IS THERE INFORMATION IN THE VOLATILITY SKEW?

JAMES S. DORAN*
DAVID R. PETERSON
BRIAN C. TARRANT

Since the 1987 crash, option prices have exhibited a strong negative skew, implying higher implied volatility for out-of-the-money puts than at- and in-the-money puts. This has resulted in incorporating multiple jumps and stochastic volatility within the data generating process to improve the Black–Scholes model in an attempt to capture negative skewness and a highly leptokurtic distribution. The general conclusion is that there is a large jump premium in the short term, which best explains the significant negative skew for short maturity options. Alternative explanations for the negative skew are related to market liquidity driven by demand shocks and supply shortages. Regardless of the explanation for the negative skew, we assess the information content in the shape of the skew to infer if the option market can accurately forecast stock market crashes and/or spikes upward.

The authors acknowledge the helpful comments and suggestions of James Ang, Paul Brockman, Gary Benesh, Don Chance, Steve Ferris, John Howe, Dave Humphrey, Bong-Soo Lee, Ehud Ronn, Sheridan Titman, and participants at a seminar held at the Florida State University. Additionally, we would like to thank Bob Webb and the comments from an anonymous referee that have significantly improved this paper.

*Corresponding author, Department of Finance, College of Business, Florida State University, Tallahassee, FL 32306; e-mail: jsdoran@cob.fsu.edu

Received May 2006; Accepted October 2006

- *James S. Doran is in the Department of Finance at Florida State University in Tallahassee, Florida.*
- *David R. Peterson is the Wachovia Professor of Finance in the Department of Finance at Florida State University in Tallahassee, Florida.*
- *Brian C. Tarrant is in the Department of Finance at Florida State University in Tallahassee, Florida.*

The Journal of Futures Markets, Vol. 27, No. 10, 921–959 (2007)

Published online in Wiley InterScience (www.interscience.wiley.com).
DOI: 10.1002/fut.20279

We demonstrate, using all options on the S&P 100 from 1984–2006, that the shape of the skew can reveal with significant probability when the market will crash or spike. However, we find the magnitude of the spike prediction is not economically significant. Our findings are strongest for the short-term out-of-the money puts, consistent with the notion of investors' aversion to large negative movements. We also find that the power of the crash/spike prediction decreases with an increase in the time to option maturity. Jrl Fut Mark 27:921–959, 2007

INTRODUCTION

Many studies have attempted to explain the empirical properties associated with option prices; a particular concern is why the implied distribution is negatively skewed and fat-tailed. Bates (1991, 2000), Bakshi, Cao, and Chen (1997), Pan (2002) and many others have fitted the distribution with stochastic volatility and jumps in attempts to improve model-fit over the traditional Black and Scholes (1973) framework. The findings from these model estimations suggest that to explain negative volatility skews it is necessary to incorporate a "jump premium." In other words, as the market becomes more volatile, investors become more worried about a market crash and are willing to pay a higher premium to purchase the put option's "insurance" attribute.

Other researchers offer explanations that refute a negative jump aversion explanation for the negative skewness in option prices. Their results are consistent with the possibility that there is both a positive jump premium and a negative jump premium embedded in option prices. The factors that lead to this conclusion include the demand pressures of dealers versus end-users as shown by Garleanu, Pedersen, and Poteshman (2005), the costs of short-selling stocks found by Evans, Geczy, Musto, and Reed (2005), and limits to arbitrage discussed in Bollen and Whaley (2004).

Our intent is not to explain why a skew exists, but to learn if there is information within the skew for future market movements. This contributes to a vast literature that has examined the information content in implied volatility, but has focused mainly on at-the-money (ATM) implied volatility. If option investors are well informed, as Manaster and Rendleman (1982) propose, then the information contained within the skew ex-ante, should reveal ex-postperformance.

Because implied volatility has been shown to predict future returns and realized volatility, and volatility skews contain information about high jump fears, we test whether large negative skews can predict future market crashes. Implied volatility from OEX S&P 100 Index put and call options are used to predict significant price movements in the underlying S&P 100 Index. Options are sorted into maturity and moneyness baskets so that the information content between the different option categories can be examined.

We add to the literature by more comprehensively defining the direct predictive link between the option markets and the asset markets than is possible when using a volatility index, such as VIX. Theoretically, the differences in the implied volatility levels within "smiles" and "smirks" provided by option prices could be evidence of a rational market if the additional premiums embedded in the implied volatility are justified by a market crash risk premium. If the market is paying an additional risk premium that does not seem to be justified by market crash fears, then the search must continue for other conclusive risk measures to justify the implied volatility smiles and smirks in a rational market. A more complete study of implied volatility across moneyness and maturities can provide more evidence about investors' risk perceptions and trading activities.

Specifically, we explore the implied volatility of deep out-of-the-money (DOTM) puts and how it relates to the implied volatility of (a) out-of-the-money OTM puts, (b) ATM puts, and (c) in-the-money (ITM) puts. To capture information across the entire implied volatility skew, we employ the nonparametric estimation of risk-neutral skewness calculated in Bakshi, Kapadia, and Madan (2003). If investors fear a market crash in the relative near-term, anticipated stock volatility is likely to increase in the options market as opinions about market expectations deviate. For instance, some traders who are fearful of a sharp market decline can trade DOTM puts with investors who do not share their fears concerning the severity of the potential market drop. If these groups of traders who fear the chance of a market crash are better informed than other traders, then more information should surface in the implied volatility of DOTM and OTM put options when compared to other options. Similarly, if there is less fear, or greater optimism in the market, then information about an apparent spike upward should be apparent in the OTM call skew. This will occur only if there is both a positive and negative jump premium, which is in direct conflict with the one-sided jump premium specification typically used in fitting the implied distribution. Thus, in the spirit of Bates (1991, 2000), we study how the option pricing skewness changes across the moneyness, and if the jump premium related to crash insurance is justified.

A refined predictive link would prove useful for practitioners as well. Many option users fall under the category of hedgers and speculators.

Hedgers are more likely to use options (especially DOTM and OTM put options) to act as insurance against a substantial market devaluation. If there is a relation between implied volatility for options with varying degrees of moneyness and movement of the underlying asset prices, the association may inform hedgers of optimal hedging times to protect their assets. If volatility skew shifts can accurately identify periods exposed to a higher market crash probability, then the additional crash premium may well be worth the expense to protect assets with a put option. Of course, if increased implied volatility cannot be linked to higher market crash probabilities, then the extra crash premium may be an inefficient use of funds and simply a function of market liquidity.

The remainder of this article is organized as follows. In the next section, the empirical data and methodology ids outlined, including the model for estimating the predictive power of the implied volatility measures. Then the results derived from the model are reported in the third section. Key results of the study and suggestions for some possible research extensions are given in the final section.

METHODOLOGY AND DATA

Methodology

To identify the information content available within implied volatilities, put and call options are sorted across moneyness and maturity. By sorting the options into various bins, the shape of the cross-sections can be captured to highlight the differences between smiles, smirks, and sneer patterns. For example, a volatility smirk is captured if 5% OTM puts have a higher implied volatility than put options ATM, and the ATM put options have an implied volatility higher than the 5% ITM put options. As Bates (2000) points out, it is necessary to distinguish between calls and puts, as higher crash concerns will result in higher implied volatility for OTM puts than the corresponding ITM calls.

We calculate implied volatilities via the Black and Scholes (1973) model. Actual market-traded prices for the associated call and put options are input into the Black–Scholes model, yielding implied volatility values for European-style options. The implied volatility values are then adjusted for the early exercise feature using the methodology in Barone-Adesi and Whaley (1987). The S&P 100 Index (the underlying asset) pays dividends, but the dividend payouts are small in magnitude and not clustered through time, avoiding any dividend-induced valuation jumps. It is critical that we use the American adjusted Black–Scholes implied volatility because the model's misspecification does not account for stochastic volatility and jumps. As a result, the implied volatility of the options should contain information about jumps and/or stochastic volatility premiums. We will address potential measurement errors in implied volatility shortly.

To capture the shape of the skew, three variables are created:

$$\Delta\sigma^P_{do,o} = \sigma^P_{do} - \sigma^P_o \tag{1}$$

$$\Delta\sigma^P_{do,a} = \sigma^P_{do} - \sigma^P_a \tag{2}$$

$$\Delta\sigma^P_{do,i} = \sigma^P_{do} - \sigma^P_i \tag{3}$$

where σ^P_{do}, σ^P_o, σ^P_a, and σ^P_i represent DOTM, OTM, ATM, and ITM puts. For the calls, the skew variables are constructed in the same fashion:

$$\Delta\sigma^C_{do,o} = \sigma^C_{do} - \sigma^C_o \tag{4}$$

$$\Delta\sigma^C_{do,a} = \sigma^C_{do} - \sigma^C_a \tag{5}$$

$$\Delta\sigma^C_{do,i} = \sigma^C_{do} - \sigma^C_i \tag{6}$$

where σ^C_{do}, σ^C_o, σ^C_a, and σ^C_i represent DOTM, OTM, ATM, and ITM calls.

We define moneyness as, $K/S(t)e^{rT}$, where K is the strike price, $S(t)$ is the price of the index at time t, r is the risk-free rate, and T is the time to maturity of the option. The moneyness categories are similar to those given in Bakshi and Kapadia (2003). The DOTM put options are assigned to a moneyness interval of .875 to .925. The OTM puts and ITM call options are assigned to a bin interval of .925 to .975. The ATM options include the interval from .975 to 1.025. The OTM calls and ITM puts have an interval of 1.025 to 1.075. And DOTM calls are assigned to the 1.075 to 1.125 bin.[1]

As shown by Hentschel (2003), inverting individual OTM and ITM options can result in incorrect inferences on the implied volatility if the option price is measured with error. By examining multiple implied volatilities over each category, individual option measurement errors can be greatly mitigated. As such, the average implied volatility within the categories will allow comparison between sections of the ITM side of the implied volatility curve and the related sections of the OTM side to capture the skewness. The strike prices of all traded options are measured against the last reported trade of the underlying asset.

