Understanding and Trading the Term Structure of Volatility

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Abstract

We study the dynamics of equity option implied volatility. We show that the dynamics depend both upon the option's time to maturity (horizon) and slope of the term structure of implied volatility for the underlying asset (term structure). Furthermore, the interaction between horizon and term structure plays a crucial role in explaining the dynamics of volatility. For assets with similar term structure, dynamics are strongly dependent upon horizon. Similarly, for assets with a given horizon, the dynamics of volatility depend upon term structure. We propose a simple, illustrative framework which intuitively captures these dynamics. Guided by our framework, we examine a number of volatility trading strategies across horizon, and the extent to which profitability of trading strategies is due to an interaction between term structure and realized volatility. While profitable trading strategies based upon term structure exist for both long and short horizon options, this interaction requires that positions in long horizon assets be very different than the position required for short horizon assets.

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1 Introduction

We study the dynamics of volatility embedded in equity option prices across different maturities. Our focus is on how the dynamics of option implied volatility is related to the term structure of volatility in the cross section of equity options. We show that volatility dynamics depend both upon time to maturity (horizon) of options and slope of the implied volatility term structure for the underlying asset (term structure). Furthermore, the dynamics crucially depend upon an interaction between horizon and term structure: for assets with similar term structure, dynamics are strongly dependent upon horizon. For options with a given horizon, the dynamics of volatility depend upon term structure. In addition, we show that the relationship between implied volatility and *realized* volatility of the underlying stock depends upon horizon and term structure. This relationship between realized and implied volatility has implications for the volatility risk premia of individual stocks.

We contribute to a rapidly growing literature seeking to understand the term structure of risk prices. Van Binsbergen, Brandt, and Koijen (2012) and Van Binsbergen, Hueskes, Koijen, and Vrugt (2013) study the prices of market risk as measured by the Sharpe Ratios of claims to dividends on the market index at different horizons. These papers sparked a large interest in the idea that even though equity is a claim on cash flows over an infinite horizon, the risks associated with different horizons could be priced differently.[1] Shortly thereafter, Dew-Becker, Giglio, Le, and Rodriguez (2015), Aıt-Sahalia, Karaman, and Mancini (2014) and Johnson (2016) extended the idea of studying the term structure of prices of risk, examining market volatility prices at different horizons.[2] These recent papers all document a consistent finding across asset classes: for *unconditional* prices of risk associated with market expected returns and volatility, the longer the horizon over which the risk is measured, the smaller the magnitude of that risk's price. The consistency of findings across asset classes and types of risk (market and volatility) suggests something fundamental about investors' risk preferences over varying time horizons. However, most theoretical asset pricing models fail to explain these findings.[3]

While the majority of volatility and equity term structure papers focus on the unconditional properties of risk prices, little is known about the dynamics of implied volatility and its term structure. A small number of papers have examined trading strategies based upon the slope of the volatility term structure: Johnson (2016) shows that the slope of the VIX term structure predicts future returns to variance assets. Specifically, he finds that

[1]See Rietz (1988), Campbell and Cochrane (1999), Croce, Lettau, and Ludvigson (2008), Bansal and Yaron (2004), and Barro (2006).

[2]See also Cheng (2016).

[3]Barro (2006), Rietz (1988), and Gabaix (2008) are consistent with these findings.

slope negatively predicts returns: An upward-sloping curve results in negative returns on variance assets; a downward-sloping curve produces relatively higher, and in some cases positive, returns. Vasquez (2015) and Jones and Wang (2012) both examine the cross-sectional returns of short-term equity options straddles, conditioned on the slopes of each stock's volatility curve. They independently find that variations in slope predict returns for short maturity straddles. Interestingly, their findings suggest the relation between term structure and future straddle returns of individual options has the opposite sign as the relation shown by Johnson (2016) who uses index options: In the cross-section of equity options, term structure *positively* predicts returns of short-maturity straddles. An upward-sloping curve results in relatively *high* returns, and an inverted curve produces *low* returns. This difference between conditional returns to index and equity option straddles highlights the importance of separately studying equity and index options.

To the best of our knowledge, no papers in the literature study the evolution of implied volatility. In order to examine the relation between the dynamics of volatility and term structure slope, we require a large cross section of assets. For this reason, we use the cross section of options on individual names in our study. While not as liquid as index options in general, the market for individual options is large and relatively liquid. The large cross section provides a nice setting for our study because it allows us to examine the joint dynamics of short and long term volatility *conditional* on a firm's term structure slope. At any point in time, we can examine the dynamics among firms with a wide array of term structure slopes. This helps give us a better sense of how term structure affects implied volatility dynamics.

By examining the movement of equity option prices using both at the money (ATM) implied volatility and ATM straddle returns with one through six month maturities, we document the term structure dynamics. We find that the term structure inverts (becomes downward sloping) due largely to an increase in one month implied volatility as opposed to an increase in volatility of the underlying asset. Thus we find a strong relationship between slope of volatility term structure and volatility risk premia in short maturity options. Accordingly, we find that as the term structure inverts, the impact of realized volatility on the slope diminishes. Whereas the risk premia in one month options increase as term structure becomes inverted, the volatility risk premium for longer maturity options reverses as the curve steepens: we find a *decrease* in the risk premium for 6 month volatility as the term structure slope decreases (becomes more inverted). Surprisingly, the average volatility risk premia for 6 month options become negative for equities whose term structure curve has the lowest slope (is more inverted).

We propose a simple framework for understanding the dynamics which encapsulate our empirical findings. Based upon these insights, we then examine the returns to trading strategies using ATM straddles with maturities of one to six months. Consistent with prior research, we find economically and statistically significant negative returns, a loss of 11.85% per month, for short-maturity straddles when the slope is most negative. As the slope increases, we find the returns of the one month straddles monotonically increase. When examining the returns of two month straddles, the pattern, although weaker, persists. This pattern disappears in the three and four month maturity options. As we look at longer maturity options we again find a monotonic relation between returns and slope. However, in the longer maturity straddles we find a significant *decrease* in returns as slope increases. A six month portfolio with the most negative slope returns an average of 3.42% per month.

Our study contributes to three strands of recent literature. First, we contribute to the literature which examines the pricing of volatility in options.[4] Second, we contribute to a growing literature seeking to understand the cross sectional pricing of individual options returns.[5] Finally, our study extends the literature on the term structure of risk premia by improving our understanding of the dynamics of volatility across the term structure.

We differ from previous literature on returns in the cross section of options in that we study returns across a range of maturities.[6] Specifically we study how option (straddle) returns depend upon volatility term structure in the cross section and across maturities. We document that the relation between volatility term structure and future returns varies across maturities of the options we examine. While short maturity options exhibit a positive relation between term structure slope and subsequent returns, the longer maturity straddles exhibit a negative relation. This pattern is closely related to the implied volatility dynamics we uncover in the first part of our study.

Our study proceeds as follows. Section 2 describes the data and methodology for forming the portfolios. Section 3 examines the term structure dynamics, and in Section 4 we describe a framework based on our analysis and propose a number of trading strategies. Section 5 reviews the returns of these strategies which verify our analysis. Section 6 concludes.

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[4]Seminal studies include Coval and Shumway (2001), Bakshi and Kapadia (2003a), and Jackwerth and Rubinstein (1996)

[5]See Goyal and Saretto (2009), Bakshi and Kapadia (2003b), Cao and Han (2013), Vasquez (2015), Boyer and Vorkink (2014), and Bali and Murray (2013).

[6]See e.g. Bakshi and Kapadia (2003b), Boyer and Vorkink (2014), Bali and Murray (2013), Cao and Han (2013), and Goyal and Saretto (2009).

2 Data and Methodology

The OptionMetrics Ivy Database is our source for all equity options prices, the prices of the underlying equities, and risk-free rates. The Database also supplies realized volatility data and implied volatility surfaces which we use as a robustness check for our calculations of annualized realized volatility and slope of the volatility term structure, respectively. Our dataset includes all U.S. equity options from January, 1996 through August, 2015. We follow the Goyal and Saretto (2009) procedures in forming portfolios. The day following the standard monthly options expiration on the third Friday of each month, typically a Monday, we form portfolios of options straddles. On this date, we deem all options ineligible from inclusion in portfolios if they violate arbitrage conditions or the underlying equity price is less than $10. We then identify the put and call option for each equity, for each expiration from one to six months, which is closest to at-the-money (ATM), as long as the delta is between 0.35 (-0.35) and 0.65 (-0.65) for the call (put).[7] If, for each equity, for each expiration, both a put and call option exists which meets the above conditions, then a straddle for that equity for that expiration will be included in a portfolio. Since the procedure for the listing of equity options is not consistent in the cross section or over time, the number of straddles included across maturities will vary for each firm and over time, as will the number of straddles in each portfolio. While we include statistics for portfolios of options with maturities of one through six months, our study focuses on the performance of portfolios holding one month and six month options. Even though individual equity options are more thinly traded than index options, we only look at ATM options *and* by taking portfolio averages, we hope to mitigate issues which may arise due to illiquidity and noisy prices.

After identifying the ATM straddles eligible for inclusion, we form portfolios based on the slope of the implied volatility term structure. For all options, we use the implied volatilities provided by OptionMetrics.[8] We define the slope of the term structure as follows. On each formation date, the day following the standard options expiration, we identify for each equity the ATM straddle with the shortest maturity between six months and one year. We use the implied volatility of this straddle, defined as the average of the implied volatilities of the put and call, as the 6 month implied volatility. We use this measure, and the implied volatility of the 1 month straddle, to calculate the slope as determined by the percentage difference between the implied volatilities of the straddle, $\frac{1mIV}{6mIV} - 1$. When determining the slope of the term structure, we allow for the flexibility

[7] The deltas are also taken from the OptionsMetrics Database. Option deltas are calculated in OptionsMetrics using a proprietary algorithm based on the Cox-Ross-Rubinstein binomial model.

[8] As with the option deltas, the implied volatilities are determined in OptionsMetrics using a proprietary algorithm based on the Cox-Ross-Rubinstein binomial model.

of maturity in the six month measure due to the fact that for each month, an equity may not have six month options due to the calendar listing cycle to which an equity is assigned. The options of each equity are assigned to one of three sequential cycles: January, February, and March. Regardless of the cycle, options are listed for the first two monthly expirations.[9] Beyond the front two months, the expirations listed vary. For example, on the first trading day of the year, January and February options are listed for all equities. The next expirations listed for options of the January cycle are April and July, the first month of following quarters; for the February cycle, the next listings are May and August, the second month of the following quarters. Those equities in the March cycle find March and June options listed. Thus, in any one month, roughly 33% of equities list a 6 month option, with the remainder listing a 7 or 8 month option. In calculating the slope, we use the shortest maturity six months or longer, and so the slopes for any month actually include 1 month - 6 month, 1 month - 7 month, and 1 month - 8 month slopes. Using this measure each month for an equity, we place all eligible straddles for that equity into a decile and maturity bucket. Decile 1 holds straddles with the most upward-sloping term structure, or positive slope; decile 10 contains those with the most inverted, downward sloping, or negative slope. We view the returns of the portfolios across both decile and maturity to examine the interaction of the two. Consistent with Goyal and Saretto (2009), these portfolios are created the day following expiration; opening prices for the options, the midpoint between the closing bid and ask, are taken the day following portfolio formation. Typically, then, opening trades for the portfolios are executed on the close the Tuesday after expiration. For one month straddles held to expiration, closing prices are calculated as the absolute value of the difference between the strike price and the stock price on expiration. For one month options held for two weeks, the exit prices of the straddles used are the midpoint of the closing bid and ask prices two weeks from the prior expiration. For the two through six month straddles, the exit prices of the straddles are the midpoint of the bid and ask of the closing prices on the following expiration day. Over the period of January, 1996 through August, 2015, our analysis includes 924,952 straddles across all maturities, representing 7,076 equities. Using the implied volatilities of these straddles, we examine the dynamics of the term structure of equity options.

3 Term Structure Dynamics

[INSERT FIGURE 1 HERE]

[9] In addition, equities with the most heavily traded options may list additional expirations.

Figure 1 and Table 1 are the starting points of our analysis. The volatility risk premiums for all portfolios are reported in Table 1. Each month on the formation date, ATM straddles are sorted into portfolios on the basis of volatility term structure. For each straddle, the $VRP = \frac{IV-RV}{RV}$, where the realized volatility of the underlying is determined using daily returns over the lifetime of the options in question. This measure differs slightly from that typically used to quantify VRP in that we examine the ratio of option-implied volatility (IV) to realized volatility (RV). This measure removes biases that can arise due to underlying assets tending to have widely disparate volatilities in the cross section. This normalization of the risk premium of course is not necessary when studying volatility risk premia in the index because the underlying asset has a stable, mean reverting volatility process. In the cross section of stocks however, there is wide variation in volatility of the underlying. This necessitates such a normalization in order to avoid single firms contributing disproportionately to a portfolio's average implied volatility. Portfolio VRP is defined as the average VRPs of the equities within a portfolio. Figure 1 plots unconditional index and equity VRP, and VRP for each conditioned on term structure. While most of our analysis sorts equity options into ten portfolios cross-sectionally, we sort into five portfolios here to be consistent with our index sort. In order to conserve space within the figure, we plot only the two extreme quintiles' average volatility risk premia. For more detailed results, Table 1 reports monthly time series averages within all portfolios sorted into deciles based upon term structure.

