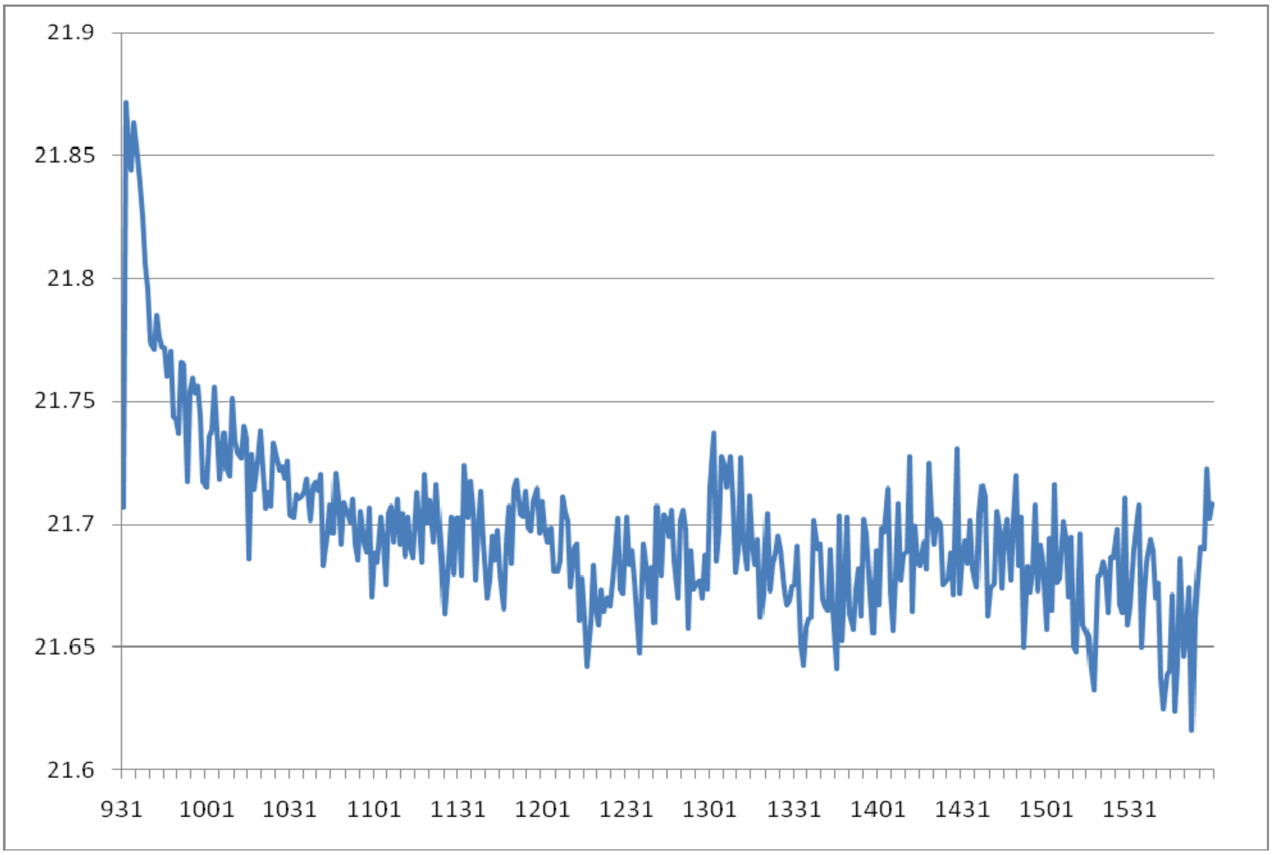
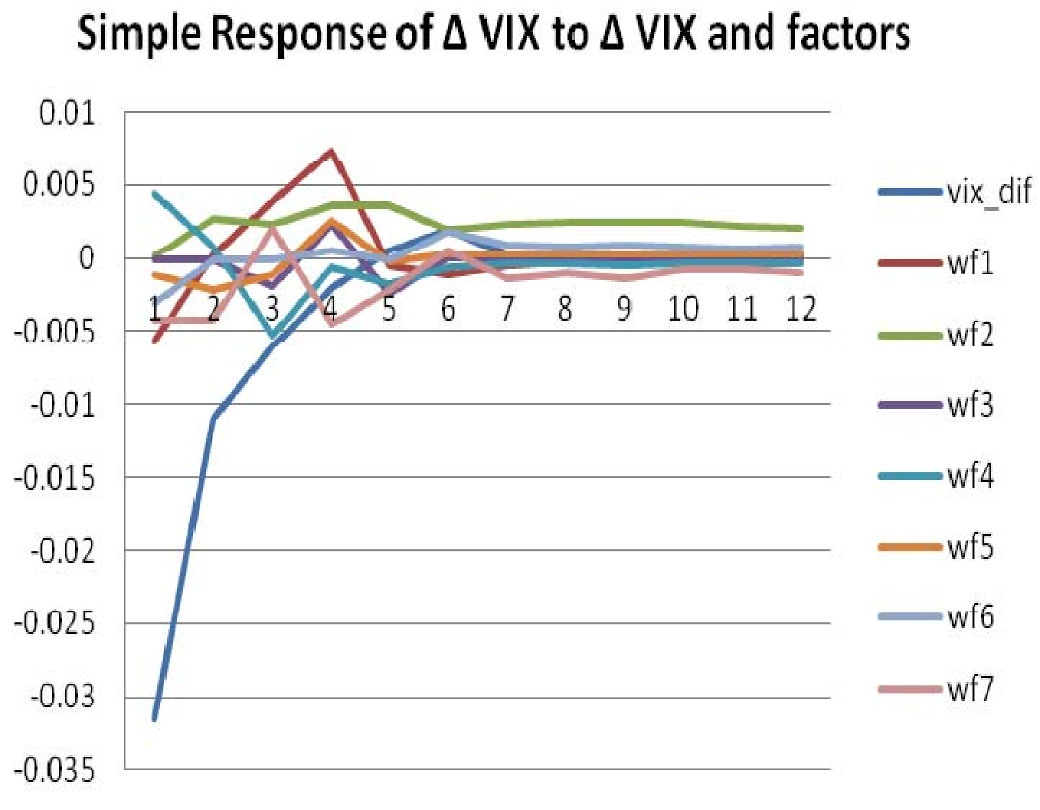