[1]For example, the .875 to .925 moneyness interval includes options with strike prices that are approximately between 12.5% and 7.5% below the current level of the forward price of the index.

Alternatively, we adopt the risk-neutral measure of skewness derived in Bakshi, Kapadia, and Madan (2003). The benefit of using this type of metric is that the calculation does not rely on a given parametric assumption, incorporating only OTM puts and calls for a given maturity. The variable is defined as:

$$BKM_t = \frac{e^{r\tau}W(t,\tau) - 3\mu(t,\tau)e^{r\tau}\nu(t,\tau) + 3\mu(t,\tau)^2}{(e^{r\tau}\nu(t,\tau) - \mu(t,\tau)^2)^{\frac{3}{2}}} \tag{7}$$

where $\mu(t,\tau)$, $\nu(t,\tau)$, $W(t,\tau)$, and $\mu(t,\tau)$ are defined in the Appendix. This measure will express the entire volatility skew as a single value, which provides a simple alternative to dividing the skew into parts. However, the major disadvantage in using this type of measure is that it cannot identify which part of the skew derives the information content.

We attempt to identify investors' option-market behavior associated with near-term market declines and increases. As such, it is important to control for macroeconomic changes that affect implied volatilities. There is a well-established link between the term structure of interest rates and future economic activity within the United States and other countries.[2] Of special interest to our study is the timing link between an inverted (or inverting) yield curve and subsequent economic downturns, notably recessionary periods in the economy. To control for the economic changes, a term structure (TS) of interest rates variable is included. By constructing the time-varying difference between the 10-year Treasury Bond and the 1-year Treasury Note, the information content associated with macroeconomic issues can be controlled.

As noted by Pan (2002) and others, the general level of risk in the options market increases as volatility levels rise. Thus, a measure of overall option market volatility is an important control. Because ATM options typically have the smallest pricing bias, ATM put (call) implied volatility is chosen as the control variable.[3]

We are particularly interested in the overall sense of movement in the OTM side of the volatility curve. As such, several factors that could mitigate or enhance skew changes must be controlled to help reveal the actual information innovations that are manifested within implied volatility curve changes. George and Longstaff (1993) and others link

[2]Chan, Karceski, and Lakonishok (1998) provide evidence that the interest rate term premium performs well as a macroeconomic factor in capturing return comovements.

[3]Hentschel (2003) discusses the potential measurement error in inverting option prices using Black–Scholes with small pricing errors. He documents that the pricing errors are significant for OTM and ITM options. The ATM implied volatility has, by comparison, fewer problems when inverting prices.

cross-sectional differences in bid-ask spreads in the S&P 100 Index option market to trading activity. Consequently, average percentage bid-ask spreads for OTM puts (calls) are included as controls, denoted as BA_o^P (BA_o^C). With higher uncertainty in the market, investors should expect wider bid-ask spreads, consistent with the conclusions in Bollen and Whaley (2004), which may have additional or independent predictive power beyond the volatility skew.

Recognizing the likely participation of both hedgers and speculators within the options market, and to address illiquidity issues for OTM put and call options, two controls are developed. We construct an open interest control variable, OI_o^P (OI_o^C), to help capture the effects of hedgers entering and exiting the market because new OTM put (OTM call) positions should be opened when more hedgers believe there is an increase in the likelihood of a market crash (increase). In addition, an OTM put (call) volume control variable, V_o^P (V_o^C), is introduced to capture the effects of changing speculator positions driven by the expectation of price movements, but not necessarily a crash (spike). With this series of volume-related variables, we hope to negate any measurement error that a few trades in thinly traded options might introduce into the results.

To understand the additional information held within implied volatilities, it is key to evaluate the role of options' maturity structures. It is reasonable to believe that market timing is a difficult task even when an option trader believes he has superior information. It is also well documented that jump concerns are more prevalent for short maturities, highlighted by muted long-term skews. To address these concerns and to understand the maturity structure of options better, three different days-to-maturity intervals are evaluated: 10 days to 30 days, 31 days to 60 days, and 61 days to 90 days. Options with maturities less than 10 days are eliminated from the sample to avoid excessive measurement error that is often embedded within short-maturity options. An impending market crash or spike upward should materialize itself in greater magnitude within the 10- to 30-day interval, with diminishing impact in 31 to 60 days and 61 to 90 days-to-maturity intervals.

To mitigate potential measurement error, all options assigned to a specific maturity bin (e.g., 10–30 days) are grouped together. Each grouping of options is then evaluated together, so the results are an average for a particular group. For example, an option with 15 days to maturity is grouped in the 10–30 days bin. All options contained within the 10–30 days bin are always the near-term month expiration option. Options within the 31–60 days bin are the second near-term month expiration, and so on. Consequently, all options grouped in the same maturity bin expire on the same day and the evaluations do not suffer from multiple confounding expiration dates.

Model

If investors have increased aversion to negative market movements, the information will manifest itself within the volatility skew. To assess this, it is necessary to define what a market crash is. We define large market movements as a given percentage change in the index over a given day. These threshold values, v, are set at -1.65% (1.72%) and -2.73% (2.93), which corresponds to the top 5% and 1% of all daily negative (positive) returns over the period, respectively. Large negative jumps (circles) and positive jumps (squares) are highlighted in Figure 1. As the figure shows, jumps can be clustered together, and tend to occur during periods of high volatility. Figure 1 includes the VIX, demonstrating the relationship between periods of high volatility and large daily movements. In particular, notice that jumps can be clustered together, and a negative jump can

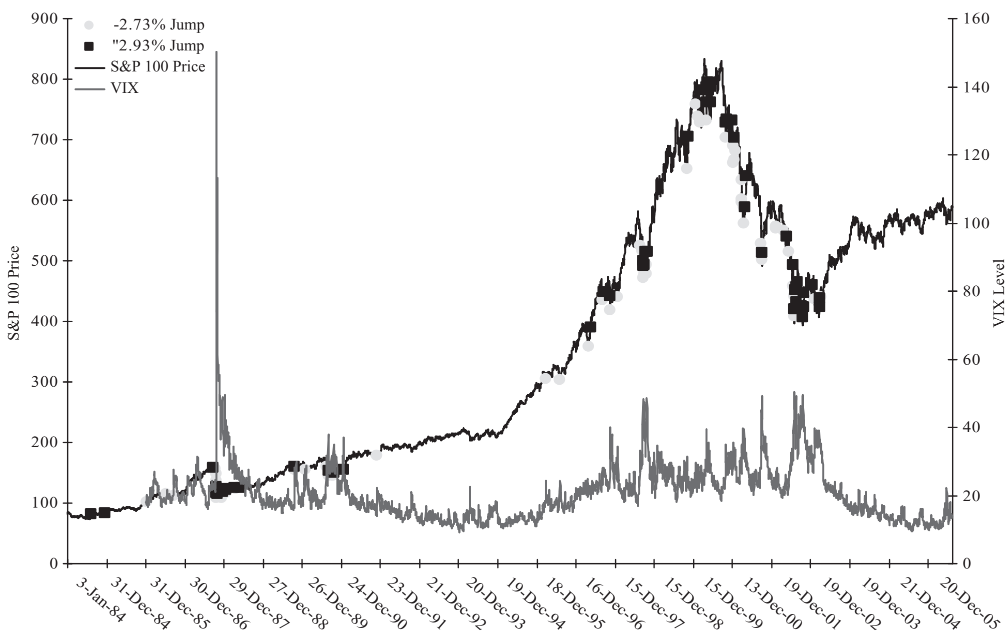

FIGURE 1

S&P 100 and major daily moves. This figure shows the S&P 100 level from January 1984 through April 2006. The circles document -2.73% or greater price drops over a given day. The squares document 2.93% or greater price increases over a given day. The VIX index (shown in %) is included to show the relationship between jumps and high levels of volatility, graphed on the right axis.

be subsequently followed by a positive jump. Consequently, it is important not only to examine a jump as a stand-alone event, but also whether a jump leads or follows another jump, and whether that jump is positive or negative.

A probit model is employed to capture the information content in the volatility skew to determine the association between the severity of the skew and the probability of a market crash or spike upward. The probit model is used to analyze the event that the S&P 100 Index experiences a return, R_t, in excess of the absolute value of v from day t, the current day, to $t + \tau$, the expiration of the option, j. If a jump occurs at any time from day t to $t + \tau$, all option days, D, up to the day the jump occurred receives a value of one. Correspondingly, that is why there are 315 option day observations in the model when the market fell 2.73%.[4] If no jump occurs any time within the options maturity, all option days receive a value of zero.

Additionally, we employ the methodology in Lee and Mykland (2006), which attempts to isolate jumps from periods of "high" absolute returns by standardizing by a local volatility, $\hat{\sigma}_t$. This identifies jumps that are not a function of the distribution of returns, and should be independent of volatility levels. Comparing realized returns at a given point in time to an estimated local volatility creates the ratio for the basis of their test statistic. This statistic, T(t), which tests on the given day whether there was a jump, is defined as:

$$T_t = \frac{\log(S_t) - \log(S_{t-1})}{\hat{\sigma}_t} \tag{8a}$$

where

$$\hat{\sigma}_t = \sqrt{\frac{1}{K-2} \sum_{j=t-K+2}^{t=1} |\log S(j) - \log S(j-1)||\log S(j-1) - \log S(j-2)|} \tag{8b}$$

where S_t is the price of the index on day t. As Lee and Mykland point out, the choice of window size K is not obvious, and can result in different levels of efficiency depending on the length and frequency of the observations. As a result, we employ two window lengths, 16 and 30 days, for the calculation of local volatility.[5] To test for the presence of a jump on a given day, the test statistic is compared against a threshold level, as defined in Lemma 1 of their article and a critical value of 95%. For the purposes of

[4]Over the estimation window the market had 62 daily decrease of at least −2.73%.