Figure 1 depicts the VRPs over different maturities. The first figure plots the average index and equity portfolio VRPs. For all maturities, the VRPs for both index and equity are positive; the equity portfolio VRPs are positive for 1 through 5 month maturities, dipping slightly negative for the 6 month maturity (-0.02). This is consistent with a negative price of volatility and a positive volatility risk premium. It is well known that the volatility risk premium implied by index options is large and positive on average, while the premia for equities is smaller. This is seen as well: the equity portfolio VRP is less than that of the index. Unlike the index, the equity portfolio VRP is downward sloping: longer maturities carry a lower premium.

Figure 1 shows that the differences in the premia also depend upon the slope of the implied volatility term structure, similar to the analysis of Johnson (2016). When the *index* term structure is upward sloping (Quintile 1), the volatility risk premia is large across all maturities. When the term structure is inverted, the volatility risk premia inherent in the index is significantly smaller. For equities, however, the patterns are strikingly dissimilar to those found in the index. While the risk premia is large when the curve is upward sloping in the index, the portfolio measure is lower across all maturities for the equity portfolio. The largest premia for the individual equities is in the 1 month options with the most inverted term structure. This contrasts with the premia in the index where the inverted term structure corresponds to the smallest premia among the 1 month options. In Quintile 5, in the individual options, the average volatility risk premia are steeply decreasing in maturity. Surprisingly, the 6 month options with the most inverted term structure actually have a negative volatility risk premium on average. This of course contrasts with the commonly held assertion that investors are willing to pay a premium to avoid exposure to volatility risk. Figure 1 also shows that the individual and index volatility premia differ in that index premia tend to decrease as the term structure becomes more inverted, regardless of maturity. For the individual options, we see *increasing* premia as the term structure increases for the shorter maturity options and the pattern slowly reverses as maturity increases. For the 5 and 6 month options, the premia decrease as term structure becomes more inverted. The remainder of the paper aims to improve our understanding of the patterns depicted in Figure 1.

[INSERT TABLE 1]

Differences between implied volatility and realized volatility are approximate risk premia. Table 1 shows a nearly monotonic relationship across deciles for the 1 and 6 month maturities. All 1 month options portfolios exhibit large VRP. This is in line with the notion that investors are averse to bearing volatility and require a premium for bearing it. In the 1 month options, VRP is strongly increasing in term structure inversion. As the maturity increases, we see a gradual shift in the VRP pattern, as average VRP is virtually flat between deciles 1 and 10 for the 3 and 4 month options. In the 5 and 6 month options, the VRPs decrease in term structure inversion, and the 6 month implied volatilities of the equities with most inverted term structures (decile 10) actually exhibit a negative risk premium: -3.71% per month. A negative VRP corresponds to realized volatility exceeding implied volatility on average. This implies a positive price of volatility which is difficult to reconcile with economic theory and recent empirical work of Ang, Hodrick, Xing, and Zhang (2006), Rosenberg and Engle (2002) and Chang, Christoffersen, and Jacobs (2013).

[INSERT FIGURE 2]

While Figure 1 and Table 1 describe unconditional averages, our analysis focuses on the dynamics of term structure. In order to get a sense of how the term structure evolves, Figure 2 depicts the time series of average implied volatilities used in the construction of our measures of term structure slope. In order to conserve space, we only show the implied volatilities from the two extreme slope deciles: the average 1 month and 6 month implied volatilities for at-the-money options on stocks within the top and bottom 10 percent each month, as defined by $\frac{1mIV}{6mIV}$. In Panel A, we see that the 1 month implied volatility is always higher in the most inverted decile (10) than in the least inverted decile (1). Furthermore, the difference is significant over most of the sample. Panel B shows the time series of 6 month implied volatilities in deciles 1 and 10. While the 6 month implied volatility in decile 10 exceeds that of decile 1 on average, the two do not exhibit much of a spread through most of the sample. This suggests that most of the variation in term structure is driven by variation in the short maturity implied volatility. Both series exhibit spikes around the dot com crash of 2000 and the financial crisis of 2008. Panel C shows the slope of volatility term structure measured each month in the sample, for the two extreme deciles, and the slope of the S&P 500 Index. The Index term structure more closely follows that of Decile 1 over the entire period, but during spikes will approach the measure of Decile 10. The average implied volatility term structure slope does not exhibit the same pattern, suggesting that average volatility term structure is not simply a measure of market volatility.

[INSERT TABLE 2 HERE]

To understand how the distributional properties of implied volatility depend upon term structure and time to maturity, Table 2 reports the means, standard deviations, and skewness of the implied volatilities of the portfolios formed using the procedure described above. Each month, the day after the standard monthly expiration, ATM straddles are sorted into portfolios by maturity and the slope of the term structure. Decile 1 holds ATM straddles with the most upward sloping term structure; decile 10 holds straddles with the most inverted, or downward sloping term structure. Table 2 uses the average implied volatility each month of the ATM straddles to calculate these summary statistics. Thus, Panel A reports the average implied volatilities over time of the portfolio's average implied volatilities calculated each month; Panels B and C hold the standard deviation and skewness, respectively, over time of the portfolio's average implied volatilities calculated each month.

By separately measuring average means, standard deviations and skewness of each portfolios' implied volatility and by examining the measures for options of different maturities, we are able to get a clear picture of the strong patterns that exist in the term structure of implied volatilities. The far right column in each panel shows summary statistics when we aggregate all deciles. Similarly, the bottom row reports summary statistics for each decile of term structure slope when aggregated across all times to maturity.

In Panel A, if we look only at the column that aggregates across all deciles, we see that average implied volatility is monotonically decreasing in time to maturity. However, this column shows a relatively small spread in the average implied volatilities of about 2.6 percentage points. If we look across the decile portfolios however, we observe that the monotonic pattern is strongest in decile 10, the most negatively sloped term structure. The spread between the 6 month and 1 month average implied volatilities in the tenth decile is more than 12 percentage points, nearly 5 times the spread we see when we aggregate across deciles. Notice that in the extreme upward sloping decile, the spread is much smaller than in the extreme inverted decile. By construction decile 1 has higher 6 month average implied volatility than the 1 month. This pattern is also monotonic in time to maturity which is not a tautology.

Similarly, if average implied volatility is aggregated across all maturities, we see that portfolios of options with the most negatively sloped volatility term structure have higher implied volatilities on average. The difference is roughly 10.5 percentage points. However, by looking at the top row, it becomes clear that the spread is driven by the shorter maturity options. The spread in the 1 month options is approximately twice that of the aggregated spread we see in the bottom row. Furthermore, the spread is monotonically decreasing in maturity. This suggests that when we see inverted term structure, it tends to be driven by large increases in short term volatility as opposed to decreasing 6 month implied volatility. Interestingly, the 6 month average implied volatilities also increase as the term structure becomes inverted. Of course the increase is much larger for the 1 month options than for the 6 month options.

Panel B of Table 2 shows that time series standard deviations of annualized implied volatilities tend to be larger the more negative the slope. Furthermore, while average time series standard deviations tend to increase monotonically as time to maturity decreases, the spread between standard deviations of decile 10 and decile 1 is most exaggerated in the 1 month options. As in Panel A, this suggests that the driver of term structure is due to movement in the short term implied volatility. Importantly for trading strategies we will investigate in Section 5, the distribution of implied volatility tends to be positively skewed for all deciles and for all times to maturity. The skewness is largest for the most inverted term structures. Furthermore, the spread between skewness in decile 10 (inverted) and decile 1 (upward sloping) tends to be larger for short term options. The skewness patterns we've shown will be explicitly incorporated into our framework in Section 4 as they are central to understanding how one can implement trading strategies that exploit dynamics in the term structure curve.

[INSERT TABLE 3]

From the summary statistics, a picture begins to emerge as to how the term structure changes. Given the spread between deciles one and ten in the one month mean and standard deviation of implied volatility, the short end drives the term structure. Table 3 shows the time series relationship between percent changes in short term (1 month) implied volatility and long term (6 month) implied volatility. The changes in one month and six month volatilities are calculated for each firm, and then the changes are averaged within each portfolio. Table 3 reports the results of regressing the change in one month volatility on the change in six month volatility for each portfolio and for the entire sample:

$$\frac{IV_{i,t}^{1m}}{IV_{i,t-1}^{1m}} - 1 = cons_i + b_{6mIV,t}\left(\frac{IV_{i,t}^{6m}}{IV_{i,t-1}^{6m}} - 1\right) + \epsilon_{i,t}. \tag{1}$$

Across all deciles, we see highly significant loadings, $b_{6mIV,t}$. The loadings are all positive and in excess of 1 meaning that changes in 6 month implied volatility are associated with *larger* changes in 1 month implied volatility. We can think of 1 month implied volatility as exhibiting dynamics similar to a levered version of the 6 month implied volatility. There is a monotonic pattern to the relation between term structure inversion and regression coefficient $b_{6mIV,t}$, suggesting that the magnification of movements from 6 month implied volatility to 1 month implied volatility is increasing in term structure inversion. For the most inverted (tenth) decile, a one percent change in 6 month implied volatility is associated with a 1.734 percent change in 1 month implied volatility on average. While the two are highly correlated, we see much larger swings in implied volatility of 1 month options than in 6 month options. This is especially true in the decile of options with the most inverted term structures. Since we know from Table 2, the distributions of implied volatilities are positively skewed, this means that we tend to see small increases in 6 month implied volatilities and these are associated with larger increases in 1 month implied volatilities.

We see that the movements of 1 month implied volatility acts as the driver of the volatility spread. We then examine the average realized volatility of each portfolio for the period leading up to the formation date, as compared to the average implied volatility, to get a snapshot of the relationship between realized and implied volatility. While Table 1 measures the relationship between realized and implied volatility averaged over time, Table 4 examines the relationship between realized and implied volatility. In order to conserve space, we report the results for only the shortest (1 month) and longest (6 month) maturities in our sample. Each month, within each decile, the implied volatilities of the ATM straddles are regressed on the realized volatilities of the underlying, calculated using past daily closes over a fixed horizon. Each of the resulting monthly cross sectional regression coefficients are then averaged over the entire time series.

[INSERT TABLE 4 HERE]

We examine past horizons of 1 month and 1 year to determine the effects of long term and short term measures of past realized volatility on current implied volatility. For each firm, at each date we run the following regressions for short and long term realized volatility respectively:

$$IV_{i,t} = cons_i + b_{i,RV} RV_{i,t-1} + \epsilon_{i,t}, \tag{2}$$

$$IV_{i,t} = cons_i + b_{i,RV} RV_{i,t-12} + \epsilon_{i,t}, \tag{3}$$

where $IV_{i,t}$ and $RV_{i,t}$ denote implied and realized volatility of firm i at month t respectively. Table 4 averages the coefficients, standard errors, and R^2s of these regressions over the sample period within each decile. The regression coefficients from Equation (2) are positive and highly significant across all deciles, for both measures of realized volatility and for both maturities.

For 1 month implied volatility, Panel A shows that there isn't much variation in slope coefficients when we regress 1 month implied volatility on the previous month's realized volatility. While the slope coefficient generally decreases as the term structure becomes inverted, the variation in point estimates is not economically significant. The R^2 of each regression is shown to generally decrease in term structure inversion, however, most of this pattern can be attributed to the substantially smaller R^2 for decile 10 whereas little variation exists between the R^2s for the other 9 deciles.

Perhaps surprisingly, the coefficients reported in Panel B suggest that short maturity implied volatility is more sensitive to realized volatility measured over the previous year than it is to measures from the previous month. Furthermore, the sensitivities are monotonically increasing in term structure inversion suggesting that when the term structure is most inverted, short term implied volatility is most sensitive to long term measures of past volatility in the underlying. In addition to the larger coefficients, we also see that in univariate regressions, the proportion of variation explained by the long term measure of realized volatility exceeds that explained by the short term measure. This is contradictory to the common view that short maturity implied volatility is more sensitive to recent changes in realized volatility than it is to the longer term, more stable measure of realized volatility.[10]

Panels C and D of Table 4 report the results of regressing long term maturity implied volatility on the two measures of realized volatility. Again, all slope coefficients are positive and significant, and some interesting patterns emerge. In Panel C, where we

[10]See for example Jones and Wang (2012).

regress long term implied volatility on the previous one month's realized volatility, we see much more variation across slope deciles than we do in Panel A, which reports the analogous regressions using short term implied volatility. While decile 1 implied volatility is very sensitive to the past month's realized volatility, the most inverted decile shows a slope coefficient just over half that of decile 1. The R^2 measures show some decline as term structure becomes more inverted but the drop off is not as large as the equivalent pattern from Panel A. While the short term implied volatility becomes slightly less sensitive to 1 month previous realized volatility when the curve becomes inverted, the long term implied volatility becomes much less sensitive. However, when the curve is least inverted, the long term implied volatility is *more* sensitive to the previous 1 month's volatility than is the short term implied volatility.