Figure 3. Impulse Response Plot for Changes in 1 Minute VIX and Factors

The factors numbered from 1 to 7 are equity direction, trading, gold direction, equity sentiment, macro conditions, gold sentiment, and equity liquidity. See Table 6 for details of their construction and Table 11 Panel A for the associated VAR estimate.



Supplement to Table 3. Summary Statistics on Explanatory Variables

Variable	Mean	Std	Min	Max	Skew	Kurt	Lag1	Lag60	LB Q (60)
SPY price rate of change	-0.000	0.07267	-6.95	5.09	-1.782	484.327	-0.01903	0.00767	1046.30
Eurodollar futures price rate of change	0.0000	0.00291	-0.424	0.216	-4.558	974.505	-0.17776	0.00099	9999.99
Gold futures price rate of change	0.000056	0.05202	-2.551	2.764	0.417	74.061	-0.02268	0.00134	488.05
SPY volume	0.3995	0.5356	0.0000	42.826	5.822	157.117	0.63388	0.34857	9999.99
SPY price-setting buy-sell imbalance	0.00187	0.4783	-1.000	1.000	-0.0086	-0.862	0.06336	0.00161	2725.56
SPY bid-ask spread change	0.0000	0.04935	-0.988	0.986	-0.0292	139.214	-0.49368	-0.00001	9999.99
GLD volume	0.0227	0.0477	0.000	4.864	13.510	567.721	0.45484	0.18812	9999.99
GLD price-setting buy-sell imbalance	0.0308	0.599	-1.000	1.000	-0.016	-1.046	0.09975	0.01918	9999.99
Feedback-	0.00049	0.018	-1.844	1.312	-0.288	662.081	0.01475	-0.00596	433.68
Feedback+	0.00064	0.0177	-1.409	1.458	4.476	477.294	0.02088	0.00100	604.85
CEF – NAV return spread	0.01217	3.14592	-812.768	258.904	-30.436	8851.929	-0.12456	0.00354	9962.31
ASA – NAV return spread	0.00666	3.109	-368.107	371.845	5.343	2999.860	-0.14547	0.00100	9999.99
CEF imbalance	-0.0152	0.708	-1.000	1.000	0.0329	-1.181	0.08577	0.03292	9999.99
ASA imbalance	0.00402	0.499	-1	1	0.00807	0.895	0.09296	0.01243	9999.99
FOMC	-0.0315	0.175	-1	0	-5.362	26.753	0.99735	0.84114	9999.99
Policy	105.974	80.404	9.390	551.655	1.800	4.289	0.99927	0.95636	9999.99