[5]The length of the window was chosen corresponding to the evidence shown in Lee and Mykland (2006). The optimal efficiency of the estimate for short maturity contracts was 16 days. For longer maturities, such as one year, it was around 30 days.

brevity, only the results for the 16-day window are shown because the 30-day window results are similar. Employing this methodology results in 13 negative jump days of −2.19% or greater, leading to 109 daily option observations. For positive jumps, there are only 4 days that exceed the critical value, resulting in too few observations to generate reliable statistical predictions. We refer to these jumps as LM (Lee and Mykland defined) jumps. The LM jumps downward (diamonds) are highlighted in Figure 2. Note, in particular the 1990–1994 period of low volatility where several jumps occur. This is quite distinct from Figure 1 where no distributional jumps occur in this period.

The actual day the jump occurs is not important to the option holder. All that is important is that a jump occurs within the maturity of the option. Concurrently, it should not be expected that the jump could be perfectly forecasted, only that there is a general fear that the market is going to experience a decline at some point. Because Standard and Poor's 100 (OEX) options have American-style execution, the option holder does not need to wait for maturity, and can sell or exercise the option right after the jump occurs. This reasoning leads to the implementation of two additional controls in the model. If there is a corresponding

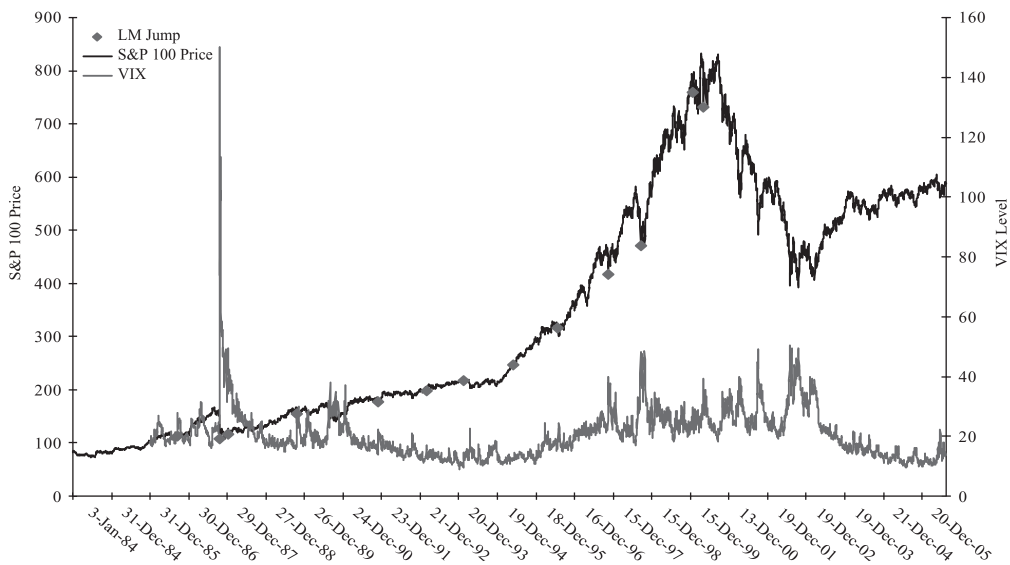

FIGURE 2
S&P 100 and Major Daily Moves using LM Jumps. This figure shows the S&P 100 level from January 1984 through April 2006. The diamonds document negative LM jumps. The VIX index (shown in %) is included to show the relationship between jumps and high levels of volatility, graphed on the right axis.

jump in the opposite direction that exceeds the jump definition, v, anytime prior to the day of the measured jump, t, the measured jump receives a value of zero. This is done to control for potential market microstructure effects such as profit taking and/or short-selling constraints, which could bias the results. Furthermore, the 5 business days after a measured jump are eliminated for similar reasoning.

The following model tests for the relationship using put contracts:

$$\mathrm{Prob}(\mathrm{D}_{\mathrm{j,t}\rightarrow\mathrm{t}+\tau} = 1) = \Phi(\alpha + \beta_1\Delta\sigma^P_{SKEW,t} + \beta_2\sigma^P_{a,t} + \beta_3 BA^P_{o,t} + \beta_4 V^P_{o,t} + \beta_5 OI^P_{o,t} + \beta_6 TS_t) + e_t \tag{9}$$

where $\mathrm{Prob}(\mathrm{D}_{\mathrm{j,t}\rightarrow\mathrm{t}+\tau} = 1)$ is the probability of jump occurring within the option window,
Φ is the standard cumulative normal probability distribution, $\Delta\sigma^P_{SKEW,t}$ is the difference in the implied volatility at time t of either:

$\Delta\sigma^P_{do,o}$ DOTM and OTM options
$\Delta\sigma^P_{do,a}$ DOTM and ATM options
$\Delta\sigma^P_{do,i}$ DOTM and ITM options

or $\mathrm{BKM_t}$ as given by Equation (7)

$\Delta\sigma^P_{a,t}$ is the average implied volatility of ATM options at time t,
$BA^P_{o,t}$ is the average percentage bid-ask spread of OTM puts at time t,
$V^P_{o,t}$ is the average volume of OTM puts at time t expressed in 100,000s,
$OI^P_{o,t}$ is the average open interest of OTM puts at time t expressed in 100,000s, and
TS_t is the difference between the 10-year U.S. Treasury Bond rate and the 1-year U.S. Treasury Note rate at time t, and
α, β are coefficients to be estimated.

The call model is similar, but $\Delta\sigma^P_{SKEW,t}$ becomes $\Delta\sigma^C_{SKEW,t}$, where the three categories become $\Delta\sigma^C_{do,o}$, $\Delta\sigma^C_{do,a}$, and $\Delta\sigma^C_{do,i}$ representing the difference in implied volatility between DOTM and OTM calls, ATM and DOTM calls, and DOTM and ITM calls, respectively. In addition, the BA, V, and OI variables are redefined to apply to OTM calls. Thus, the call model is:

$$\mathrm{Prob}(\mathrm{D}_{\mathrm{j,t}\rightarrow\mathrm{t}+\tau} = 1) = \Phi(\alpha + \beta_1\Delta\sigma^C_{SKEW,t} + \beta_2\sigma^C_{a,t} + \beta_3 BA^C_{o,t} + \beta_4 V^C_{o,t} + \beta_5 OI^C_{o,t} + \beta_6 TS_t) + e_t \tag{10}$$

The appropriate model is initially applied to call and put options in the 10–30 day maturity bin. In subsequent tests, the model is used to evaluate longer maturities.

Ex-Ante Expectations

Four scenarios are explicitly examined: market crashes and upward spikes using put and call contracts. We first examine the case of significant market declines. If there is information contained within the volatility skew, and investors have aversion to market crashes, our expectation for Equation (9) is that $\beta_1 > 0$ for our definitions of the skew variable cases using put contracts. The positive β_1 coefficients are reflective of an increase in the implied volatility skewness on the OTM side of the put curve when a jump occurs. For market crashes, the DOTM and OTM puts will become more valuable, so their implied volatilities will likely increase compared to ATM and ITM put implied volatilities whose owners have little reason to trade. This implies that a positive coefficient β_1 is associated with an increase in the probability of a market decline. For the BKM variable, we expect $\beta_1 < 0$ because BKM will become more *negative* as OTM options become expensive relative to ATM and ITM options. However, this negative coefficient still implies an increase in the probability of a decline. In addition, because volatility and the occurrence of jumps are related, for put contracts we expect that $\beta_2 > 0$. Using the LM jumps as the dependent variable, however, we expect β_2 to be insignificant. This is by construct because the statistic is designed to separate jumps from volatility.

For the call contracts using the model in Equation (10), there are two probable scenarios. If investors have greater aversion to crashes than upward spikes, consistent with the concept of a negative jump premium as proposed in Pan (2002) and Bates (2000), β_1 may be of either sign, but will be statistically insignificant.[6] However, if the market reacts to demand pressures of dealers and end-users by changing the implied volatilities of the call options, we expect β_1 to be positive and statistically significant. Additionally, as in the case for the put contracts, we expect $\beta_2 > 0$. Again, β_2 should be insignificant when using the LM jump as the dependent variable.

[6]It is possible that there is both a negative jump premium for the probability of a market crash and a positive jump premium for the probability of a market spike that results in a net negative premium; however, the models in Pan (2002) and Bates (2000) depict a single affine-Gaussian jump premium. As such, b_1 should be statistically indistinguishable from zero for the call option model.

This leads to our first two formal hypotheses:

Hypothesis 1a: In periods of high volatility, when the market experiences a significant market decline, the put volatility skew in prior days will be more negatively skewed than on low volatility days and when no market crashes occur.

Hypothesis 2a: In periods of high volatility, when the market experiences a significant market decline, the call volatility skew in prior days may be more negatively skewed than on low volatility days and when no market crashes occur.

To test for symmetry in option markets, we explore the case of positive jumps. For put contracts, our expectation is that $\beta < 0$ for our definitions of the skew and $\beta_1 > 0$ for the BKM variable. The rational is that positive jumps traders would be willing to sell puts for lower implied volatility if there is an expected market increase. However, it is plausible that β_1 may be insignificant if the market shows less aversion to upward spikes, with traders less likely to adjust the put volatility skew in response. The coefficient for $\sigma^P_{a,t}$, β_2, is expected to be positive, consistent with higher volatility conditions regardless of the direction of the jump, except in the LM jump case, where it should be insignificant.