In Panel D where we examine the relation between the previous year's realized volatility and long term maturity implied volatility we see higher slope coefficients as compared with Panel C. This is consistent with the finding for the 1 month implied volatility in Panels A and B. However, here we see a weak decreasing pattern in the slope coefficients as the term structure becomes more inverted. While this contrasts with the increasing pattern seen in Panel B, it is more in line with the general intuition that as the term structure becomes inverted, long term maturity implied volatility is less sensitive to previous realized volatility measured over long horizons.

[INSERT TABLE 5 HERE]

We extend our analysis of the impact of realized volatility to include the term structure itself. Table 5 reports the results of cross sectional regressions similar to those in Table 4 except with term structure slope as the dependent variable. Each month, within each decile, term structure slopes are regressed on the realized volatilities of the underlying, calculated using past daily returns over a fixed horizon. Each of the resulting monthly cross sectional regression coefficients are then averaged over the entire time series.

Panel A reports the results for regressions with realized volatility calculated using the returns of the underlying over the previous month. Panel B reports the results from similar regressions where realized volatility is measured over the previous year's daily returns. Recall that our term structure measure is a percentage difference between long and short term maturity implied volatility so that we are essentially controlling for the level of implied volatility. In both regressions we see a monotonic decline in both slope coefficients and R^2s as we move from least inverted to most inverted term structure. This suggests that as the term structure becomes more inverted, the slope is less determined by past realized volatility. If we compare across Panels A and B, we notice that all of the slope coefficients and R^2s in Panel B are smaller than those in Panel A. This suggests that across all slope deciles, the long term past realized volatility is less of a determinant of term structure. The results here, the regressions in Table 4 and the VRPs in Table 1 together show that as the term structure inverts, it becomes less a function of realized volatility. The increase in implied volatility outpaces realized volatility for one month options, the R^2 decrease from decile 1 to decile 10, and the term structure becomes much less sensitive to realized volatility as it inverts.

[TABLE 6 HERE]

The results presented thus far suggest that short maturity implied volatility tends to drive the movement which in turn drives changes in the term structure. In Table 6 we examine how this relationship depends upon a lagged relationship between long and short maturity implied volatility. In Table 6 we examine the dynamic relationship between two month and one month IV and six month and one month IV. The day after the standard options expiration, we first identify one, two and six month ATM straddles for firms, subject to standard filters. We then sort the straddles on the basis of the slope of the term structure into five quintiles, and calculate the averages of the one, two and six month IVs for each month for each maturity.

Next, we measure the percentage change in 1 month implied volatility over the subsequent two weeks. Here, we again use an ATM measure of implied volatility in order to isolate the term structure dynamics and remove any impact skew may play. As a result, we are not necessarily comparing the implied volatility of the straddle at time t_0 with the implied volatility of that same straddle at time t_1. Based on the percentage change in 1 month ATM volatility, we sort into another five quintiles within each of the term structure quintiles. The sorting enables us to examine how 2 and 6 month implied volatility relates to term structure slope *depending upon* how the short term implied volatility evolves following the observation of term structure slope. When we first observe term structure slope, this measure tells us the relation between 1 month and 6 month implied volatility. Suppose term structure is inverted at our formation date so that short term implied volatility exceeds long term volatility. Over the course of the next month, does implied volatility on the short term options decrease? This could be the case for instance if the term structure we observe is due to overreaction in the more volatile, 1 month options. If short term implied volatility continues to increase over the course of the month, it is more likely that the inversion was the result of some persistent shock to risk-neutral volatility. Hence this double sorting allows us to observe how the joint dynamics of short and long term implied volatility depend upon the term structure and persistence of implied volatility.

In Section 5, we will examine straddle trading strategies based upon 1 month holding periods. In order to understand the monthly straddle returns, in Table 6 we examine *intra monthly* implied volatility data within each of the 25 portfolios. We measure implied volatilities every two weeks within each portfolio. By looking at higher frequency data, our goal is to understand the joint dynamics of short and long term volatility within each of the 25 double sorted portfolios.

Within each portfolio, at time t_1 we regress 2 and 6 month ATM implied volatility on contemporaneous 1 month implied volatility and the two-week lagged implied volatility of the 1 month options calculated at formation of the portfolios:

$$IV_t^{6m} = c + b_1 IV_t^{1m} + b_2 IV_{t-1}^{1m} + \epsilon_t. \tag{4}$$

For each of the 25 portfolios double sorted by term structure and percentage change in subsequent implied volatility, we separately report the results of regressions described by Equation (4) in Table 6. We observe very strong patterns across both dimensions of our double sorting: term structure slope and subsequent implied volatility percentage change. These dynamics are, to the best of our knowledge, new to the literature.

By regressing 6 month implied volatility on 1 month implied volatility alone, we expect to be able to describe a large part of the variation in our dependent variable. In our regressions we include the additional lagged as well as the contemporaneous 1 month implied volatility. Across all but one of the 25 portfolios, the regression R^2s exceed 92%. The portfolio with the steepest upward sloped term structure and the lowest subsequent percentage change in implied volatility (portfolio (1,1)) has an R^2 of only 82.2%. In each of the portfolios, the parameters of the regression equations are estimated with a high degree of precision.

We observe several novel results within Table 6. The patterns relating dynamics across portfolios are important for informing the trading strategies we will describe in Section 5. First, we find that regardless of the percentage change in implied volatility the month following portfolio formation, the sensitivity of 6 month implied volatility to contemporaneous 1 month implied volatility monotonically decreases in term structure inversion. On the other hand, the sensitivity of 6 month to the (2 week) lagged 1 month implied volatility is monotonically *increasing* in term structure inversion regardless of subsequent changes in implied volatility. That is, within each implied volatility change quintile, 6 month implied volatility's sensitivity to contemporaneous short term volatility decreases in term structure inversion while the sensitivity to lagged short term inversion increases in term structure inversion. More succinctly, the more inverted the term structure is, the more 6 month implied volatility lags behind 1 month implied volatility. Within each of the 5 quintiles sorted on implied volatility we have strict monotonicity. This combined with the fact that the regression coefficients are estimated with strong precision suggests that the relationship is very robust.

In addition to the patterns across term structure inversion, we also look across the portfolios sorted on implied volatility changes. Interestingly, the pattern described in the previous paragraph is stronger for portfolios with the larger change in subsequent 1 month implied volatility. The relationship is monotonic in the following sense: within each term structure portfolio, the sensitivity of long term implied volatility to contemporaneous short term implied volatility is decreasing in subsequent short term implied volatility change. On the other hand the sensitivity to the lagged short term implied volatility is *increasing* as we move down the table from quintile 1 to quintile 5. In fact, for the 5-5 portfolio which has the most inverted term structure and the largest subsequent percentage change in short term volatility, 6 month implied volatility is actually *more* sensitive to lagged than it is to contemporaneous short term volatility.

When we examine the regressions of two month ATM implied volatility on contemporaneous and lagged one month ATM implied volatility, we find the same pattern, although the sensitivity to contemporaneous one month IV remains higher across term structure and implied volatility change. As expected, R^2 of these regressions are higher, as the relationship is tighter between two and one month volatility. All are greater than 0.95, with the exception of the 1-1 portfolio, with an R^2 of 0.949. The sensitivity to contemporaneous (lagged) one month IV is decreasing (increasing) across both term structure and IV change. In the 5-5 portfolio, two month ATM IV has a loading of 0.681 on one month ATM IV, compared to 0.359 for the six month ATM IV.

Overall, the results of Table 6 suggest that when implied volatility term structure is more inverted, the long term implied volatility tends to lag behind short term volatility: the loading on contemporaneous volatility is lowest when the term structure is most inverted. When the cause of the term structure inversion is found to be short-lived, this lagged relationship is weaker. In this case, loading on contemporaneous volatility is highest among the five quintiles of IV change. On the other hand, if the shock to short term volatility that caused term structure inversion persists, long-term volatility continues to lag, as the loading on lagged 1m IV (0.471) is greater than that of the contemporaneous IV (0.359). We can thus think of the long term implied volatility as taking a wait and see stance. If the shock is short-lived, then long-term volatility is less affected by the shock, as its initial and subsequent reactions are muted. Conversely, if the shock persists, long term volatility continues to react cautiously, loading more on lagged volatility. These new results are important for our understanding of the dynamic nature of the implied volatility term structure. Below we investigate whether this relationship can be exploited in a profitable trading strategy.

4 Framework

In this section we encapsulate the basic properties of long and short term implied volatility uncovered above. In Section 5, we examine trading strategies as a verification of our findings. While we take the information presented in Tables 2 through 6 as the basis for our framework, we use only the most salient features. As a result, the framework we describe below is intentionally very simple in order to plainly show where potential for profitable trading strategies emerge.

Here, we assume that when we see the term structure invert, there has been some sort of positive shock to implied volatility in the pricing of short term (1 month) options. Of course it is a simplification to assume that the inverted term structure is due only to a positive shock to implied volatility of short term options. However, the summary statistics in Table 2 show that the majority of movement in implied volatility resulting in inverted term structure is due to the short term options. To see this, note that for the 1 month options, the difference between the average IV for the least inverted and most inverted volatility term structure is more than 20% annualized versus a difference in the long term options of under 5% vol annualized. The fact that Table 2b shows time series standard deviations of average implied volatilities are much larger for the 1 month options than for the 6 month options further informs our simplifying assumption that term structure inversion is due solely to movement in implied volatilities to 1 month options.

In Panel C of Table 2, we see that average implied volatility has a positively skewed distribution for all bins and the skewness is greatest among the most inverted bin (decile 10). For this reason, when we model shocks to implied volatility of firms with inverted term structure, we will only look at positive shocks to volatility. As a result our simplified distributions will have only two levels: a baseline and high level of implied volatility. This is the simplest way for us to model a positively skewed distribution, where the baseline volatility has a larger probability mass than that of the high level. Let V_B^s denote the baseline volatility and let V_H^s denote the high level volatility of short term options, where $V_B^s < V_H^s$. We will further assume that returns to straddles are exactly replicated by buying and selling the level of implied volatility. So, if we buy a short term straddle at time t and sell it at time $t+1$, then our straddle returns are given by $(V_{t+1}^s - V_t^s)/V_t^s$, where V_t^s denotes short term (1 month) implied volatility at time t.

Here, an inverted term structure is driven by a shock to only short term volatility. We further assume that if the shock ultimately persists, then the long term implied volatility will then adjust accordingly, after it is determined that the shock was not noise. Importantly, this revelation takes place sometime after we first observe the inverted term structure but before the end of the holding period in which we trade. This is a simplification of the results presented in Table 6 where we show that when the term structure becomes inverted and we witness a persistent shock to short term implied volatility, 6 month implied volatility tends to load more heavily on lagged short term implied volatility. On the other hand, when term structure is inverted but the shock turns out not to be persistent, 6 month implied volatility tends to load less heavily on lagged short term implied volatility.

Assume that we observe a shock to short term volatility, or equivalently, an inverted term structure of volatility. Given the inverted term structure curve, the probability that the shock causing the inversion is fundamental (as opposed to just noise) we denote by p_f. The probability of the shock being pure noise is $1 - p_f$. The trading strategies we describe are based upon first observing that a shock has occurred, and then buying and selling option straddles accordingly.

If we observe an inverted term structure today, then at the end of our holding period, we either realize that the shock was just noise, in which case 1 month implied volatility reverts to it's baseline level V_B^s, or, if the shock turns out to be fundamental, then the volatility remains at the high level, V_H^s. Similarly, 6 month implied volatility has a skewed distribution (see Table 2) and we assume that it has a baseline and high level $V_B^L < V_H^L$, where V_B^L denotes the baseline and V_H^L denotes the high level for long term options.

There are two trading strategies we examine once we observe an inverted term structure. Strategy 1 buys short term straddles. Strategy 2 buys long term straddles. Strategy 1 realizes negative returns when the shock we observe turns out to be noise. Strategy 2 makes money when the shock persists.

The expected returns to Strategy 1 are

$$\mathbb{E}(R_1) = 0 \cdot p_f + (1 - p_f)\frac{(V_B^s - V_H^s)}{V_H^s} < 0.$$

The expected returns to Strategy 2 are given by

$$\mathbb{E}(R_2) = p_f\frac{(V_H^L - V_B^L)}{V_B^L} + 0 \cdot (1 - p_f) > 0.$$

In terms of comparative statics, both strategies will see a larger return when the spread between V_H and V_B is higher. Also, if the probability of a shock turning out to be fundamental (p_f) is large, then Strategy 2 has a higher (positive) expected return. On the other hand the returns to Strategy 1 are most negative when if the probability of a shock being fundamental (p_f) is low.