Supplement to Table 6. Factor Analysis for 30th September 2008 – June 2010 Period

	Factor							
	1	2	3	4	5	6	7	8
Factor characteristics:								
Eigenvalue (principal component)	2.17999	1.42896	1.411146	1.32966	1.026912	1.011785	1.008201	1.004907
Variance explained	0.1147	0.0752	0.0743	0.07	0.054	0.0533	0.0531	0.0529
Cumulative variance explained	0.1147	0.1899	0.2642	0.3342	0.3882	0.4415	0.4946	0.5475
Loadings on:								
SPY return	0.79273	-0.00851	0.08148	-0.18167	0.00604	-0.01377	0.01297	0.00077
Eurodollar return	-0.08045	-0.00754	-0.01079	0.04734	0.12408	0.56408	0.12685	-0.16577
Gold return	0.40738	-0.07434	-0.29827	0.64969	-0.02945	-0.00121	-0.08299	-0.00041
Summed absoluste new surprise	0.00431	0.02388	0.119	0.05922	0.47646	0.18664	-0.24479	-0.124
SPY volume	0.01767	0.10013	0.71156	0.32778	0.07352	-0.01606	-0.01663	-0.02087
SPY imbalance	0.79564	-0.00572	0.0756	-0.17097	-0.00488	0.05567	0.01423	0.02261
GLD volume	-0.00334	0.06805	0.46083	0.1749	0.1714	-0.00494	0.03626	-0.03054
GLD imbalance	0.32907	-0.06601	-0.33289	0.66726	-0.04891	0.01115	-0.14149	0.00204
Feedback-	-0.54104	-0.01033	0.05471	0.2494	0.20126	-0.23222	-0.21569	0.04702
Feedback+	0.56852	0.02695	0.23728	-0.12986	0.19747	-0.14482	-0.17594	0.05114
SPY bid-ask spread change	-0.01108	-0.01103	0.00901	0.00741	-0.04884	-0.6194	-0.03325	0.32922
CEF-NAV return spread	-0.10439	0.02137	-0.05462	0.14227	0.12332	0.265	0.14257	0.44543
ASA –NAV return spread	0.07019	-0.02354	-0.08634	0.26194	0.13788	-0.11683	0.4556	-0.06985
CEF imbalance	0.04917	0.01265	-0.01036	-0.03526	0.43184	0.11321	0.15817	0.67003
ASA imbalance	0.04228	0.00457	-0.04121	0.03275	0.25555	-0.25012	0.7046	-0.2878
ΔCDX spread	-0.02574	-0.83587	0.11656	-0.01562	-0.0007	0.01175	0.01094	0.00927
CDX bid-ask spread change	0.02626	0.83406	-0.12984	0.0193	-0.00885	-0.0113	-0.01108	-0.01169
Policy	-0.00359	0.08096	0.59246	0.28959	-0.29584	0.03611	0.08596	-0.00719
FOMC	-0.00144	0.02579	0.11389	0.03947	-0.53935	0.18892	0.26025	0.33409
Correlation with:								
ΔVIX	-0.19648	-0.01693	-0.03697	0.0044	-0.00518	0.00313	-0.0079	0.00678
ΔVRP	-0.15821	-0.01042	-0.03087	0.00062	-0.00723	0.00073	-0.00889	0.00649
ΔVRP_Jump	-0.15806	-0.01234	-0.02977	-0.00994	-0.00855	0.0035	-0.00907	0.00566