Our expectation for the call options in the advent of a market spike upward is for $\beta_1 > 0$. If the market expects a large positive movement, then DOTM calls should be expensive relative to ITM calls compared to nonjump periods. The arguments raised earlier against a positive jump premium still stand; however, we expect the information innovation related to a near-term market spike to materialize in the put implied volatility curve. As with the other conditions of significant market movements, we expect $\beta_2 > 0$ except in the LM jump case, where it should be insignificant.

This leads to our second set of hypotheses:

Hypothesis 1b: In periods of high volatility, when the market experiences a significant market increase, the put volatility skew in prior days may be more positively skewed than on low volatility days and when no market spikes occur.

Hypothesis 2b: In periods of high volatility, when the market experiences a significant market increase, the call volatility skew in prior days will be more positively skewed than on low volatility days and when no market spikes occur.

Finally, because jump premiums are strongest in shorter maturity options, in part due the short-run inability to recover from an exposure to a significant market movement in either direction, our expectation is that longer-term volatility skews will have less information about future market crashes and spikes upward than shorter-term volatility skews. This is consistent with the empirical observation of muted longer-term skews in equity options. This leads to our third hypothesis.

Hypothesis 3: For both puts and calls, as the maturity of the option increases, longer-term volatility skews have little predictive power in forecasting future crashes/spikes due to longer time to recovery.

It is not clear how the coefficients for the percentage bid-ask spread control variable (β_3) will react to market-crash conditions. Increasing risk associated with increasing volatility and decreasing spreads associated with increasing volume are likely to have mitigating effects upon each other. As such, it is not clear ex-ante the directional signs for coefficients for the percentage bid-ask spread control variables, or if OTM put and call options will have the same sign. The same uncertainty exists for market spikes and thus the sign of the bid-ask spread coefficient is unclear ex-ante when there are market positive jumps.

Ex-ante, the coefficient for the put open interest expected sign is $\beta_5 > 0$ for market crashes. For call options, the sign should be reversed. For market spikes upward we expect $\beta_5 < 0$ for the put contracts, whereas the coefficients for call options should be positive. This expectation is consistent with increased trading of put (call) options when option traders believe there is an increased probability of a market crash (spike). Hedgers are likely to seek an increase in their put positions when they believe the probability of a market crash increases. A caveat is necessary for our expectations. If there is asymmetric information in the market and the better-informed traders are options traders, it might be hard to find an offsetting buyer for new open put positions. This could lead to little change in the open interest variable, or an impact linked to the restriction of the supply for OTM put contracts. The reverse could exist for the call option open interest when there is a market increase.

The volume control variable is adopted to capture the effects of illiquidity in the market. Volume will also likely capture the effects of increased speculator activity in the marketplace. As such, we expect the coefficient β_5 to be positive during all times of large market movements, consistent with an increased dispersion of market expectations.

For the term structure of interest rates control variable, the expectation is that the coefficient $\beta_6 < 0$ if a crash is likely to occur. As noted previously, there is a negative relation between narrowing or inverting term structures of interest rates and general economic activity. Therefore, ex-ante, a negative coefficient for the term structure of interest rates is likely to be associated with increases in the probability of a market crash for call and puts. By contrast, for market spikes upward, the coefficient should have a positive sign.

Data

Several sources are utilized to acquire the data. Daily S&P 100 Index option prices are secured from Optionmetrics (New York, NY). The data set covers the period from January 1984 through April 2006.[7] The data includes option trades covering a variety of strike prices, providing a rich range of moneyness coverage. Options with prices below \$0.25 are removed from the sample. Option maturities range from 1 to 360 days, resulting in well over one million total observations over the sample period.

Daily best closing bid and ask prices are reported; so, all option prices in the sample are set to be the midpoint of the two reported observations. Daily best closing bid and ask prices for OTM puts (calls) are scaled by the midpoint price to create the bid-ask control variable. Any option that has a zero bid price is removed from the sample. Daily open interest and volume for each option traded are collected, so the open interest and volume control variables are constructed by aggregating both variables for all options within the OTM moneyness classification (e.g., open interest of OTM puts).

The daily settlement value of the S&P 100 Index is collected from the Chicago Board of Exchange (CBOE) and is adjusted for dividends. Values for the 10-year U.S. Treasury Bond and the 1-year U.S. Treasury Note are assembled from data supplied by the Federal Reserve.

RESULTS

Descriptive Statistics and Preliminary Findings

For the sample period covering January 1984 through April 2006, there are 2,585 option trading days that are used in our sample.[8] Within the sample period, there are 186 trading days where the S&P 100 Index experiences at least a −1.65% daily valuation decline, 46 days with at least a −2.73% daily valuation decline, 172 days with a daily market gain of 1.72% or more, and 47 days with a positive daily jump of 2.93% or greater.

[7]We thank the referee for supplying the data from 1984 through 1995. This data does not include information on bid-ask spreads, option volume, or open interest.

[8]Over the time period, there are considerably more trading days, but not all days have enough options to construct a usable sample given our constraints.

Descriptive statistics are presented in Table I. Moneyness-based maturity bins ranging from DDOTM (deep-deep-out-of-the-money) to DDITM (deep-deep-in-the-money) are presented with the representative mean implied volatility, standard deviation of the implied volatility, number of observations, percentage bid-ask spread, volume, and open interest. Although not all of the moneyness bins are used in estimation due to a small number of observations or low liquidity, all are shown to present an idea of the shape of the skew at each category. As is evident in Panel A, pronounced implied volatility curve skewness exists for both puts and calls for the 10–30 day maturity bin. The skewness is much less pronounced for longer maturities, with a 3.26% drop in the difference between DOTM and ATM puts for the 31–60-day as compared to 10–30-day maturities. This is consistent with Hypothesis 3.

For Panel B, it is important to note the relative lack of volume and open interest for ITM options compared to OTM options. For example, the 10–30-day maturity ITM put options have an average volume of 108 (in 100,000s) compared to the OTM put volume of 1566. Because options on the ITM side of the volatility curves are traded less frequently than the OTM side, we use the OTM moneyness bins to construct the control variables employed in Equations (9) and (10). This choice of control variables gives a more representative depiction of the changes in the shape of the OTM side of the put and call implied volatility curves.

Table II reports the means, standard deviations, and number of observations for the differences in implied volatility between DOTM and OTM, DOTM and ATM, and DOTM and ITM put and call options between 10–30 days to maturity. The options are segmented by periods when a jump occurs, $D = 1$, and when no jumps occur, $D = 0$. For puts, the difference in mean values between jumps and no jumps for all three measures of skew are significant at the 1% level, for both -1.65% and -2.73% market crashes. For positive jumps, the pattern of the volatility skew for the put has mixed statistical significance for differences between upward spikes and nonspike periods.

For the call option volatility curve, the results during market crashes are mixed. Although the difference on the OTM and ATM sides of the curve are statistically significant, at the 1% level, for both levels of crashes and upward spikes, the differences on the ITM side are insignificant in all four tests. This inconsistency casts a doubt on any measurable predictability by the implied volatility of the call curve for either direction jump. Thus, it should be reemphasized that the differences in means tests are rudimentary at best and do not necessarily cement the presence of forecast ability in implied volatilities. This further motivates the use of

TABLE I

Descriptive Statistics of Sample

Panel A

		Call							Put						
Moneyness	K/Se^{rT}	$<.875$	.875–.925	.925–.975	.975–1.025	1.025–1.075	1.075–1.125	>1.125	$<.875$	.875–.925	.925–.975	.975–1.025	1.025–1.075	1.075–1.125	>1.125
		DDITM	*DITM*	*ITM*	*ATM*	*OTM*	*DOTM*	*DDOTM*	*DDOTM*	*DOTM*	*OTM*	*ATM*	*ITM*	*DITM*	*DDITM*
10–30 days	*M*	61.45%	37.35%	27.36%	20.24%	17.91%	20.72%	25.51%	35.65%	29.24%	24.50%	20.56%	23.09%	33.71%	51.35%
	SD	26.33%	12.94%	8.59%	6.97%	6.21%	5.00%	4.61%	7.69%	7.40%	7.29%	6.96%	7.97%	13.19%	23.25%
	N	2291	2484	2581	2585	2522	1347	369	1845	2436	2585	2585	2553	2003	1542
31–60 days	*M*	35.15%	26.58%	22.99%	20.04%	18.01%	18.57%	20.72%	30.19%	25.71%	22.77%	20.29%	19.24%	21.37%	28.60%
	SD	7.49%	6.48%	6.38%	6.24%	5.88%	4.78%	5.39%	7.02%	6.23%	6.21%	6.09%	5.48%	4.36%	6.34%
	N	2431	2571	2585	2585	2580	1987	1077	2449	2575	2585	2585	2571	2148	1536
61–90 days	*M*	31.60%	25.09%	22.43%	20.15%	18.45%	18.26%	19.55%	28.85%	24.67%	22.37%	20.37%	19.24%	20.10%	24.11%
	SD	6.25%	6.07%	5.98%	5.84%	5.61%	5.09%	3.86%	6.05%	5.80%	5.76%	5.64%	5.28%	4.21%	4.85%
	N	2222	2537	2583	2585	2559	2016	1139	2240	2542	2584	2585	2548	2071	1456

(*Continued*)

TABLE I

Descriptive Statistics of Sample (*Continued*)

Panel B		Call							Put						
		DDITM	*DITM*	*ITM*	*ATM*	*OTM*	*DOTM*	*DDOTM*	*DDOTM*	*DOTM*	*OTM*	*ATM*	*ITM*	*DITM*	*DDITM*
10–30	BA	1.8%	3.0%	4.7%	6.0%	15.6%	30.0%	47.2%	32.6%	22.0%	12.1%	6.0%	4.8%	3.3%	2.2%
days	V	3	29	214	2362	1510	550	305	424	662	1566	2239	108	19	2
	OI	51	362	1575	4852	4913	3024	2302	3247	4006	5399	4042	594	135	27
31–60	BA	1.9%	3.0%	4.5%	6.4%	14.0%	24.8%	46.7%	29.8%	14.6%	8.9%	6.1%	4.5%	3.3%	2.3%
days	V	1	5	25	130	134	91	67	81	110	146	107	10	3	2
	OI	41	159	534	1204	1225	1026	965	1106	1449	1404	929	207	77	28
61–90	BA	2.0%	3.1%	4.2%	5.9%	10.1%	19.9%	34.8%	22.6%	10.2%	7.3%	5.6%	4.2%	3.3%	2.4%
days	V	1	2	13	50	53	31	24	31	50	59	61	5	2	1
	OI	44	92	412	692	638	533	569	564	701	886	626	128	69	26

Note. DDITM = deep-deep-in-the money; DITM = deep-in-the money; ITM = in-the money; ATM = at-the-money; OTM = out-of-the-money; DOTM = deep-out-of-the-money; DDOTM = deep-deep-out-of-the-money. This table reports summary statistics for the seven volatility bins for the three maturity classifications. Panel A reports the average implied volatility (M = Mean), standard deviation (SD), and number of observations (N), for each volatility bin over the January 1984–April 2006 period that qualified using the data screen. Panel B reports the average option percentage bid-ask spread (BA), volume (V) in 100,000, and open interest (OI) in 100,000 for each maturity/implied volatility bin for January 1996–April 2006.