[TABLE 7 HERE]

5 Trading

Given the joint dynamics we've shown for short and long term implied volatility, we next investigate whether these translate to profitable trading strategies using option straddles. Based upon our framework from Section 4 for understanding the patterns observed in the implied volatility data, we propose trading strategies which we show bear out the predictions of our framework.

Table 7 reports the returns and standard errors for straddle portfolios of different maturities and the long/short portfolio which owns portfolio ten and shorts portfolio one. Sharpe Ratios are included for the one and six month options portfolios and the calendar spread portfolios. The holding period for all is one month, with the exception of the first stanza, which shows the returns of portfolios of one month straddles held for two weeks. The returns for both versions of the one month portfolios echo the findings of Vasquez (2015): the returns on straddle positions decrease as the term structure becomes more inverted. Holding the decile 10 portfolio to expiry costs 11.85% monthly, while owning decile 1 portfolio returns 2.55% per month. A portfolio which buys decile 1, and sells decile 10 returns 14.41% monthly, posting a Sharpe Ratio of 2.723. While the returns of decile 1 are not statistically significant, those of decile 10 and the long-short position are highly significant. As discussed above, as term structure becomes more inverted, the change in implied volatility outpaces that of realized volatility; one interpretation is the implied volatility is overreacting to the movement of the underlying.

The returns for the two month options generally follow the pattern seen in the one month options. While not monotonic, the returns decrease moving from decile 1 to 10. The decile 1 portfolio returns 2.46%, while decile 10 loses 45 bps per month. A portfolio that is long decile 1 and short decile 10 returns 2.91% monthly, and is highly significant. Throughout the paper, we include 2 month option portfolios as a short term strategy alternative to the 1 month straddles. We do this to ameliorate any concerns that the abnormally large returns in the 1 month options are the result of biases arising around the time of option expirations.

For the three to five month portfolios, a change in sign of the 10-1 portfolios is seen. For the long-short portfolios with one and two month maturities, a positive return is generated if we *buy* portfolio 1 and *sell* portfolio 10. For spread portfolios with maturities of four and five months, the opposite position is needed to post a positive return. The

10-1, 4 month portfolio (long decile 10, short decile 1) earns 0.58% per month and is statistically significant at the 10% level; the 10-1, 5 month portfolio posts a significant 2.61% monthly return. In addition, the five month returns increase monotonically across deciles, with the exception of decile 9.

Recall from Table 2 that for portfolios of 6 month maturity options, implied volatilities increase as the term structure becomes more inverted. From Table 1, however, we know that the difference in implied volatilities across deciles of 6 month options is smaller than the average difference in realized volatility across deciles. The returns for long maturity straddle portfolios mirrors this pattern insofar as straddle returns mirror percentage changes in implied volatility and we see higher returns in decile 10 than in decile 1. In contrast to the findings of Vasquez (2015) for the short maturity straddles, the long maturity returns are strongly monotone and *increase* from decile 1 to 10. Buying portfolio 10 earns 3.42% month, is statistically significant and posts a Sharpe Ratio of 1.391. As this is a long volatility portfolio, the returns are negatively correlated to the S&P 500 Index (-0.416). The 10-1 portfolio, while earning less than decile 10 since decile 1 also has positive returns, posts a higher Sharpe Ratio, 1.697, due to the lower volatility of the spread portfolio.

In practice, a common options strategy is the calendar, or time spread, whereby options with the same strike but different maturities on the same underlying are bought and sold. The bottom panel in Table 7 holds the returns of calendar spreads in aggregate. For each decile, the returns represent a trade where the six month options portfolio is bought and the one month portfolio is sold. Given the dynamics seen in both the 1 and 6 month options portfolios, it is perhaps unsurprising that we see increasing monotonicity in the returns. Decile 1 loses 1.56% monthly, while the decile 10 spread earns a significant 15.35% per month, with a Sharpe Ratio of 3.123. Finally, a calendar spread spread: a position which buys the calendar spread of decile 10 and sells that of decile 1 (buying six month, decile 10, selling one month, decile 10; selling six month, decile 1, buying one month, decile 1) returns 16.90%, with a Sharpe Ratio of 3.312.

[FIGURE 3 HERE]

Figure 3 shows the monthly returns to the one, two, and six month long/short straddle portfolios based upon term structure slope. The return spikes seen for the one month portfolio coincide with market deciles. The portfolio formed after the August 2001 expiration posts the largest monthly loss, 94.5%, for the sample. Other spikes occur during the financial crisis, the European debt crisis, and the mini-flash crash in August, 2015. During volatility spikes, then, the losses from shorting the undervalued options in decile

1 outpace the gains from owning the overvalued options in decile 10. The returns of the two month portfolio are highly correlated (0.82) to those of the one month portfolio, as in both cases decile 1 is bought and decile 10 is sold, and as shown above the dynamics of the two are similar. In contrast, the correlation of the six month returns to the one month is -0.28, as the positioning reverses: decile 10 is bought while decile 1 is sold.

[TABLE 8 HERE]

Returning to our framework, we expect the returns of the one month straddles to be most negative when the term structure is inverted and the volatility shock turns out to be transitory. And, if the shock persists, the returns seen are muted, as implied volatility already is elevated. In contrast, if the volatility shock has no follow through, we expect the losses on the six month straddles to be mollified as there was an underreaction relative to the front part of the curve. We test our model by performing an *ex post* double sort on returns. The day after the standard options expiration, we identify one, two and six month ATM straddles for firms, subject to standard filters. We then sort the straddles on the basis of the slope of the term structure into five quintiles, and hold the positions for one month. After one month, we sort the portfolios into three buckets, based on the average percentage change in realized volatility for the underlying firms over the course of the month-long holding period. Portfolio sorting exercises are typically used as a model free way to test whether a premium is earned via a trading strategy as a result bearing risk. The sorting we do in Table 8 is obviously not meant to analyze a trading strategy as the second sort is done *ex post*. We include the *ex post* sorting procedure as a way to further analyze the predictions of our simple model of the dynamics of implied volatility. Table 8 helps us understand where the returns described in Table 7 come from.

The columns of Table 8 represent quintile portfolios based upon the term structure slope: column 1 represents least inverted while column 5 represents most inverted. The last column contains the returns of a 5-1 portfolio, which is long portfolio five and shorts portfolio one. The first three rows within each panel represent the *ex post* sorting by percentage change in realized volatility of the underlying stock: within the five deciles, the first row represents the averages of those stocks whose percentage change in realized volatility is smallest while the third row represents those with the largest percentage change in realized volatility. Finally, the intersection of the right-most column with the final row measures the return of a portfolio which is long the 5-1 portfolio of Δ RV bucket 3 and short the 5-1 portfolio of Δ RV bucket 1, where Δ RV denotes the *percentage* change in realized volatility. This portfolio buys the high minus low portfolio in the highest Δ RV tercile and shorts the high minus low portfolio in the lowest Δ RV tercile.

We can think of the double sorted portfolios as a model free way of examining how returns vary across straddles when we vary both term structure slope and percentage changes in subsequent realized volatility. The 5-1 portfolios represent differences in returns due to differences in term structure slope, controlling for ΔRV terciles. Similarly, differences along the ΔRV columns show how straddle returns vary *within* quintiles defined by term structure slope. The bottom row, right most column which reports the difference in the long short portfolios across Δ RV tercile can be interpreted as a non-parametric measure of the interaction between term structure slope and Δ RV: it measures how variation in returns across term structure slope will vary as Δ RV varies. The analogous regression would regress straddle returns on term structure slope, ΔRV and an interaction term:

$$r^s = a + \beta_1 TS + \beta_2 \Delta RV + \beta_3 TS \cdot \Delta RV + \epsilon, \tag{5}$$

where r^s denotes straddle returns and TS denotes term structure slope. In all three Panels of Table 8 we see large and significant spreads across all ΔRV and term structure portfolios. This is akin to significant point estimates of β_1 and β_2. The bottom right entry in each panel is akin to the point estimate of β_3. The advantage of the double sorts as opposed to the regression equation is that the sorting does not rely on any parametric assumption. The regression equation in (5) on the other hand assumes a very specific linear relationship between straddle returns, the two explanatory variables and the interaction term.

Table 8 is similar to Table 6 in that we look at portfolios which are first sorted on volatility term structure and then, within each slope portfolio, sorted by subsequent *ex post* changes in volatility. Whereas the second sort in Table 6 is based upon 1 month option implied volatility, the second sort in Table 8 is based upon changes in *realized* volatility in the underlying. Table 6 is informative for understanding the dynamic relationship between short term and long term implied volatility. However, in order to compare the returns of 1 month, 2 month and 6 month straddles in Table 8 we measure subsequent volatility using *realized* volatility of the underlying asset rather than 1 month implied volatility so that there is less of a mechanical relation between returns and changes in subsequent volatility.

As we show in Table 8, the behavior of long-term implied volatility depends upon whether or not volatility persists after the portfolio formation date. When our variable of interest is straddle returns, we sort on subsequent changes in realized volatility as our measure. If term structure is inverted on the sort date and realized volatility of the underlying asset grows over the subsequent month, we consider this a fundamental change in volatility that was captured by the inverted term structure. Our framework of volatility term structure dynamics suggests that if term structure becomes inverted and volatility persists then the long term straddle will see positive returns. Furthermore, if the long term straddle returns are largely reliant on a positive relation to fundamental volatility of the underlying asset, then we expect to see larger returns to the long term volatility, high minus low strategy when Δ RV is large rather than small. This is exactly what we see in Table 8. Consistent with Table 7 the high minus low strategy for long term volatility earns positive returns in all three Δ RV terciles. The returns for the high minus low strategy are increasing in Δ RV terciles. Furthermore, as the last column, final row shows, the difference between the high minus low returns in the largest and smallest Δ RV deciles is both statistically and economically significant at 2.73% per month, suggesting a significant interaction between term structure slope and subsequent volatility. This is consistent with the results of Table 6 where we see that the dynamics of 6 month implied volatility depend upon the slope of the term structure and the contemporaneous volatility (measured by 1 month implied volatility). Here, we also observe an interaction effect. That is, the relation between 6 month implied volatility, 1 month implied volatility and lagged 1 month implied volatility varies across term structure quintiles but this pattern in variation also varies across the quintiles sorted on subsequent 1 month implied volatility. This is a nonparametric way of observing an interaction effect between term structure slope and subsequent volatility.

Panels A and B of Table 8 report the returns for the 1 month and 2 month straddles respectively. We discuss these two panels together as the short maturity straddle returns. In both cases, the high minus low term structure portfolios earn negative returns in all three Δ RV terciles, consistent with Table 7. In neither panel is the difference between the high minus low strategy siginificantly different between the highest and lowest Δ RV terciles. We can however see a large spread between returns in Δ RV terciles 3 and 1 within each of the term structure quintiles. This suggests that both the term structure and changes in realized volatility over the holding period are significant determinants of straddle returns. However, unlike the returns of the long maturity straddles, it does not appear that there is as significant an interaction effect between the term structure and subsequent volatility sorts. It is important to remember that the sorts used for Panels A, B and C are all exactly the same since they are based upon the underlying as opposed to the options. So the fact that we see an interaction for the 6 month options but not a strong interaction effect for the short term options is not due to differences in break points for the sorts. Rather this difference is due to differences in the pricing of short and long maturity options.

Surprisingly, for the 1 month straddles in Panel A, the high minus low portfolio returns are fairly consistent across Δ RV terciles and the point estimate are not monotonic.

While there are very large spreads across Δ RV terciles, *within* each of the term structure quintiles, there does not seem to be any sign of an interaction between the term structure and realized volatility in determining straddle returns. For the 2 month straddle returns of Panel B, just as in Panel A, the spread in returns across the Δ RV terciles is significant for each of the five term structure portfolios. For the 2 month straddle returns however, there is a week monotonic relation in the high minus low column but the difference between the high Δ RV and low Δ RV terciles is not significant in this column. Since the sorting in all three panels of Table 8 is the same, we can confidently say that the interaction effect is stronger for the long term options than it is for the short term options.

Overall, the results presented in Table 8 suggest that the spread we observe in straddle returns based upon term structure sorts in the longer maturity options is, to a large extent due to interaction between the term structure and changes in volatility of the underlying. There is a positive relationship between the term structure-based, long maturity trading strategy described in Table 7 and changes in the underlying volatility. The reason for the positive interaction is also alluded to in Table 6. There we show that the way 6 month implied volatility reacts to changes in short term *implied* volatility differs across portfolios formed on term structure slope. The way it varies across term structure portfolios actually depends upon subsequent changes in short term implied volatility. In other words the patterns we see in regression estimates across columns of Table 6 actually changes as we move from the top row to the botton row. This suggests an interaction between the two: term structure slope and subsequent changes in volatility, in determining long maturity implied volatility. We see another manifestation of the interaction effect in Panel C of Table 8 where difference in long short portfolio returns across ΔRV terciles is significant.