Supplement to Table 7. 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	-	-0.3153***(0.000)	-0.2537***(0.000)	-0.1597***(0.000)	-0.0903***(0.000)	-0.0363***(0.000)
SPY price rate of change	-0.5023***(0.000)	-0.4986***(0.000)	-0.3123***(0.000)	-0.2394***(0.000)	-0.1598***(0.000)	-0.0904***(0.000)
Eurodollar futures price rate of change	0.3652***(0.006)	-0.4660***(0.001)	-0.4262***(0.002)	-0.2142(0.112)	-0.6768***(0.000)	-0.1179(0.370)
Gold futures price rate of change	-0.0393***(0.000)	-0.0328***(0.000)	0.0048(0.489)	-0.0086(0.213)	0.0001(0.994)	0.0032(0.640)
CDX spread change	-29.6484(0.189)	28.4950(0.194)	53.4424**(0.013)	58.6920***(0.005)	254.6191***(0.000)	179.3259***(0.000)
Summed absolute news surprise	-0.0537***(0.000)	0.0406***(0.000)	0.0024(0.802)	0.0122(0.197)	0.0094(0.318)	0.0147(0.121)
SPY volume	-0.0024***(0.002)	-0.0076***(0.000)	-0.0016*(0.055)	0.0131***(0.000)	0.0017**(0.045)	-0.0016**(0.046)
SPY price-setting buy-sell imbalance	0.0138***(0.000)	0.0081***(0.000)	0.0034***(0.002)	-0.0013(0.234)	0.0038***(0.001)	-0.0018*(0.097)
SPY bid-ask spread change	0.0045(0.703)	-0.0026(0.865)	-0.0010(0.950)	-0.0200(0.231)	0.0020(0.898)	-0.0070(0.560)
CDX bid-ask spread change	0.3466(0.217)	0.1913(0.492)	0.2862(0.297)	0.2281(0.396)	0.2696(0.294)	0.0075(0.251)
GLD volume	0.0075(0.251)	0.0251***(0.000)	0.0058(0.389)	-0.0096(0.157)	-0.0065(0.336)	-0.0078(0.235)
GLD price-setting buy-sell imbalance	0.0020 **(0.015)	0.0012(0.149)	0.0004(0.636)	0.0000(0.974)	-0.0004(0.618)	-0.0001(0.923)
Feedback-	0.1311***(0.000)	0.1485***(0.000)	0.0572***(0.004)	-0.0504**(0.011)	0.0820***(0.000)	0.0135(0.423)
Feedback+	-0.1036***(0.000)	-0.0333*(0.099)	-0.0289(0.152)	0.0645***(0.001)	-0.1398***(0.000)	-0.0240(0.175)
CEF – NAV return spread	0.0004***(0.000)	0.0001(0.199)	0.0001(0.527)	-0.0001(0.377)	-0.0003**(0.012)	-0.0001(0.182)
ASA – NAV return spread	-0.0001(0.606)	0.0003**(0.024)	-0.0002(0.114)	0.0004***(0.001)	0.0003***(0.007)	0.0003***(0.003)
CEF price-setting buy-sell imbalance	-0.0017***(0.002)	-0.0001(0.834)	0.0010*(0.059)	-0.0009*(0.100)	-0.0008(0.138)	-0.0012**(0.026)
ASA price –setting buy-sell imbalance	-0.0012(0.117)	0.0007(0.389)	0.0007(0.371)	0.0001(0.868)	0.0005(0.550)	-0.0001(0.893)
FOMC	0.0007(0.754)					
Policy	0.0000(0.133)					
Adjusted R-squared	22.2%					

Supplement to Table 8. 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		-0.3825***(0.000)	-0.3008***(0.000)	-0.1956***(0.000)	-0.1169***(0.000)	-0.0536***(0.000)
SPY price rate of change	-26.4254***(0.000)	-26.8257***(0.000)	-18.3720***(0.000)	-13.5420***(0.000)	-9.1954***(0.000)	-5.6001***(0.000)
Eurodollar futures price rate of change	45.0581***(0.000)	0.0761(0.993)	-2.8417(0.736)	4.4419(0.598)	-29.7905***(0.000)	-0.2737(0.973)
Gold futures price rate of change	-2.5197***(0.000)	-2.4903***(0.000)	0.4553(0.293)	-0.8329*(0.054)	-0.1630(0.706)	0.0385(0.929)
CDX spread change	-1807.9374(0.198)	688.7241(0.613)	2760.6075**(0.038)	2673.0271**(0.040)	15376.0000***(0.000)	11524.0000***(0.000)
Summed absolute news surprise	-1.0443*(0.076)	1.3816**(0.019)	0.3922(0.504)	0.2713(0.644)	0.5658(0.336)	0.6343(0.280)
SPY volume	-0.2627***(0.000)	-0.5582***(0.000)	-0.1821***(0.001)	0.7334***(0.000)	0.1401***(0.008)	-0.0602(0.233)
SPY price-setting buy-sell imbalance	1.4061***(0.000)	1.2251***(0.000)	0.6580***(0.000)	0.2409***(0.000)	0.4513***(0.000)	0.0774(0.244)
SPY bid-ask spread change	0.1344(0.857)	-0.4554(0.634)	-0.8157(0.435)	-1.5149(0.147)	-0.2855(0.766)	-0.4602(0.536)
CDX bid-ask spread change	29.3764*(0.091)	29.2505*(0.094)	21.0615(0.224)	22.7713(0.183)	23.4544(0.161)	21.4727(0.179)
GLD volume	0.0062(0.988)	1.2597***(0.003)	0.2696(0.522)	-0.6106(0.146)	-0.4633(0.268)	-0.5244(0.197)
GLD price-setting buy-sell imbalance	0.1611***(0.002)	0.1078**(0.037)	0.0262(0.612)	0.0040(0.939)	-0.0074(0.886)	-0.0021(0.967)
Feedback-	9.3743***(0.000)	13.7646***(0.000)	4.3827***(0.000)	-0.3743(0.762)	4.9886***(0.000)	0.6939(0.506)
Feedback+	-8.3971***(0.000)	-7.7699***(0.000)	-5.2613***(0.000)	2.0365(0.105)	-10.6829***(0.000)	-2.8175**(0.011)
CEF – NAV return spread	0.0213***(0.002)	0.0093(0.182)	0.0084(0.224)	-0.0011(0.869)	-0.0163**(0.017)	-0.0086(0.198)
ASA – NAV return spread	-0.0183**(0.011)	0.0081(0.269)	-0.0178**(0.016)	0.0213***(0.004)	0.0177**(0.015)	0.0210***(0.003)
CEF price-setting buy-sell imbalance	-0.1097***(0.001)	-0.0050(0.880)	0.0478(0.153)	-0.0566*(0.091)	-0.0612*(0.067)	-0.0745 **(0.026)
ASA price –setting buy-sell imbalance	-0.0750(0.123)	0.0142(0.772)	0.0313(0.523)	-0.0071(0.885)	0.0220(0.655)	-0.0261(0.595)
FOMC	0.0666(0.608)					
Policy	0.0002(0.569)					
Adjusted R-squared	22.99%					