TABLE II

Descriptive Statistics of Volatility Skew

		Put			*Call*			*Put*			*Call*		
		$\Delta\sigma^P_{do,o}$	$\Delta\sigma^P_{do,a}$	$\Delta\sigma^P_{do,i}$	$\Delta\sigma^C_{do,o}$	$\Delta\sigma^C_{do,a}$	$\Delta\sigma^C_{do,i}$	$\Delta\sigma^P_{do,o}$	$\Delta\sigma^P_{do,a}$	$\Delta\sigma^P_{do,i}$	$\Delta\sigma^C_{do,o}$	$\Delta\sigma^C_{do,a}$	$\Delta\sigma^C_{do,i}$
		−1.65% Jump (95%)						1.72% Jump (95%)					
$D = 0$	*M*	4.17%	7.83%	4.14%	−0.56%	−3.10%	−10.83%	4.23%	7.87%	4.32%	−0.47%	−3.14%	−10.80%
	SD	1.70%	2.61%	7.22%	0.99%	2.21%	7.15%	1.63%	2.58%	7.14%	0.84%	2.09%	7.47%
	N	975	975	951	270	270	270	1087	1087	1061	330	330	330
$D = 1$	*M*	4.89%	8.47%	7.30%	−0.99%	−4.04%	−10.75%	4.48%	8.64%	8.05%	−1.05%	−4.07%	−10.09%
	SD	2.16%	3.25%	6.91%	1.20%	2.21%	6.22%	1.98%	3.02%	6.28%	1.37%	2.41%	5.23%
	N	670	670	668	455	455	455	557	557	556	431	431	431
	t-statistic	(5.23)**	(3.06)**	(6.30)**	(3.71)**	(3.91)**	(0.11)	(1.86)	(3.75)**	(7.68)**	(5.14)**	(4.03)**	(1.07)
		−2.73% Jump (99%)						2.93% Jump (99%)					
$D = 0$	*M*	4.28%	7.59%	5.56%	−0.81%	−3.69%	−10.95%	4.27%	8.20%	5.68%	−0.81%	−3.70%	−10.86%
	SD	1.90%	2.86%	7.11%	1.11%	2.37%	7.02%	1.93%	2.92%	7.15%	1.04%	2.23%	6.82%
	N	1868	1868	1841	875	875	875	2046	2046	2018	999	999	999
$D = 1$	*M*	4.98%	8.44%	8.00%	−1.29%	−4.42%	−9.85%	4.55%	8.53%	9.04%	−1.27%	−4.58%	−9.91%
	SD	2.33%	3.42%	7.26%	1.69%	2.51%	4.95%	1.61%	2.55%	5.42%	1.42%	2.38%	4.19%
	N	316	316	315	242	242	242	159	159	159	150	150	150
	t-statistic	(3.98)**	(3.28)**	(4.26)**	(3.27)**	(3.04)**	(1.93)	(1.63)	(1.24)	(5.71)**	(3.08)**	(3.33)**	(1.69)

Note. This table reports summary statistics of the difference between volatility skews of puts and calls given jump ($D = 1$) and nonjump ($D = 0$) periods for the 30-day maturity bin. $\Delta\sigma^P_{do,o}$, $\Delta\sigma^P_{do,a}$, and $\Delta\sigma^P_{do,i}$ denote the difference between the implied volatility of DOTM (deep-out-of-the-money) puts and OTM (out-of-the-money) puts, ATM (at-the-money) puts, and ITM (in-the-money) puts, respectively. $\Delta\sigma^C_{do,o}$, $\Delta\sigma^C_{do,a}$, and $\Delta\sigma^C_{do,i}$ denote the difference between the implied volatility of DOTM calls and OTM calls, ATM calls, and ITM calls, respectively. *M* (Mean) is the average difference between the implied volatility of the relevant two option groups, expressed in percentage difference. *SD* is the standard deviation of the implied volatility difference. *N* denotes the number of trading days that satisfy the binary jump variable. *t*-statistics test the difference in means between periods of jumps and nonjumps using unequal variances.

*Significant at 5%. **Significant at 1%.

the probit model to more completely examine the effects of changes in volatility curves while controlling for other important varying factors.

Short-Term Maturities

Initially, the probit model is tested on each jump definition using only the skew explanatory variable for the 10–30-day maturities. This is done to incorporate all the data and test for the significance of the skew variables without other factors, reducing spurious significance. The results of the estimations are shown in Table III. Newey and West (1987) standard errors are used in all estimations in Table III and subsequent tables to correct the overlapping problem associated from inferring the implied volatility from the same option. The results demonstrate positive significance for the coefficients on $\Delta\sigma^P_{do,o}$, $\Delta\sigma^P_{do,a}$, and $\Delta\sigma^P_{do,i}$, for big, small, and LM downward jumps. This suggests the larger the skew, the higher the likelihood of a jump. For positive jumps, only $\Delta\sigma^P_{do,i}$ is significant, but the coefficient is positive, suggesting that even with positive jumps there is still high concern for a subsequent jump in the other direction. The results for the call skew mirror that of the put results, with significant

TABLE III

Univariate Probit Model Estimation Results for 10–30-Day-Maturity Window

	$\Delta\sigma^P_{do,o}$	$\Delta\sigma^P_{do,a}$	$\Delta\sigma^P_{do,i}$	$\Delta\sigma^C_{do,o}$	$\Delta\sigma^C_{do,a}$	$\Delta\sigma^C_{do,i}$	BKM
Jump < 21.65%	9.55	7.54	4.71	224.34	213.01	0.26	20.25
	(2.34)*	(3.15)**	(5.30)**	(2.37)*	(3.07)**	(0.26)	(5.61)**
Jump < 22.73%	3.75	2.65	2.90	215.51	27.01	1.63	20.38
	(2.30)*	(2.55)*	(5.75)**	(4.37)**	(3.77)**	(1.89)	(7.90)**
Jump > 1.72%	7.67	7.24	4.21	5.57	13.02	5.70	0.28
	(1.01)	(2.77)**	(3.87)**	(3.16)**	(3.06)**	(0.82)	(4.03)**
Jump > 2.93%	3.89	1.90	2.72	12.92	11.65	7.19	0.49
	(1.11)	(1.10)	(2.46)*	(1.29)	(2.32)*	(3.89)**	(6.55)**
LM Jump down	3.41	1.87	5.26	27.43	26.38	0.32	20.13
	(2.35)	(2.34)*	(6.13)**	(2.29)*	(2.71)**	(0.35)	(2.65)*

Note. The results are the coefficient estimates for the 10–30-day maturity bin for call and put options probit regressions of jump or no jump on the skew variable only. The dependent variable equals one if the option window contains a daily jump greater than the given threshold, zero otherwise. The LM jump is defined as given in Equations (8a, 8b). Standard errors are corrected by Newey–West procedures. The reported parameter values for $\Delta\sigma^P_{do,o}$, $\Delta\sigma^P_{do,a}$, and $\Delta\sigma^P_{do,i}$ represent the coefficients for the difference between the implied volatility of DOTM (deep-out-of-the-money) puts and OTM (out-of-the-money) puts, ATM (at-the-money) puts, and ITM (in-the money) puts, respectively. $\Delta\sigma^C_{do,o}$, $\Delta\sigma^C_{do,a}$, and $\Delta\sigma^C_{do,i}$ represent the coefficients for the difference between the implied volatility of DOTM calls and OTM calls, ATM calls, and ITM calls, respectively. BKM is the value calculated from Equation (7). Absolute values of *z*-scores for the parameter estimates are reported in parentheses. For brevity, the constant term is suppressed.

*Significant at 5%. **Significant at 1%.

negative coefficients for negative jumps, except for $\Delta\sigma^{C}_{do,i}$. This suggests there is a higher probability of a negative crash if there is a larger difference in implied volatilities between DOTM calls and OTM, ATM, or ITM calls. For calls with positive jumps, the coefficient is positive as expected. The BKM variable is significant and negative for negative jumps, and positive and significant for positive jumps, consistent with the findings of the other variables.

Given these initial findings, the fully specified probit model in Equation (9) is applied to the put option data and the model specified in Equation (10) is applied to the call option data. Both estimations employ the 10–30-days option maturities. The results are portrayed in Table IV for both negative (market crashes) and positive (market gains) jumps for both puts (Panel A) and calls (Panel B).[9]

For put options, an increase in the difference between the implied volatility levels of DOTM put options and the related OTM, ATM, and ITM put options ($\Delta\sigma^{P}_{do,o}$, $\Delta\sigma^{P}_{do,a}$, $\Delta\sigma^{P}_{do,i}$) is associated with a significant increase, at the 5% level, in the likelihood for both a -1.65% and -2.73% market crash 5 out of 6 times. The BKM measure is also negative and significant at the 5% level, suggesting a positive increase in the likelihood of a negative crash.[10] Because the coefficient on the level of volatility is also positive and significant, at the 1% level, the results here support Hypothesis 1a. This suggests that prior to a large negative daily movement of at least -1.65%, the volatility skew is more negative.