Various measures have been proposed in the literature to examine whether options markets overreact. The measures we are aware of do not necessarily consider specific events with respect to which we observe a reaction. Rather, short term implied volatility is compared with a longer term measure of volatility. Movements away from this long term measure have been deemed to be overreactions. The summary statistics described in Table 2 show that short term options show higher implied volatility as well as more volatile and skewed distributions of average implied volatilities. Furthermore, the dichotomy between implied volatility of short term and long term options is magnified when we look at the most inverted term structure portfolio. As a result, we examine the relation between overreaction of short term options and the implied volatility term structure.

[INSERT TABLE 9]

While we witness an interaction between term structure and realized volatility in the long-term options, we fail to see the same in the short-term options. We posit that the movement in the short-term options may be an overreaction to an expectation of future volatility, and so, in our model, the returns may be muted from any persistence in volatility. We examine three measures of overreaction in the short term options. The first, $\frac{1mIV}{12mRV} - 1$, compares one month IV to twelve month RV (Goyal and Saretto (2009)); the second is the VRP, measured as $\frac{1mIV}{1mRV} - 1$; and the third, $\frac{1mIV}{IV_{ave}} - 1$, compares one month IV to a six month average of one month IV. For measures 1 and 2, realized volatility is calculated based on the daily closes of the underlying. After firms are sorted into ten portfolios according to term structure, the averages of these three measures and the term structure are calculated for each firm and then averaged for each portfolio each month. Table 9 reports the time series correlations of the three measures with that of IV term structure.

Panel A reports the average of each overreaction measure for each decile over the entire sample. All three of the measures are increasing in term structure inversion deciles. This suggests that as term structure becomes more inverted so that the 1 month implied volatility exceeds 6 month implied volatility, the overreaction measures monotonically increase. This is intuitive since the overreaction measures depend on an increase as current 1 month implied volatility increases, and the same is true of term structure inversion. Of course each of the overreaction measures has a different volatility measure with which to compare current 1 month implied volatility. In this sense, the volatility term structure can be thought of as a measure of overreaction in that it compares short term implied volatility to 6 month IV, a more stable measure.

Panel B describes the time series correlation between our measure of volatility term structure and each overreaction measure within each portfolio. All three of the overreaction measures are positively correlated with the volatility term structure and we see an increasing pattern in the correlations as we move from decile 1 to decile 10. This suggests that the inverted term structure is more correlated with measures of overreaction in short term implied volatility, and is explored in Vasquez (2015). To test whether the movement in short-term volatility may be an overreaction, we take the monthly portfolio returns summarized in Table 7, and regress them on the returns of an "under" and "over" portfolio. The "under" and "over" portfolios are formed by sorting eligible straddles according to the overreaction measure $\frac{1mIV}{12mRV} - 1$ from Goyal and Saretto (2009). The "under" portfolio consists of firms in decile one: underreaction. The "over" portfolio consists of firms in decile ten: overreaction. Table 10 examines the possibility that overreaction or underreaction is driving the results presented in Table 5. Vasquez (2015) finds limited evidence suggesting that overreaction can explain some of the returns to a trading strategy involving 1 month straddles held for a week long period.

[TABLE 10 HERE]

We examine the ability of our overreaction measure to account for returns to the straddle portfolio strategy described in Table 7. We focus only on the short term and long maturity straddle portfolios since these are where we see the largest and most significant returns. For the long maturity straddles, we use only the 6 month straddles. For the short maturity straddles we examine both 1 month and 2 month straddle portfolios. We look at both because the 1 month straddle portfolios potentially could be adulterated by events around option expiration. Since the 2 month straddles are sold with 1 month remaining on the straddles, this avoids any noise that could be attributed to erratic movements around expiration.

Panel A of Table 10 reports the results for 1 month options held to expiration. The coefficients on the underreaction as well as the overreaction factor returns are significant at the 1% level for most of the ten portfolios. We observe an increasing trend in each of the coefficients across deciles. As one would expect, the loading on "underreaction" tends to be higher for the lower deciles and lower for the higher deciles. Conversely, there is a monotonic pattern in the "overreaction" coefficient. Loadings on the overreaction factor are increasing as we move from least inverted (decile 1) to most inverted (decile 10). In the final column of Panel A, we regress the high minus low portfolio on the high minus low overreaction factor. The alpha is significantly different from zero however, at -5.03%, its magnitude is about one third of high minus low straddle return of -14.41% reported in Table 7. This means that the traded overreaction measure captures about two thirds of the returns associated with the 1 month straddle strategy based upon term structure slope.

In Panel B, we further investigate the relation between short maturity straddle returns and the overreaction measure, using 2 month options. Recall that the high minus low trading for two month options described in Table 7 shows highly significant negative returns. The mean returns to the 2 month straddles are only 2.91% per month, not nearly as large as the 1 month straddle returns. In Panel B of Table 10, we see the same general pattern as described in Panel A. The most important difference however is that when we control for the overreaction factor, the returns to the high minus low portfolio are no longer statistically significant for the 2 month straddles. The intercept or the point estimate for unexplained returns are actually positive but insignificant at 0.21% per month. This further suggests that a large part of the returns we described in Table 7 for the short maturity options can be attributed to the measure of overreaction.

Panel C of Table 10 shows the results when portfolios of our 6 month straddles are regressed on the over and underreaction factors and the high minus low portfolio is regressed on the overreaction minus underreaction factor. Each portfolio is regressed on both the underreaction and overreaction separately. Although the loadings on each of these factors are not monotonic across the deciles, there is a general pattern of increasing sensitivity to the overreaction measure and a decreasing sensitivity to the underreaction factor as term structure becomes more inverted. When we regress the high minus low straddle portfolio on the high minus low overreaction factor, the intercept remains highly significant and the magnitude actually increases from the returns reported in Table 7: from 2.62% to 3.37% per month.

The results of Table 10 suggest that a large portion of the returns to the short maturity straddle portfolio strategy based upon term structure slope can be attributed to a measure of overreaction documented by Goyal and Saretto (2009). For the 1 month straddles, about two thirds of the returns to the high minus low straddle portfolio can be attributed to the overreaction factor but the unexplained returns are still significant. When we use 2 month straddles as our short maturity options in order to avoid calculating returns near expiration, we find that the returns unexplained by the overreaction factor are no longer significant. On the other hand, when we examine the long maturity straddles held for the same 1 month holding period, the overreaction factor cannot explain the returns shown in Table 7.

6 Conclusion

We examine the term structure of volatility in the cross-section of equity options to reveal several novel facts. We show that term structure of volatility among individual stocks behaves differently from that of the index. In the cross-section we find that movements in the term structure are driven by changes in short term volatility, and unlike in the index, the premia associated with volatility is strongly dependent upon *both* horizon and slope of the volatility term structure. We show that long term implied volatility is slow to react to these shocks in short term implied volatility. Furthermore, the speed with which long term volatility reacts to shocks depends upon the slope of the implied volatility curve. We propose a simplified framework for understanding our empirical findings. Based upon our analysis and proposed framework, we propose strategies for trading ATM option straddles across maturities. The returns to these trading strategies perform consistent with the volatility term structure dynamics and the predictions of our framework. We find that the profitability of our strategies in long maturity straddles are driven by an interaction between the term structure and realized volatility. On the other hand, short maturity straddle returns appear not to be be driven by this type of interaction.

While the literature studying index options is much larger than that of options on individual equities, the number of studies empirically examining the cross-section of individual equity options has rapidly grown in recent years. The vast majority of papers studying the cross-section of individual options examine only those options with a fixed, single month to maturity. A number of option pricing anomalies have been uncovered in the cross-section of these options. Often, these anomalies are not existent in index options. This highlights the need for empirical research in the cross-section of individual options *in addition to* the empirical work studying index options. Our results provide a new and important way of understanding option prices in the cross-section. We contribute to the literature by studying the dynamics of options prices across maturities and term structure. This allows us to uncover new empirical facts about the relative pricing of options across maturities, a dimension that has until now been unexplored in the literature.

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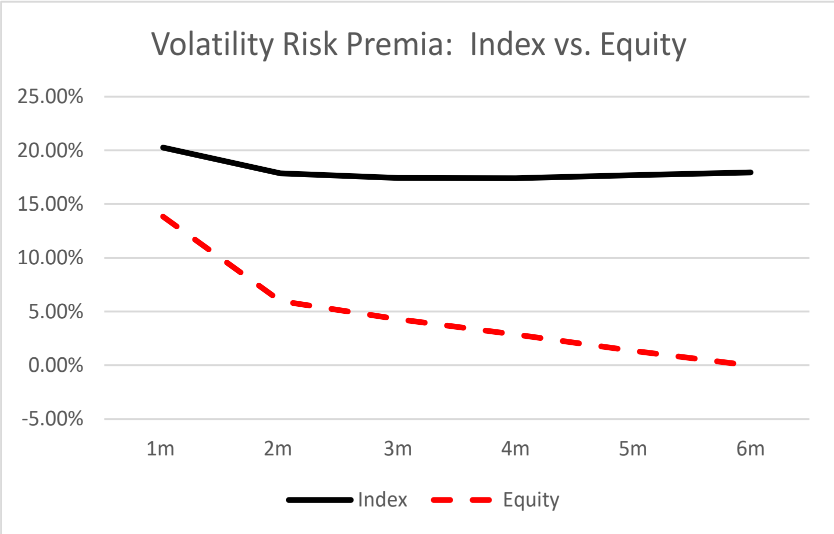
Figure 1: Term Structure of Volatility Risk Premia

The top figure plots the time series averages of the portfolio averages of realized and implied volatilites for the quintile 1 and 5 portfolios. Each month, we place ATM straddles into five portfolios according to the implied volatility term structure. The bottom figure sorts the S&P 500 Index *ex post* on term structure. In each case, portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; portfolio 5 holds straddles which have the most inverted term structure. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.



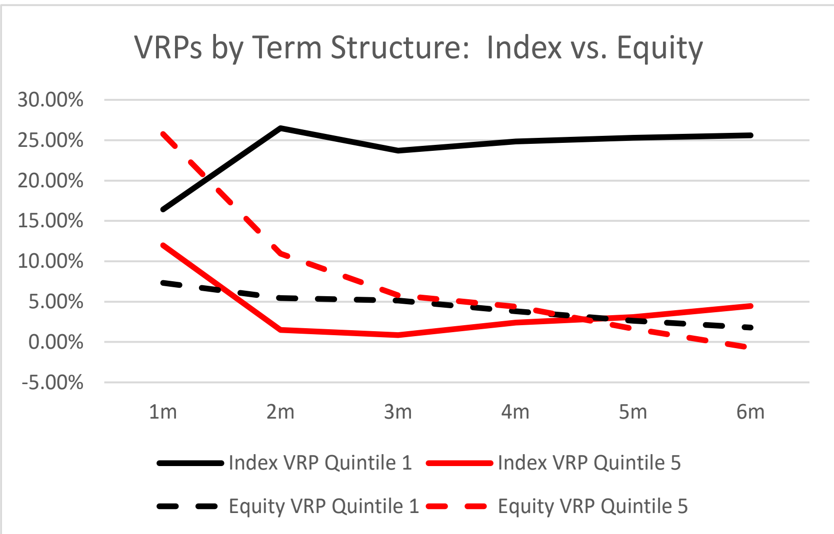


Figure 2: Time Series of Implied Volatilities

This figure plots the time series of the average 1 month and 6 month implied volatilities, and the 1-6 month implied volatility spread, for the decile 1 and 10 portfolios. Each month, ATM straddles are placed into ten portfolios according to the implied volatility term structure. Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; portfolio 10 holds straddles which have the most inverted term structure. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