Supplement to Table 9. Subsample Regression of Changes in Volatility Risk Premium with Jumps (VRP_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		-0.3210***(0.000)	-0.2359***(0.000)	-0.1335***(0.000)	-0.0686***(0.000)	-0.0258***(0.000)
SPY price rate of change	-60.2675***(0.000)	-56.3090***(0.000)	-34.9447***(0.000)	-22.9447***(0.000)	-12.7807***(0.000)	-6.4554***(0.000)
Eurodollar futures price rate of change	58.4128***(0.002)	-59.4187***(0.002)	-10.7006(0.582)	23.0208(0.236)	-59.4302***(0.002)	3.9113(0.836)
Gold futures price rate of change	-6.4740***(0.000)	-5.5915***(0.000)	1.0861(0.279)	-2.4860**(0.013)	-1.6717*(0.094)	-1.5880(0.110)
CDX spread change	-4491.1279(0.168)	-132.2294(0.967)	11242.0000***(0.000)	5546.0395*(0.066)	28997.0000***(0.000)	20925.0000***(0.000)
Summed absolute news surprise	-2.5808*(0.058)	3.1936 **(0.019)	0.7073(0.604)	0.3430(0.801)	1.1365(0.404)	1.3633(0.316)
SPY volume	-1.2576***(0.000)	-1.5096***(0.000)	-0.3710***(0.003)	1.6854***(0.000)	0.1358(0.270)	-0.2020*(0.084)
SPY price-setting buy-sell imbalance	3.3689***(0.000)	2.6228***(0.000)	1.1597***(0.000)	0.1611(0.306)	0.6306***(0.000)	0.0703(0.647)
SPY bid-ask spread change	0.5077(0.767)	-0.8112(0.713)	-5.0616 **(0.036)	-7.3797***(0.002)	-3.1496(0.154)	-2.4945(0.146)
CDX bid-ask spread change	58.3640(0.147)	40.2487(0.320)	19.1569(0.633)	33.0164(0.404)	28.1332(0.468)	49.0381(0.185)
GLD volume	0.0722(0.939)	3.0120***(0.002)	0.4883(0.616)	-1.4438(0.138)	-0.6356(0.512)	-0.9456(0.315)
GLD price-setting buy-sell imbalance	0.3219***(0.007)	0.1853(0.122)	-0.0095(0.937)	-0.0303(0.800)	-0.0869(0.468)	-0.0519(0.664)
Feedback-	19.9416***(0.000)	25.5202***(0.000)	-0.7751(0.787)	-10.3673***(0.000)	4.3810(0.126)	1.5464(0.523)
Feedback+	-22.4914***(0.000)	-21.0634***(0.000)	-16.9998***(0.000)	2.0132(0.488)	-26.0518***(0.000)	-11.0573***(0.000)
CEF – NAV return spread	0.0642***(0.000)	0.0214(0.183)	0.0271*(0.092)	0.0017(0.918)	-0.0244(0.122)	-0.0026(0.864)
ASA – NAV return spread	-0.0718***(0.000)	-0.0149(0.379)	-0.0528***(0.002)	0.0388 **(0.023)	0.0416 **(0.014)	0.0391 **(0.018)
CEF price-setting buy-sell imbalance	-0.2168***(0.005)	0.0459(0.554)	0.1751 **(0.024)	-0.1056(0.173)	-0.0856(0.269)	-0.1327*(0.086)
ASA price –setting buy-sell imbalance	-0.1527(0.176)	0.0849(0.454)	0.1074(0.345)	0.0109(0.924)	0.0657(0.565)	-0.0901(0.429)
Adjusted R-squared	18.46%					