In the case of upward market swings for put options, an increase in the difference between the implied volatility levels of DOTM put options and the related OTM and ATM put options ($\Delta\sigma^{P}_{do,o}$, $\Delta\sigma^{P}_{do,a}$) does not yield statistically significant differences. Although the results for the difference between the implied volatility levels of DOTM put options and the related ITM put options ($\Delta\sigma^{P}_{do,i}$) is associated with a significant increase, at the 1% level, in the likelihood of a positive market jump the BKM measure is statistically insignificant. This finding is not compelling evidence for or against Hypothesis 1b.

The overall result for the put implied volatility curve is that there is information embedded within the entire curve. In fact, the results are consistent with a general fear of a large devaluation in the market when

[9]The results are presented for the difference between the levels of implied volatility across moneyness. Alternatively, relative implied volatility was used. The results of the relative implied volatility are available upon request and are not qualitatively different from the results presented.

[10]Given that BKM uses both puts and calls, it is not necessary to reproduce the results in the call table because the variable would not change. The only difference would be to use the call control variables. However, the results do not change.

TABLE IV

Probit Model Estimation Results for 10–30-Day Maturity Window

$$\text{Put Model}: \text{Prob}(D_{j,t\to t+\tau} = 1) = \Phi(\alpha + \beta_1 \Delta\sigma^{P}_{SKEW,t} + \beta_2 \sigma^{P}_{a,t} + \beta_3 BA^{P}_{o,t} + \beta_4 V^{P}_{o,t} + \beta_5 OI^{P}_{o,t} + \beta_6 TS)_t + e_t$$

$$\text{Call Model}: \text{Prob}(D_{j,t\to t+\tau} = 1) = \Phi(\alpha + \beta_1 \Delta\sigma^{C}_{SKEW,t} + \beta_2 \sigma^{C}_{a,t} + \beta_3 BA^{C}_{o,t} + \beta_4 V^{C}_{o,t} + \beta_5 OI^{C}_{o,t} + \beta_6 TS)_t + e_t$$

Panel A *Puts*	*Jump* < −2.73%				*Jump* < −1.65%				*Jump* > 2.93%				*Jump* > 1.72%			
$\Delta\sigma^P_{do,o}$	**10.80**				**2.86**				**5.30**				**4.10**			
	(1.99)*				**(1.93)**				**(1.26)**				**(1.19)**			
$\Delta\sigma^P_{do,a}$		**9.43**				**2.21**				**4.86**				**1.53**		
		(2.72)**				**(1.97)***				**(1.68)**				**(0.80)**		
$\sigma^P_{do,i}$			**5.24**				**2.38**				**3.46**				**2.76**	
			(3.82)**				**(4.43)****				**(3.05)****				**(2.74)****	
BKM				**−0.08**				**−0.15**				**0.09**				**0.21**
				(1.98)*				**(2.54)***				**(0.42)**				**(1.50)**
σ^P_a	17.52	17.19	17.67	17.59	7.71	7.65	7.68	9.94	16.85	16.76	16.92	15.23	11.45	11.41	11.38	12.99
	(3.35)**	(3.41)**	(3.10)**	(3.35)**	(13.30)**	(13.28)**	(13.11)**	(3.75)**	(5.11)**	(5.28)**	(5.03)**	(1.48)	(12.59)**	(12.43)**	(12.56)**	(4.60)**
BA^P_o	−0.17	−0.23	1.00	0.55	−2.77	−2.90	−1.95	−1.43	−1.52	−1.55	−0.47	−1.57	−0.76	−1.19	0.15	−0.24
	(0.10)	(0.14)	(0.54)	(0.45)	(3.53)**	(3.70)**	(2.50)*	(1.24)	(0.83)	(0.88)	(0.26)	(0.65)	(0.53)	(0.83)	(0.11)	(0.11)
V^P_o	−0.95	−4.60	−0.03	6.62	1.94	1.18	1.67	1.92	15.94	14.02	16.33	2.25	14.91	14.40	15.40	−3.81
	(0.13)	(0.64)	0.00	(0.77)	(1.75)	(1.51)	(1.83)	(1.47)	(1.49)	(1.30)	(1.44)	(0.15)	(1.95)	(1.88)	(1.89)	(0.32)
OI^P_o	−4.75	−5.34	−4.72	−3.46	−8.98	−9.22	−9.18	−5.06	−3.55	−3.79	−3.67	0.93	−9.83	−9.83	−10.18	−2.12
	(2.68)**	(2.99)**	(2.63)**	(1.49)	(6.09)**	(6.18)**	(6.05)**	(1.90)	(1.80)	(1.91)	(1.83)	(0.20)	(3.83)**	(3.78)**	(3.76)**	(0.46)
TS	−10.64	−8.96	−8.24	−8.14	−14.35	−13.82	−13.77	−8.42	−10.31	−9.27	−9.16	−11.56	−17.05	−16.46	−16.54	−8.96
	(1.87)	(1.55)	(1.29)	(1.44)	(4.24)**	(4.09)**	(4.09)**	(1.33)	(1.91)	(1.71)	(1.65)	(0.85)	(2.70)**	(2.58)**	(2.57)*	(0.96)
α	−3.56	−3.73	−3.62	−3.57	−2.14	−2.16	−2.27	−2.36	−3.66	−3.77	−3.77	−2.69	−3.73	−3.63	−3.82	−3.48
	(2.59)**	(2.80)**	(2.52)*	(2.73)**	(9.67)**	(9.72)**	(11.18)**	(3.03)**	(3.81)**	(4.21)**	(3.95)**	−1.03	(11.00)**	(11.27)**	(11.97)**	(3.71)**
OBS	1827	1827	1801	1783	2184	2184	2156	1783	1807	1807	1780	1783	2240	2240	2212	178

Panel B

$\Delta\sigma^C_{do,o}$	**13.68**			**4.13**			**8.96**			**17.50**		
	(0.53)			**(0.91)**			**(0.76)**			**(1.60)**		
$\Delta\sigma^C_{do,a}$		**7.03**			**7.79**			**16.63**			**15.83**	
		(0.63)			**(3.18)****			**(2.19)***			**(2.87)****	
$\Delta\sigma^C_{do,i}$			**4.14**			**5.07**			**5.61**			**8.29**
			(1.82)			**(5.97)****			**(3.60)****			**(4.32)****
σ^C_a	15.39	15.78	16.14	7.30	8.85	8.99	14.65	18.66	16.46	13.54	15.38	14.95
	(1.43)	(1.34)	(1.46)	(6.39)**	(7.17)**	(8.67)**	(3.36)**	(3.03)**	(3.53)**	(6.56)**	(7.59)**	(9.13)**
BA^C_o	0.18	0.21	0.61	−1.12	−1.20	−0.91	−3.34	−3.50	−3.01	1.94	1.77	2.27
	(0.08)	(0.09)	(0.24)	(1.09)	(1.22)	(0.93)	(1.90)	(1.98)*	(1.68)	(1.00)	(0.90)	(1.21)
V^C_o	24.35	22.89	19.14	1.12	2.86	2.14	−7.60	−11.30	−12.95	8.72	6.61	4.43
	(0.84)	(0.83)	(0.71)	(4.59)	(4.34)	(4.10)	(0.47)	(0.72)	(0.87)	(1.03)	(0.86)	(0.58)
OI^C_o	−11.80	−11.04	−10.61	−5.92	−4.80	−4.10	7.82	9.30	9.04	−3.25	−1.17	−0.45
	(1.13)	(1.10)	(1.02)	(1.57)	(1.29)	(1.16)	(1.16)	(1.35)	(1.34)	(1.06)	(0.40)	(0.15)
TS	0.84	0.64	2.01	−16.99	−19.89	−18.97	−7.91	−11.85	−7.61	−22.56	−26.63	−24.17
	(0.08)	(0.06)	(0.17)	(3.78)**	(4.34)**	(4.32)**	(1.15)	(1.64)	(0.97)	(3.29)**	(3.88)**	(3.63)**
α	−2.80	−2.75	−2.68	−2.39	−2.47	−2.34	−2.70	−3.02	−2.63	−4.25	−4.23	−4.03
	(1.18)	(1.12)	(1.09)	(7.23)**	(7.82)**	(7.84)**	(2.55)*	(2.41)*	(2.40)*	(7.61)**	(8.14)**	(8.26)**
OBS	893	893	893	1117	1117	1117	874	874	874	1181	1181	1181

Note. The results shown in this table are the parameter estimates for the 10–30−day maturity bin for put and call options. The put results (Panel A) come from the probit regression of equation (9); the call results (Panel B) are from Equation (10). The dependent variable equals one if the option window contains a daily jump below (above) −1.65% (+1.72%) or −2.73% (2.93%), zero otherwise. Standard errors are corrected by Newey–West procedures. The reported parameter values for $\Delta\sigma^P_{do,o}$, $\Delta\sigma^P_{do,a}$, and $\Delta\sigma^P_{do,i}$ represent the coefficients for the difference between the implied volatility of DOTM (deep-out-of-the-money) puts and OTM (out-of-the-money) puts, ATM (at-the-money) puts, and ITM (in-of-the-money) puts, respectively. $\Delta\sigma^C_{do,o}$, $\Delta\sigma^C_{do,a}$, and $\Delta\sigma^C_{do,i}$ represent the coefficients for the difference between the implied volatility of DOTM calls and OTM (out-of-the-money) calls, ATM (at-the-money) calls, and ITM (in-the money) calls, respectively. BKM is the value calculated from Equation (7). σ^P_a and σ^C_a represent the coefficients for implied volatility of ATM put and call options. BA^P_o and BA^C_o represent the coefficients for the OTM put and call percentage bid/ask spreads. V^P_o and V^C_o represent the coefficients for the volume of OTM put and call options, and are expressed in 100,000s. OI^P_o and OI^C_o represent the coefficients for the open interest of OTM put and call options, and are expressed in 100,000s. TS represents the coefficients of the difference between the 10-year U.S. Treasury Bond rate and the 1-year U.S. Treasury Note rate. OBS is the number of observations. Absolute values of z-scores for the parameter estimates are reported in parentheses.