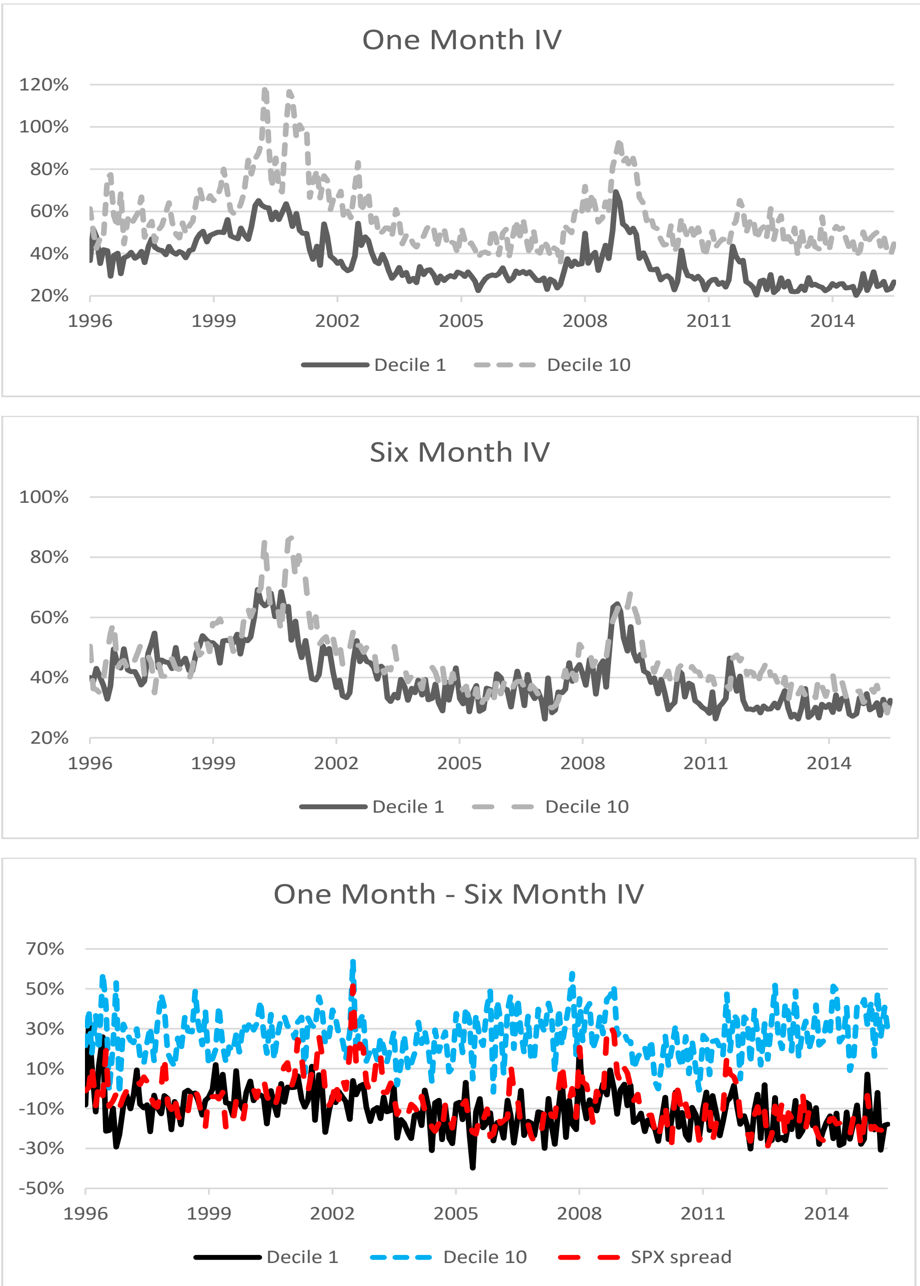


Figure 3: Time Series of Monthly Returns

The figure below plots the monthly time series of returns for three long/short options portfolios. Each month, ATM straddles are placed into ten portfolios according to the implied volatility term structure. Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; portfolio 10 holds straddles which have the most inverted term structure. The first portfolio in this figure owns portfolios 1 and shorts portfolio 10 for one month options the second portfolio does the same with two month options. The third portfolio holds the opposite position: it owns decile 10 and shorts decile one. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

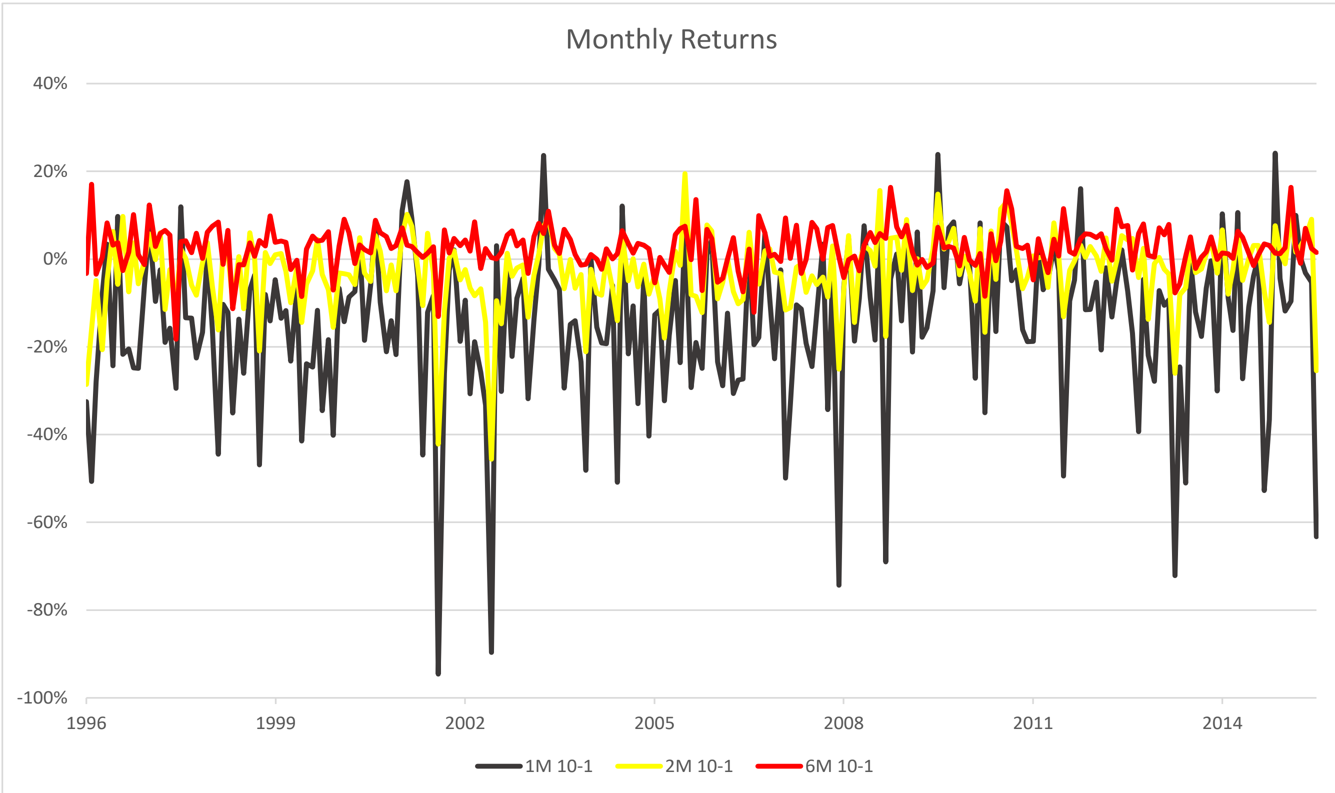


Table 1: Volatility Risk Premia for Portfolios

This table reports the average volatility risk premiums of the straddles contained in each portfolio, as defined by $\frac{1mIV}{1mRV} - 1$, where for each ATM straddle in each portfolio, IV is the implied volatility of the ATM straddle, RV is the annualized volatility realized by the underlying over the period equal to the straddles' maturity. (For example, the three month portfolios use three month annualized realized volatility.) Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; portfolio 10 holds straddles which have the most inverted term structure. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

	Decile 1	2	3	4	5	6	7	8	9	Decile 10
1m	0.0175	0.0304	0.0446	0.0548	0.0630	0.0718	0.0801	0.0968	0.1213	0.2025
2m	0.0224	0.0147	0.0127	0.0153	0.0135	0.0158	0.0140	0.0219	0.0382	0.0832
3m	0.0284	0.0175	0.0172	0.0160	0.0136	0.0126	0.0091	0.0058	0.0120	0.0328
4m	0.0185	0.0064	0.0047	0.0036	0.0008	-0.0016	-0.0010	0.0013	0.0068	0.0192
5m	0.0080	-0.0022	-0.0070	-0.0076	-0.0116	-0.0123	-0.0138	-0.0132	-0.0128	-0.0092
6m	-0.0010	-0.0115	-0.0143	-0.0197	-0.0214	-0.0236	-0.0271	-0.0313	-0.0328	-0.0371

Table 2: Summary Statistics of Implied Volatility by Decile and Maturity

This table reports the means, standard deviations, and skewness of the implied volatilities of portfolios of equity options at the money (ATM) straddles. Each month, the day following the standard options expiration, ten portfolios of options with maturities from one to six months are formed based on the volatility term structure. Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; portfolio 10 holds straddles which have the most inverted term structure. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities. Panel A contains the means of the average implied volatility of the options in the portfolios; Panel B contains the standard deviations. Panel C holds the skewness of the implied volatility of the portfolios.

Panel A: Means of Implied Volatility by Decile and Maturity

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All deciles
1m	0.3594	0.3821	0.4010	0.4184	0.4335	0.4460	0.4600	0.4826	0.5076	0.5708	0.4461
2m	0.3869	0.3964	0.4085	0.4200	0.4319	0.4402	0.4516	0.4649	0.4807	0.5178	0.4399
3m	0.3972	0.3990	0.4062	0.4162	0.4258	0.4311	0.4409	0.4517	0.4629	0.4897	0.4321
4m	0.3923	0.3950	0.4082	0.4169	0.4238	0.4310	0.4390	0.4450	0.4593	0.4777	0.4288
5m	0.3923	0.3931	0.4014	0.4135	0.4219	0.4266	0.4324	0.4433	0.4475	0.4595	0.4231
6m	0.4007	0.3982	0.4036	0.4109	0.4171	0.4220	0.4266	0.4335	0.4385	0.4496	0.4201
All	0.3882	0.3940	0.4048	0.4160	0.4257	0.4328	0.4417	0.4535	0.4661	0.4942	0.4317

Panel B: Standard Deviations of Implied Volatility by Decile and Maturity

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All deciles
1m	0.1091	0.1186	0.1230	0.1253	0.1281	0.1284	0.1286	0.1333	0.1416	0.1545	0.1424
2m	0.1036	0.1099	0.1129	0.1139	0.1160	0.1171	0.1167	0.1195	0.1274	0.1359	0.1235
3m	0.1022	0.1114	0.1110	0.1127	0.1141	0.1138	0.1157	0.1151	0.1206	0.1284	0.1179
4m	0.1002	0.1022	0.1061	0.1105	0.1109	0.1105	0.1079	0.1109	0.1196	0.1292	0.1139
5m	0.1002	0.1042	0.1027	0.1067	0.1028	0.1051	0.1042	0.1044	0.1122	0.1116	0.1075
6m	0.0973	0.1050	0.1045	0.1048	0.1055	0.1050	0.1048	0.1010	0.1055	0.1102	0.1055
All	0.1029	0.1087	0.1101	0.1124	0.1131	0.1137	0.1137	0.1155	0.1236	0.1352	0.1194

Panel C: Skewness of Implied Volatility by Decile and Maturity

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All deciles
1m	0.8435	0.8204	0.8214	0.8510	0.8582	0.9017	0.9802	1.1051	1.2608	1.5439	1.0302
2m	0.8129	0.8121	0.8285	0.8543	0.8817	0.9427	0.9745	1.1031	1.2514	1.5400	1.0406
3m	0.8166	0.7921	0.8392	0.8964	0.9014	0.8957	1.0443	1.1149	1.1592	1.4084	1.0068
4m	0.8306	0.8861	0.7800	0.8357	0.8947	0.9106	0.9489	1.0749	1.1997	1.5725	1.0551
5m	0.7615	0.8506	0.8318	0.8787	0.8201	0.8684	0.8357	0.9595	1.2468	1.3486	0.9271
6m	0.8599	0.8082	0.8619	0.8871	0.9352	0.9166	0.9466	1.0290	1.1115	1.3728	0.9574
All	0.7676	0.8105	0.8243	0.8716	0.8994	0.9318	0.9949	1.1303	1.2695	1.5230	1.0654

Table 3: Movements of One Month Implied Volatility vs. Six Month Implied Volatility

Each month, the portfolios are formed based on the implied volatility term structure. Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; portfolio 10 holds straddles which have the most inverted term structure. The changes in one and six month implied volatility for each firm in each portfolio are calculated, and then averaged for each month for each decile. Reported below are the results of regressing the change in one month volatility on the change in six month volatility for each decile and for the entire sample. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All
b_{6mIV}	1.301***	1.356***	1.454***	1.488***	1.548***	1.522***	1.635***	1.604***	1.637***	1.734***	1.585***
	(0.0677)	(0.0702)	(0.0778)	(0.0779)	(0.0825)	(0.0873)	(0.0928)	(0.0947)	(0.103)	(0.120)	(0.0261)
cons	-0.118***	-0.0647***	-0.0391***	-0.0218***	-0.00620	0.0111*	0.0285***	0.0517***	0.0940***	0.203***	0.014***
	(0.0041)	(0.0044)	(0.0048)	(0.0049)	(0.0052)	(0.0056)	(0.0060)	(0.0066)	(0.0075)	(0.0094)	(0.0016)
R-squared	0.615	0.617	0.601	0.611	0.603	0.567	0.572	0.553	0.519	0.473	0.611