Supplement to Table 10. Coefficients from 1-Minute VAR Sub Period Regression Estimation

The table presents selected coefficients from a VAR in which ΔVIX and all other variables are 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)	-0.145***(0.000)	-0.088***(0.000)	-0.039***(0.000)	0.1856	0.019048
SPY price rate of change	-0.699***(0.000)	-0.357***(0.000)	-0.233***(0.000)	-0.172***(0.000)	-0.152***(0.000)	-0.0218	0.001677
Eurodollar futures price rate of change	-0.962***(0.000)	-0.471****(0.004)	-0.077(0.635)	-0.684***(0.000)	-0.179(0.263)	0.0001	1.53E-05
Gold futures price rate of change	-0.001(0.864)	0.019(0.028)	-0.009(0.314)	0.008(0.322)	0.00(0.469)	-0.0026	0.000462
CDX spread change	6.016***(0.000)	1.213***(0.000)	0.858***(0.000)	1.285***(0.000)	1.330***(0.000)	6.45E-6	3.39E-05
Summed absolute news surprise	0.038***(0.001)	0.000(0.993)	0.016(0.172)	0.002(0.863)	0.013(0.248)	-0.0005	0.000269
SPY volume	-0.008***(0.000)	-0.001(0.491)	0.015***(0.000)	0.002(0.013)	-0.003***(0.001)	-0.0051	0.004162
SPY price-setting buy-sell imbalance	0.022***(0.000)	0.006***(0.000)	-0.001(0.406)	-0.004***(0.001)	0.002*(0.099)	-0.0447	0.003914
CDX bid-ask spread change	-0.616**(0.038)	-0.246(0.411)	-0.053(0.859)	-0.214(0.474)	0.166(0.575)	-0.00001	1.99E-05
GLD volume	0.049***(0.000)	0.009(0.249)	-0.018(0.026)	-0.010(0.232)	-0.003(0.707)	-0.0001	0.000227
GLD price-setting buy-sell imbalance	0.001(0.553)	0.000(0.770)	-0.001(0.533)	-0.000(0.801)	0.000(0.816)	-0.0094	0.001081
Feedback-	-0.081***(0.000)	-0.032(0.115)	-0.097***(0.000)	-0.343***(0.000)	-0.054***(0.008)	0.0029	0.000567
Feedback+	0.252***(0.000)	0.045**(0.039)	0.113*** (0.000)	0.023(0.285)	0.03823*(0.074)	-0.0023	0.000334
CEF – NAV return spread	-0.000***(0.000)	-0.000(0.178)	-0.000(0.898)	-0.001***(0.000)	-0.000***(0.002)	0.0558	0.017975
ASA – NAV return spread	-0.000(0.578)	-0.000***(0.000)	-0.000(0.408)	0.000*(0.049)	0.000***(0.002)	-0.0163	0.015165
CEF imbalance	0.001(0.388)	0.001(0.177)	-0.001(0.368)	-0.000(0.626)	-0.001(0.175)	-0.0063	0.001664
ASA imbalance	0.000(0.905)	0.001(0.307)	-0.001(0.362)	0.001(0.455)	0.000(0.914)	-0.0035	0.000853
SPY bid-ask spread change	0.000(0.989)	-0.012(0.505)	-0.025(0.195)	0.003(0.871)	-0.009(0.540)	0.0001	0.000167
Policy	-0.002***(0.000)	0.002***(0.000)	0.000(0.038)	0.000***(0.000)	-0.000***(0.002)	-0.0007	0.044715
FOMC	-0.056(0.114)	0.089(0.074)	-0.052(0.301)	-0.016(0.747)	0.035(0.315)	0.00004	7.69E-05