*Significant at 5%. **Significant at 1%.

the put implied volatility curve becomes more negative. It seems that the short-termed nature of the 10–30 day to maturity options does not allow enough time for the market to correct itself in the event that a valuation fluctuation does occur.

Examining the evidence for call options, the results are generally the opposite of those for put options. For $\Delta\sigma^C_{do,o}$, the coefficients are statistically insignificant regardless of the jump size and direction. For the volatility difference between DOTM call options and ATM and ITM call options ($\Delta\sigma^C_{do,a}$, $\Delta^C_{do,i}$), the coefficients are significant for small market crashes and both small and large upward spikes. This suggests there is some information in the call volatility skew when there are market declines, consistent with the suggested weak or no pattern offered in Hypothesis 2a, and stronger information when there are upward market spikes as offered in Hypothesis 2b.

For the control variables, the percentage bid-ask spread coefficients have little to no significance regardless of size and direction of the market jump. The evidence suggests that bid-ask spreads do not play an important role in forecasting market crashes and that market crashes are not associated with an increased uncertainty through a lack of liquidity that often is manifested within a widening of the spreads. For put options, increases in open interest are associated with a significant decrease, at the 1% level, in the probability of a market crash and small positive market jump. The same is true for call options, but the coefficients are insignificant. The sign for the OI^P_o coefficient implies that hedgers and/or speculators are closing short positions, which is the opposite of the predicted behavior because buying a put would protect against a market crash.[11] This is consistent with the possibility that hedgers are having a hard time finding an opposing trading partner to increase their put positions, or speculators cannot unload their exposed position, such as Garleanu et al. (2005) claim. The volume variable is insignificant for puts and calls, implying that few parties are willing to take the opposite of these contracts. For both puts and calls, the term structure is negatively associated with negative and positive market jumps, but is significant for only the small jumps. This result suggests that an increase in the term structure variable, which moves the yield curve towards an inverted state, increases the likelihood of a jump regardless of direction. However, the results are somewhat perplexing given the weak results for larger jumps, and in general, are inconsistent

[11]The alternative is that the long positions are being closed out, but this seems unlikely given the option is currently OTM and is acting as a hedge.

with our ex-ante expectations of a negative sign for market crashes and a positive sign for spikes upward.

Intermediate and Longer-Term Maturities

Table V modifies the probit models in Equations (9) and (10) by changing the maturity bin setting to 31–60 days. Table VI reports the results for the same probit model regression modified to a maturity bin setting of 61–90 days. For brevity, we show the results using only the difference in implied volatility between DOTM options and OTM and ITM option.[12] We also only examine crashes less than -1.65% and spikes upward greater than 1.72%. A possible concern with the prior estimation is that longer maturity option skews have information content, but the effect may be diluted because the options are not near-term expiration. If there is a significant term structure of volatility (TSOV), then the effect of a possible crash/spike may be incorporated not only in the cross section, but in the time-series as well. As such, control variables that account for the difference between the implied volatility for longer maturity options and the implied volatility of 10 to 30-day options are created for ATM options.[13] These variables are then added to Equations (9) and (10). TSOV is measured for puts in Equation (11) and for calls in Equation (12).

The amended probit model is represented by the following for the put options:

$$\text{Prob}(\text{D}_{j,t\rightarrow t+\tau} = 1) = \Phi(\alpha + \beta_1 \Delta\sigma^P_{SKEW,t} + \beta_2 \sigma^P_{a,t} + \beta_3 BA^P_{o,t} + \beta_4 V^P_{o,t} + \beta_5 OI^P_{o,t} + \beta_6 TS_t + \beta_7 TSOV^P_{a,t}) + e_t \quad (11)$$

and for the call options:

$$\text{Prob}(\text{D}_{j,t\rightarrow t+\tau} = 1) = \Phi(\alpha + \beta_1 \Delta\sigma^C_{SKEW,t} + \beta_2 \sigma^C_{a,t} + \beta_3 BA^C_{o,t} + \beta_4 V^C_{o,t} + \beta_5 OI^P_{o,t} + \beta_6 TS_t + \beta_7 TSOV^C_{a,t}) + e_t \quad (12)$$

where $TSOV^P_{a,t}$ is the difference between the average implied volatility of 10–30-day maturity ATM put options and longer-term ATM put options (31–60 or 61–90 days), and $TSOV^C_{a,t}$ is the difference between the average implied volatility of 10–30-day maturity ATM call options and longer-term ATM call options (31–60 or 61–90 days).

[12]The results using the difference in implied volatility between DOTM and ATM options follow a similar pattern and are available upon request.

[13]For example, TSOV signifies the difference between the implied volatility of a 10–30-day maturity bin ATM put and the implied volatility of a 31–60-day maturity bin ATM put.

TABLE V

Probit Model Estimation Results for 31–60-Day Maturity Window

Puts	*Jump* $< -1.65\%$						*Jump* $> 1.72\%$					
$\Delta\sigma^{P}_{do,o}$	**−6.37**	**28.44**					**−14.48**	**−26.09**				
	(0.18)	**(0.62)**					**(1.36)**	**(2.73)****				
$\Delta\sigma^{P}_{do,i}$			**−1.27**	**−0.55**					**1.60**	**−3.41**		
			(0.21)	**(0.13)**					**(0.32)**	**(0.94)**		
BKM					**−0.16**	**−0.01**					**0.22**	**0.27**
					(0.85)	**(0.10)**					**(2.25)***	**(1.68)**
σ^{P}_{a}	30.17	18.17	30.26	17.94	27.26	17.82	18.64	14.31	19.19	13.98	18.71	15.20
	(1.43)	(4.51)**	(1.45)	(4.48)**	(1.38)	(3.36)**	(4.19)**	(10.47)**	(4.07)**	(10.07)**	(3.32)**	(4.91)**
BA^{P}_{o}	4.06	0.91	3.84	0.57	0.62	−0.26	−1.92	6.03	−1.21	5.62	−0.61	1.71
	(0.37)	(0.36)	(0.33)	(0.21)	(0.15)	(0.18)	(0.66)	(3.00)**	(0.37)	(2.79)**	(0.43)	(0.91)
V^{P}_{o}	37.21	15.51	32.78	15.60	14.70	35.15	15.55	38.25	14.09	35.79	81.37	58.32
	(0.47)	(0.46)	(0.41)	(0.45)	(0.29)	(1.22)	(0.72)	(1.82)	(0.62)	(1.67)	(1.69)	(0.90)
OI^{P}_{o}	−7.93	−14.57	−8.55	−15.99	−1.72	−10.32	−6.73	−11.56	−6.08	−15.93	−17.28	−19.21
	(0.48)	(2.18)*	(0.47)	(2.32)*	(0.16)	(1.73)	(0.89)	(1.41)	(0.77)	(1.91)	(2.28)*	(1.22)
TS	−27.70	−12.26	−28.15	−12.19	−23.14	−11.97	−23.84	−21.19	−23.07	−20.88	−28.63	−10.04
	(2.09)*	(2.54)*	(2.19)*	(2.50)*	(2.09)*	(2.76)**	(4.68)**	(3.60)**	(4.54)**	(3.62)**	(4.61)**	(1.12)
$TSOV^{P}_{a}$		**11.47**		**12.92**		**10.17**		**6.53**		**7.35**		**7.54**
		(7.36)**		**(7.69)****		**(2.32)***		**(2.19)***		**(2.45)***		**(2.17)***
α	−4.84	−3.15	−4.91	−3.26	−3.93	−3.27	−2.75	−4.09	−3.04	−4.44	−2.16	−4.07
	(0.90)	(2.69)**	(1.02)	(2.97)**	(1.01)	(2.74)**	(2.15)*	(8.71)**	(2.40)*	(9.49)**	(1.75)	(4.46)**
OBS	1959	1959	1945	1945	1837	1837	2379	2379	2365	2365	1837	1837

Calls

$\Delta\sigma^{P}_{do,o}$	**64.85**	**9.39**			**17.65**	**25.47**		
	(0.62)	**(0.41)**			**(0.57)**	**(2.06)***		
$\Delta\sigma^{P}_{do,i}$			**22.55**	**6.59**			**7.60**	**11.34**
			(0.92)	**(1.01)**			**(0.85)**	**(2.75)****
σ^{C}_{a}	51.39	18.90	49.46	19.65	24.07	14.45	24.16	14.69
	(0.74)	(2.01)*	(0.77)	(2.16)*	(1.80)	(7.68)**	(1.94)	(8.55)**
BA^{C}_{o}	−3.34	−3.42	−1.74	−3.02	0.28	1.76	0.83	2.52
	(0.27)	(1.28)	(0.12)	(1.01)	(0.08)	(1.63)	(0.23)	(2.54)*
V^{C}_{o}	8.40	39.77	19.51	42.28	71.65	53.61	73.27	56.26
	(0.10)	(1.09)	(0.25)	(1.16)	(1.17)	(1.64)	(1.18)	(1.77)
OI^{C}_{o}	9.27	−17.65	11.63	−16.14	−21.06	−17.39	−19.10	−14.31
	(0.42)	(2.18)*	(0.53)	(1.94)	(2.06)*	(2.06)*	(1.78)	(1.71)
TS	6.42	−0.16	9.69	−0.33	−25.46	−21.24	−24.47	−21.78
	(0.31)	(0.02)	(0.42)	(0.05)	(3.47)**	(3.66)**	(3.22)**	(3.80)**
$TSOV^{C}_{a}$		**6.52**		**6.05**		**10.27**		**9.91**
		(0.77)		**(0.71)**		**(2.99)****		**(2.91)****
α	−8.55	−3.16	−7.78	−3.08	−3.67	−4.12	−3.52	−3.88
	(0.62)	(1.56)	(0.60)	(1.58)	(1.32)	(10.21)**	(1.34)	(9.89)**
OBS	1417	1417	1417	1417	1796	1796	1796	1796