Table 4: Explanatory Power of Realized Volatility on Implied Volatility

Each month, for each portfolio, the ATM implied volatility of each firm is regressed on the firm's one month and one year annualized realized volatility calculated using daily closes of the underlying. The coefficients and standard errors reported are the time series averages of the cross-sectional regressions. Each month, the portfolios are formed based on the implied volatility term structure. Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; portfolio 10 holds straddles which have the most inverted term structure. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All deciles
Panel A: One month implied volatility regressed on one month realized volatility											
b_{RV}	0.5821***	0.5820***	0.5848***	0.5689***	0.5622***	0.5573***	0.5523***	0.5561***	0.5408***	0.5244***	0.5619***
	(0.0512)	(0.0492)	(0.0492)	(0.0482)	(0.0485)	(0.0489)	(0.0499)	(0.0499)	(0.0509)	(0.0674)	(0.0177)
$cons$	0.1564***	0.1660***	0.1768***	0.1900***	0.2005***	0.2104***	0.2244***	0.2365***	0.2599***	0.3275***	0.2114***
	(0.0202)	0.0201)	0.0206)	0.0210)	(0.0218)	(0.0223)	(0.0234)	(0.0240)	(0.0256)	(0.0350)	(0.0081)
R^2	0.5436	0.5681	0.5721	0.5688	0.5579	0.5533	0.5401	0.5477	0.5243	0.3940	0.4924
Panel B: One month implied volatility regressed on one year realized volatility											
	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All deciles
b_{RV}	0.6079***	0.6855***	0.6919***	0.7086***	0.7202***	0.7473***	0.7528***	0.7814***	0.8202***	0.8687***	0.7203***
	(0.0364)	(0.0322)	(0.0326)	(0.0334)	(0.0345)	(0.0358)	(0.0373)	(0.0390)	(0.0447)	(0.0779)	(0.0168)
$cons$	0.0961***	0.0873***	0.1006***	0.1042***	0.1092***	0.1088***	0.1185***	0.1235***	0.1272***	0.1726***	0.1199***
	(0.0174)	(0.0152)	(0.0156)	(0.0163)	(0.0170)	(0.0175)	(0.0185)	(0.0195)	(0.0223)	(0.0386)	(0.0081)
R^2	0.7055	0.7995	0.7979	0.7964	0.7931	0.7933	0.7802	0.7808	0.7574	0.5540	0.6280
Panel C: Six month implied volatility regressed on one month realized volatility											
	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All deciles
b_{RV}	0.7037***	0.6305***	0.6108***	0.5773***	0.5563***	0.5377***	0.5189***	0.5074***	0.4707***	0.3955***	0.4930***
	(0.0670)	(0.0533)	(0.0515)	(0.0490)	(0.0481)	(0.0472)	(0.0469)	(0.0456)	(0.0444)	(0.0456)	(0.0155)
$cons$	0.1786***	0.1769***	0.1821***	0.1909***	0.1970***	0.2019***	0.2101***	0.2143***	0.2262***	0.2557***	0.2216***
	(0.0255)	(0.0214)	(0.0212)	(0.0210)	(0.0213)	(0.0213)	(0.0217)	(0.0216)	(0.0221)	(0.0239)	(0.0070)
R^2	0.5099	0.5675	0.5715	0.5686	0.5579	0.5532	0.5403	0.5480	0.5245	0.4294	0.4926
Panel D: Six month implied volatility regressed on one year realized volatility											
	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All deciles
b_{RV}	0.7368***	0.7387***	0.7204***	0.7165***	0.7096***	0.7173***	0.7040***	0.7088***	0.7109***	0.6600***	0.6706***
	(0.0476)	(0.0344)	(0.0338)	(0.0335)	(0.0339)	(0.0344)	(0.0349)	(0.0352)	(0.0385)	(0.0491)	(0.0126)
$cons$	0.1047***	0.0928***	0.1028***	0.1042***	0.1070***	0.1047***	0.1110***	0.1120***	0.1109***	0.1352***	0.1234***
	(0.0222)	(0.0160)	(0.0160)	(0.0163)	(0.0166)	(0.0167)	(0.0172)	(0.0176)	(0.0192)	(0.0246)	(0.0061)
R^2	0.6794	0.8006	0.7981	0.7969	0.7934	0.7939	0.7807	0.7817	0.7598	0.6253	0.7140

Table 5: Impact of Realized Volatility on Term Structure

Each month, for each portfolio, the slope of the implied volatility term structure of each firm is regressed on the firm's one month and one year annualized realized volatility calculated using daily closes of the underlying. The coefficients and standard errors reported are the time series averages of the cross-sectional regressions. Each month, the portfolios are formed based on the implied volatility term structure. Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; portfolio 10 holds straddles which have the most inverted term structure. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

Panel A: Term structure regressed on one month realized volatility

	Decile 1	2	3	4	5	6	7	8	9	Decile 10
b_{RV}	0.412***	0.385***	0.352***	0.326***	0.299***	0.288***	0.266***	0.242***	0.221***	0.127***
	(0.0238)	(0.0245)	(0.0258)	(0.0267)	(0.0274)	(0.0280)	(0.0292)	(0.0286)	(0.0287)	(0.0310)
$cons$	-0.295***	-0.219***	-0.178***	-0.145***	-0.114***	-0.0858***	-0.0530***	-0.0118	0.0431***	0.237***
	(0.00920)	(0.00990)	(0.0108)	(0.0116)	(0.0122)	(0.0128)	(0.0137)	(0.0139)	(0.0146)	(0.0167)
R^2	0.575	0.527	0.458	0.403	0.352	0.322	0.272	0.245	0.212	0.071

Panel B: Term structure regressed on one year realized volatility

	Decile 1	2	3	4	5	6	7	8	9	Decile 10
b_{RV}	0.355***	0.301***	0.254***	0.208***	0.176***	0.158***	0.130***	0.114***	0.0860**	-0.0328
	(0.0323)	(0.0331)	(0.0332)	(0.0343)	(0.0346)	(0.0355)	(0.0368)	(0.0372)	(0.0381)	(0.0431)
$cons$	-0.301***	-0.204***	-0.152***	-0.107***	-0.0690***	-0.0360**	0.00375	0.0446**	0.107***	0.317***
	(0.0146)	(0.0150)	(0.0154)	(0.0162)	(0.0167)	(0.0172)	(0.0181)	(0.0185)	(0.0192)	(0.0221)
R^2	0.354	0.273	0.209	0.143	0.105	0.083	0.053	0.041	0.023	0.003

Table 6: Reaction of Implied Volatility to Short Term Implied Volatility

Each month, firms are sorted twice. First, at t_0, they are sorted into quintiles, based on the implied volatility term structure, as measured by $\frac{1mIV}{6mIV} - 1$. Second, at t_1, within each quintile, firms are sorted based on the percentage change in one month implied volatility, two weeks subsequent to sorting based on structure. At both points of formation, we average the one and six month implied volatility in each portfolio. For each of the 25 portfolios, we regress the average t_1 six month implied volatility on the contemporaneous, t_1, and lagged, t_0 measure of one month implied volatility. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

Two Month Options					
	Term Structure Quintile				
Change IV: Quintile 1	1	2	3	4	5
Contemporaneous 1m IV	1.037***	0.963***	0.957***	0.863***	0.835***
	(0.0631)	(0.0671)	(0.0231)	(0.0198)	(0.0166)
Lagged 1m IV	-0.0214	0.0281	0.0188	0.111***	0.141***
	(0.0534)	(0.0635)	(0.0225)	(0.0199)	(0.0184)
Constant	0.0248***	0.0230***	0.0210***	0.0200***	0.0164***
	(0.0063)	(0.0051)	(0.0019)	(0.0019)	(0.00262)
R-squared	0.949	0.962	0.994	0.995	0.992
Quintile 2					
Contemporaneous 1m IV	0.995***	0.976***	0.899***	0.856***	0.830***
	(0.0326)	(0.0212)	(0.0190)	(0.0172)	(0.0147)
Lagged 1m IV	-0.00684	-0.00724	0.0692***	0.110***	0.146***
	(0.0278)	(0.0198)	(0.0182)	(0.0171)	(0.0166)
Constant	0.0209***	0.0205***	0.0166***	0.0151***	0.00806***
	(0.0031)	(0.0018)	(0.0018)	(0.0019)	(0.0024)
R-squared	0.985	0.995	0.996	0.995	0.994
Quintile 3					
Contemporaneous 1m IV	0.999***	0.951***	0.882***	0.876***	0.832***
	(0.0229)	(0.0172)	(0.0174)	(0.0173)	(0.0192)
Lagged 1m IV	-0.0250	0.0215	0.0726***	0.0796***	0.140***
	(0.0200)	(0.0159)	(0.0166)	(0.0171)	(0.0215)
Constant	0.0235***	0.0147***	0.0180***	0.0150***	0.00408
	(0.00233)	(0.00174)	(0.00190)	(0.00223)	(0.00361)
R-squared	0.992	0.996	0.996	0.995	0.988
Quintile 4					
Contemporaneous 1m IV	0.980***	0.920***	0.899***	0.861***	0.724***
	(0.0182)	(0.0163)	(0.0168)	(0.0175)	(0.0270)
Lagged 1m IV	-0.00230	0.0411***	0.0592***	0.0903***	0.255***
	(0.0152)	(0.0149)	(0.0160)	(0.0176)	(0.0312)
Constant	0.0162***	0.0146***	0.0116***	0.0132***	0.00366
	(0.00200)	(0.00190)	(0.00217)	(0.00261)	(0.00607)
R-squared	0.995	0.996	0.995	0.993	0.972
Quintile 5					
Contemporaneous 1m IV	0.918***	0.897***	0.858***	0.848***	0.681***
	(0.0141)	(0.0177)	(0.0206)	(0.0250)	(0.0310)
Lagged 1m IV	0.0333***	0.0507***	0.0845***	0.0955***	0.296***
	(0.0121)	(0.0162)	(0.0197)	(0.0260)	(0.0361)
Constant	0.0167***	0.0115***	0.0101***	0.00818**	-0.00291
	(0.00209)	(0.00239)	(0.00299)	(0.00403)	(0.00843)
R-squared	0.996	0.995	0.992	0.987	0.961

Table 6 cont.: Six Month Options

	Term Structure Quintile				
Quintile: Change IV	1	2	3	4	5
Quintile 1					
Contemporaneous 1m IV	1.119***	0.813***	0.746***	0.645***	0.571***
	(0.130)	(0.0839)	(0.0392)	(0.0342)	(0.0239)
Lagged 1m IV	-0.0701	0.117	0.160***	0.261***	0.336***
	(0.110)	(0.0793)	(0.0382)	(0.0344)	(0.0265)
Constant	0.0421***	0.0580***	0.0570***	0.0528***	0.0504***
	(0.0131)	(0.0064)	(0.0032)	(0.0033)	(0.0037)
R-squared	0.822	0.935	0.982	0.981	0.979
Quintile 2					
Contemporaneous 1m IV	0.972***	0.848***	0.711***	0.679***	0.564***
	(0.0429)	(0.0350)	(0.0336)	(0.0298)	(0.0240)
Lagged 1m IV	-0.0241	0.0442	0.177***	0.201***	0.337***
	(0.0366)	(0.0328)	(0.0323)	(0.0296)	(0.0270)
Constant	0.0481***	0.0531***	0.0481***	0.0458***	0.0336***
	(0.0041)	(0.0031)	(0.0032)	(0.0033)	(0.0039)
R-squared	0.971	0.984	0.984	0.983	0.981
Quintile 3					
Contemporaneous 1m IV	0.866***	0.791***	0.698***	0.657***	0.530***
	(0.0362)	(0.0336)	(0.0337)	(0.0306)	(0.0269)
Lagged 1m IV	0.0293	0.0941***	0.166***	0.195***	0.348***
	(0.0316)	(0.0311)	(0.0321)	(0.0302)	(0.0301)
Constant	0.0572***	0.0465***	0.0486***	0.0487***	0.0352***
	(0.00368)	(0.00341)	(0.00369)	(0.00393)	(0.00505)
R-squared	0.978	0.983	0.981	0.979	0.970
Quintile 4					
Contemporaneous 1m IV	0.810***	0.741***	0.704***	0.632***	0.453***
	(0.0336)	(0.0324)	(0.0322)	(0.0300)	(0.0315)
Lagged 1m IV	0.0709**	0.118***	0.145***	0.203***	0.417***
	(0.0281)	(0.0296)	(0.0306)	(0.0303)	(0.0364)
Constant	0.0515***	0.0479***	0.0447***	0.0463***	0.0311***
	(0.00369)	(0.00377)	(0.00416)	(0.00448)	(0.00710)
R-squared	0.979	0.981	0.978	0.974	0.948
Quintile 5					
Contemporaneous 1m IV	0.701***	0.690***	0.654***	0.624***	0.359***
	(0.0264)	(0.0308)	(0.0354)	(0.0347)	(0.0363)
Lagged 1m IV	0.113***	0.128***	0.165***	0.184***	0.471***
	(0.0226)	(0.0282)	(0.0338)	(0.0361)	(0.0422)
Constant	0.0558***	0.0441***	0.0364***	0.0362***	0.0291***
	(0.00390)	(0.00417)	(0.00514)	(0.00561)	(0.00986)
R-squared	0.980	0.979	0.970	0.967	0.922

Table 7: Straddle Returns Sorted by Term Structure

This table reports the returns of portfolios of ATM straddles created by sorting on the implied volatility term structure. Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; portfolio 10 holds straddles which have the most inverted term structure. The portfolios listed contain options of one to six months maturity, respectively, and the returns of a long/short portfolio which owns 6 month options and shorts 1 month options for each decile. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

One Month Options: Held for Two Weeks

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0315***	0.0182*	0.0086	0.0042	0.0032	0.0045	0.0030	0.0021	-0.0079	-0.0239***	-0.0554***
St. Error	(0.0079)	(0.0082)	(0.0077)	(0.0077)	(0.0075)	(0.0076)	(0.0077)	(0.0072)	(0.007)	(0.0061)	(0.0053)

One Month Options: Held Until Expiry

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0255	0.0040	-0.0141	-0.0336*	-0.0330*	-0.0336*	-0.0452***	-0.0530***	-0.0744***	-0.1185***	-0.1441***
St. Error	(0.0195)	(0.0192)	(0.0182)	(0.0182)	(0.0177)	(0.0175)	(0.017)	(0.0169)	(0.0154)	(0.0137)	(0.0118)
Sharpe Ratio	0.273	0.017	-0.190	-0.434	-0.437	-0.459	-0.608	-0.714	-1.117	-1.964	-2.723

Two Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0246**	0.0210**	0.0152	0.0131	0.0109	0.0156	0.0145	0.0150	0.0077	-0.0045	-0.0291***
St. Error	(0.0104)	(0.0104)	(0.0101)	(0.0099)	(0.0099)	(0.0099)	(0.0095)	(0.0095)	(0.0093)	(0.0082)	(0.0055)

Three Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0225***	0.0200**	0.0187**	0.0196**	0.0172**	0.0184**	0.0173**	0.0233***	0.0236***	0.0168**	-0.0057
St. Error	(0.008)	(0.0083)	(0.0076)	(0.0078)	(0.0079)	(0.0073)	(0.0076)	(0.0078)	(0.008)	(0.0071)	(0.0052)

Table 7, cont. Four Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0129**	0.0135*	0.0135**	0.0084	0.0131**	0.0199***	0.0195***	0.0198***	0.0160**	0.0188***	0.0058*
St. Error	(0.0065)	(0.007)	(0.0067)	(0.0065)	(0.0063)	(0.007)	(0.0064)	(0.0067)	(0.0063)	(0.0061)	(0.0038)

Five Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0065	0.0103*	0.0118**	0.0130**	0.0163***	0.0171***	0.0193***	0.0238***	0.0205***	0.0279***	0.0214***
St. Error	(0.0057)	(0.0057)	(0.0057)	(0.0057)	(0.006)	(0.0059)	(0.0057)	(0.0059)	(0.0058)	(0.0055)	(0.0033)

Six Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0080	0.0125**	0.0126**	0.0167***	0.0147***	0.0165***	0.0203***	0.0266***	0.0266***	0.0342***	0.0261***
St. Error	(0.005)	(0.0052)	(0.005)	(0.0052)	(0.0052)	(0.005)	(0.0053)	(0.0053)	(0.0054)	(0.0052)	(0.0032)
Sharpe Ratio	0.256	0.443	0.464	0.633	0.544	0.650	0.775	1.036	1.022	1.391	1.697

Six Minus One: Calendar Spreads

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	-0.0156	0.0110	0.0278*	0.0516***	0.0487***	0.0522***	0.0660***	0.0801***	0.1026***	0.1535***	0.1690***
St. Error	0.0159	0.0155	0.0145	0.0145	0.0139	0.0140	0.0133	0.0131	0.0118	0.0109	0.0113
Sharpe Ratio	-0.254	0.127	0.397	0.769	0.755	0.806	1.085	1.339	1.920	3.123	3.312

Table 8: Straddle Returns Sorted on Change in Realized Volatility

This table reports the results of straddle returns sorted on term structure and realized volatility. Straddle returns for one, two, and six months are first sorted into quintiles based on the implied volatility term structure as measured by $\frac{1mIV}{6mIV} - 1$. Within each term structure, portfolios are then sorted into three buckets according to the change in realized volatility.

Panel A: One Month Options Held to Expiry

	Term Structure					
ΔRV	1 (depressed)	2	3	4	5 (inverted)	5-1
1 (Low)	-0.1556***	-0.1734***	-0.1807***	-0.2040***	-0.2589***	-0.1033***
	(0.0176)	(0.0158)	(0.0154)	(0.015)	(0.0132)	(0.0103)
2	-0.0482**	-0.0751***	-0.0782***	-0.1082***	-0.1613***	-0.1131***
	(0.0190)	(0.0191)	(0.0179)	(0.0171)	(0.0159)	(0.0114)
3 (High)	0.2347***	0.1712***	0.1608***	0.1668***	0.1271***	-0.1075***
	(0.0231)	(0.0217)	(0.0222)	(0.0206)	(0.0179)	(0.0165)
3-1						-0.0042
						(0.0159)

Panel B: Two Month Options Held to Expiry

	Term Structure					
ΔRV	1 (depressed)	2	3	4	5 (inverted)	5-1
1 (Low)	-0.0658***	-0.0657***	-0.0705***	-0.0734***	-0.0908***	-0.0249***
	(0.0177)	(0.0189)	(0.0171)	(0.0182)	(0.0171)	(0.0046)
2	-0.0115	-0.0151	-0.0103	-0.0193	-0.0327**	-0.0212***
	(0.016)	(0.016)	(0.018)	(0.015)	(0.0142)	(0.0048)
3 (High)	0.1397***	0.1245***	0.1225***	0.1394***	0.1242***	-0.0155**
	(0.0129)	(0.01)	(0.0123)	(0.0112)	(0.0091)	(0.0068)
3-1						0.0094
						(0.0065)

Panel C: Six Month Options Held to Expiry

	Term Structure					
Δ RV	1 (depressed)	2	3	4	5 (inverted)	5-1
1 (Low)	-0.0237***	-0.0169***	-0.0189***	-0.0147***	-0.0147***	0.0090***
	(0.0044)	(0.0043)	(0.0042)	(0.0044)	(0.0043)	(0.0027)
2	-0.0010	0.0018	0.0058	0.0126**	0.0149***	0.0159***
	(0.0048)	(0.005)	(0.0051)	(0.0052)	(0.0053)	(0.0031)
3 (High)	0.0520***	0.0586***	0.0606***	0.0747***	0.0883***	0.0363***
	(0.0064)	(0.0065)	(0.0064)	(0.0068)	(0.0071)	(0.0046)
3-1						0.0273***
						(0.0050)

Table 9: Summary Statistics and Correlations: Overreaction Measures by Decile

Each month, firms are sorted according to the implied volatility term structure, as measured by $\frac{1mIV}{6mIV} - 1$. Panel A (B) lists the averages (correlations) of three overreaction measures for each term structure decile. The three measures are calculated for each firm, for each month, for each decile. Each month, the measures are averaged; the table reports the averages of the monthly averages for each decile. The first measure, $\frac{1mIV}{12mRV} - 1$, compares one month implied volatility against realized volatility calculated over one year, as defined in Goyal and Saretto. The second, VRP, measures the volatility risk premium, as defined by $\frac{1mIV}{1mRV} - 1$. The third, $\frac{1mIV}{IV_{ave}} - 1$, measures one month implied volatility against its twelve month average. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

Panel A: Summary Statistics

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All
$\frac{1mIV}{12mRV} - 1$	-0.1390	-0.0866	-0.0568	-0.0327	-0.0111	0.0131	0.0371	0.0723	0.1188	0.2727	0.0187
VRP	0.0849	0.0974	0.1113	0.1228	0.1329	0.1469	0.1610	0.1838	0.2201	0.3842	0.1645
$\frac{1mIV}{IV_{ave}} - 1$	-0.0100	-0.0100	-0.0094	-0.0078	-0.0069	-0.0063	-0.0050	-0.0040	-0.0020	-0.0014	-0.0063

Panel B: Correlations

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All
$\frac{1mIV}{12mRV} - 1$	0.5812	0.6193	0.6327	0.6558	0.6560	0.6575	0.6702	0.6692	0.6836	0.7474	0.6581
VRP	0.0134	0.0380	0.0934	0.1123	0.1104	0.1168	0.1215	0.1178	0.0803	0.2361	0.0183
$\frac{1mIV}{IV_{ave}} - 1$	0.5223	0.6124	0.6484	0.6575	0.6496	0.6903	0.6846	0.6920	0.7156	0.7099	0.7201

Table 10: Straddle Return Portfolios Regressed on "Underreaction" and "Overreaction" Portfolios

The returns of portfolios of ATM straddles created by sorting on the implied volatility term structure are regressed on "underreaction" and "overreaction" portfolios. The portfolios are sorted on the implied volatility term structure, as defined by $\frac{1mIV}{6mIV} - 1$. Portfolio 1 (10) holds straddles which have the most upward-sloping (inverted) term structure. The "overreaction" and "underreaction" portfolios hold ATM straddles, and are created by sorting into declies on $\frac{1mIV}{12mRV} - 1$. The "underreaction" portfolio is decile one, where implied volatility is lowest relative to realized volatility; the "overreaction" portfolio is decile 10, where implied volatility is highest relative to realized volatility. The final column regresses the 10-1 portfolio, created by sorting on term structure, on the 10-1, overreaction- underreaction portfolio, created by sorting on $\frac{1mIV}{12mRV} - 1$. In each case below the portfolio returns are regressed on portfolios with matching maturities. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

Panel A: One Month Options Held to Expiry

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
over	0.350***	0.467***	0.430***	0.450***	0.492***	0.575***	0.609***	0.610***	0.613***	0.591***	
	(0.0541)	(0.0545)	(0.0505)	(0.0521)	(0.0522)	(0.0490)	(0.0530)	(0.0503)	(0.0476)	(0.0379)	
under	0.722***	0.621***	0.596***	0.561***	0.522***	0.472***	0.394***	0.381***	0.317***	0.224***	
	(0.0361)	(0.0364)	(0.0337)	(0.0348)	(0.0348)	(0.0327)	(0.0354)	(0.0336)	(0.0318)	(0.0253)	
overunder											-0.5307***
											(0.0491)
Constant	0.0457***	0.0421***	0.0222**	0.0110	0.0157	0.0271***	0.0260**	0.0215**	-0.00342	-0.0409***	-0.0503***
	(0.0107)	(0.0108)	(0.0100)	(0.0103)	(0.0103)	(0.0097)	(0.0105)	(0.0099)	(0.0094)	(0.0075)	(0.0129)
R-squared	0.869	0.859	0.864	0.850	0.846	0.863	0.824	0.834	0.827	0.846	0.346

Panel B: Two Month Options Held for One Month

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
over	0.342***	0.446***	0.453***	0.492***	0.447***	0.551***	0.598***	0.595***	0.648***	0.641***	
	(0.0444)	(0.0426)	(0.0402)	(0.0438)	(0.0412)	(0.0388)	(0.0415)	(0.0448)	(0.0438)	(0.0333)	
under	0.693***	0.619***	0.586***	0.536***	0.570***	0.501***	0.417***	0.413***	0.351***	0.262***	
	(0.0342)	(0.0328)	(0.0309)	(0.0337)	(0.0317)	(0.0298)	(0.0319)	(0.0345)	(0.0337)	(0.0256)	
overunder											-0.4396***
											(0.0462)
Constant	0.0026	0.0045	0.0038	0.0017	0.0000	0.0079**	0.0137***	0.0138***	0.0085**	0.0010	0.0021
	(0.0042)	(0.0041)	(0.0038)	(0.0042)	(0.0039)	(0.0037)	(0.0039)	(0.0043)	(0.0042)	(0.0032)	(0.0056)
R-squared	0.900	0.908	0.912	0.893	0.904	0.916	0.895	0.878	0.878	0.909	0.290

Panel C: Six Month Options Held for One Month

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
over	0.276***	0.501***	0.504***	0.424***	0.560***	0.512***	0.462***	0.548***	0.437***	0.607***	
	(0.0350)	(0.0376)	(0.0393)	(0.0380)	(0.0434)	(0.0380)	(0.0420)	(0.0476)	(0.0495)	(0.0392)	
under	0.672***	0.499***	0.447***	0.553***	0.407***	0.434***	0.520***	0.433***	0.544***	0.382***	
	(0.0322)	(0.0346)	(0.0361)	(0.0350)	(0.0399)	(0.0350)	(0.0386)	(0.0438)	(0.0455)	(0.0361)	
overunder											-0.3044***
											(0.0491)
Constant	-0.0141***	-0.0059***	-0.0039*	-0.0025	-0.0002	0.0005	0.0025	0.0118***	0.0075**	0.0190***	0.0337***
	(0.0020)	(0.0022)	(0.0023)	(0.0022)	(0.0025)	(0.0022)	(0.0024)	(0.0028)	(0.0029)	(0.0023)	(0.0032)
R-squared	0.877	0.865	0.841	0.859	0.817	0.848	0.833	0.793	0.783	0.851	0.148