Note. The results shown in this table are the parameter estimates for the 31–60 day maturity bin for put and call options. The put results come from the probit regression of Equations (9) and (11); the call results are from Equations (10) and (12). The dependent variable equals one if the option window contains a daily jump below (above) −1.65% (1.72%), zero otherwise. Standard errors are corrected by Newey–West procedures. The reported parameter values for $\Delta\sigma^{P}_{do,o}$ and $\Delta\sigma^{P}_{do,i}$ represent the coefficients for the difference between the implied volatility of DOTM (deep-out-of-the-money) puts and OTM (out-of-the-money) puts and ITM (in-the money) puts, respectively. $\Delta\sigma^{C}_{do,o}$ and $\Delta\sigma^{C}_{do,i}$ represent the coefficients for the difference between the implied volatility of DOTM calls and OTM calls and ITM calls, respectively. BKM is the value calculated from Equation (7). σ^{P}_{a} and σ^{C}_{a} represent the coefficients for implied volatility of ATM (at-the-money) put and call options. BA^{P}_{o} and BA^{C}_{o} represent the coefficients for the OTM put and call percentage bid/ask spreads. V^{P}_{o} and V^{C}_{o} represent the coefficients for the volume of OTM put and call options, expressed in 100,000s. OI^{P}_{o} and OI^{C}_{o} represent the coefficients for the open interest of OTM put and call options, expressed in 100,000s. TS represents the coefficients of the difference between the 10-year U.S. Treasury Bond rate and the 1-year U.S. Treasury Note rate. $TSOV^{P}_{a}$ and $TSOV^{C}_{a}$ represent the coefficients of the difference between the ATM 30-day and 60-day implied volatility for the put and the call options, respectively. OBS is the number of observations. Absolute values of z-scores for the parameter estimates are in parentheses.

*Significant at 5%. **Significant at 1%.

TABLE VI

Probit Model Estimation Results for 61–90-Day Maturity Window

Puts			*Jump* $<-1.65\%$						*Jump* $>1.72\%$			
$\Delta\sigma^{P}_{do,o}$	**−46.14**	**−11.38**					**−21.40**	**2.78**				
	(0.72)	**(0.83)**					**(0.53)**	**(0.22)**				
$\Delta\sigma^{P}_{do,i}$			**−21.12**	**−4.88**					**−4.55**	**2.02**		
			(0.91)	**(0.94)**					**(0.25)**	**(0.41)**		
BKM					**−0.06**	**−0.02**					**0.50**	**0.19**
					(0.16)	**(0.16)**					**(2.03)***	**(0.86)**
σ^{P}_{a}	33.67	19.27	36.61	19.25	38.29	18.21	27.05	20.71	28.25	20.44	28.74	18.08
	(0.69)	(5.91)**	(0.69)	(6.08)**	(0.58)	(4.27)**	(1.74)	(8.53)**	(1.69)	(8.30)**	(1.02)	(1.95)
BA^{P}_{o}	−8.52	1.89	−11.09	0.99	0.47	0.42	−4.87	−0.29	−5.11	−0.23	−0.10	−0.19
	(0.52)	(0.62)	(0.59)	(0.31)	(0.05)	(0.23)	(0.58)	(0.09)	(0.50)	(0.08)	(0.02)	(0.05)
V^{P}_{o}	−1.66	−0.86	−0.69	−0.71	6.23	−32.37	−17.63	5.56	−17.85	5.92	−20.45	0.67
	(0.02)	(0.02)	(0.01)	(0.01)	(0.13)	(0.71)	(0.39)	(0.18)	(0.38)	(0.20)	(0.32)	(0.01)
OI^{P}_{o}	−4.81	−9.73	−5.88	−10.65	−28.06	−24.37	6.44	−11.02	6.42	−10.90	−26.24	−24.82
	(0.63)	(2.12)*	(0.61)	(2.23)*	(1.30)	(2.85)**	(1.62)	(1.98)*	(1.42)	(1.99)*	(2.81)**	(1.00)
TS	−69.48	−9.74	−71.99	−10.14	−75.44	−8.03	−41.14	−11.95	−42.14	−11.65	−55.26	−13.46
	(0.67)	(2.01)*	(0.63)	(2.09)*	(0.63)	(1.54)	(1.62)	(2.74)**	(1.59)	(2.71)**	(1.36)	(1.09)
$TSOV^{P}_{a}$		**8.19**		**8.14**		**11.31**		**1.44**		**1.70**		**6.60**
		(1.28)		**(1.23)**		**(1.63)**		**(0.43)**		**(0.51)**		**(0.51)**
α	−2.25	−3.58	−2.43	−3.48	−4.48	−3.36	−2.74	−4.25	−3.15	−4.25	−2.05	−3.01
	(0.30)	(3.95)**	(0.31)	(3.93)**	(0.49)	(3.46)**	(0.85)	(5.89)**	(0.89)	(6.03)**	(0.50)	(1.37)
OBS	1936	1936	1905	1905	1827	1827	1919	1919	1888	1888	1827	1827

Calls

$\Delta\sigma^{C}_{do,o}$	**103.91**	**15.21**			**163.35**	**5.66**		
	(0.56)	**(0.77)**			**(0.80)**	**(0.39)**		
$\Delta\sigma^{C}_{do,i}$			**40.43**	**8.13**			**61.04**	**2.79**
			(0.75)	**(1.27)**			**(0.81)**	**(0.44)**
σ^{C}_{a}	59.01	21.44	57.19	21.80	45.27	21.03	42.95	21.05
	(0.62)	(2.96)**	(0.60)	(3.06)**	(0.68)	(5.23)**	(0.66)	(5.20)**
BA^{C}_{o}	5.22	−0.24	7.45	0.18	−3.63	1.04	0.40	1.17
	(0.20)	(0.07)	(0.24)	(0.05)	(0.26)	(0.41)	(0.02)	(0.45)
V^{C}_{o}	−35.09	−35.37	−11.39	−29.86	14.44	−9.18	22.26	−8.07
	(0.15)	(0.46)	(0.07)	(0.39)	(0.20)	(0.24)	(0.34)	(0.21)
OI^{C}_{o}	−26.26	−41.82	−23.96	−41.35	−30.58	−15.70	−25.64	−15.17
	(0.72)	(2.96)**	(0.65)	(2.88)**	(1.60)	(2.11)*	(1.56)	(2.03)*
TS	−54.77	−3.73	−53.00	−3.96	−61.39	−11.05	−58.85	−11.07
	(0.66)	(0.55)	(0.66)	(0.58)	(0.91)	(2.28)*	(0.90)	(2.33)*
$TSOV^{C}_{a}$		**9.75**		**8.98**		**0.88**		**0.87**
		(1.10)		**(1.03)**		**(0.22)**		**(0.22)**
α	−8.27	−3.85	−7.33	−3.73	−3.88	−4.28	−2.61	−4.22
	(0.51)	(2.26)*	(0.45)	(2.20)*	(0.41)	(4.25)**	(0.31)	(4.20)**
OBS	1494	1494	1493	1493	1466	1466	1465	1465

Note. The results shown in this table are the parameter estimates for the 61–90-day maturity bin for put and call options. The put results come from the probit regression of Equations (9) and (11); the call results are from Equations (10) and (12). The dependent variable equals one if the option window contains a daily jump below (above) −1.65% (1.72%), zero otherwise. Standard errors are corrected for Newey–West procedures. The reported parameter values for $\Delta\sigma^{P}_{do,o}$ and $\Delta\sigma^{P}_{do,i}$ represent the coefficients for the difference between the implied volatility of DOTM (deep-out-of-the-money) puts and OTM (out-of-the-money) puts, and ITM (in-the money) puts, respectively. $\Delta\sigma^{C}_{do,o}$, and $\Delta\sigma^{C}_{do,i}$ represent the coefficients for the difference between the implied volatility of DOTM calls and OTM calls and ITM calls, respectively. BKM is the value calculated from Equation (7). σ^{P}_{a} and σ^{C}_{a} represent the coefficients for implied volatility of ATM (at-the-money) put and call options. BA^{P}_{o} and BA^{C}_{o} represent the coefficients for the OTM put and call percentage bid/ask spreads. V^{P}_{o} and V^{C}_{o} represent the coefficients for the volume of OTM put and call options, expressed in 100,000s. OI^{P}_{o} and OI^{C}_{o} represent the coefficients for the open interest of OTM put and call options, expressed in 100,000s. TS represents the coefficients of the difference between the 10-year U.S. Treasury Bond rate and the 1-year U.S. Treasury Note rate. $TSOV^{P}_{a}$ and $TSOV^{C}_{a}$ represents the coefficients of the difference between the ATM 30-day and 90-day implied volatility for the put and the call options, respectively. OBS is the number of observations. Absolute values of *z*-scores for the parameter estimates are reported in parentheses.

*Significant at 5% .**Significant at 1% .

We expect that the TSOV variables are positively related to a market crash or spike upward for all options because the jump fears should materialize in short-term options. It is unclear if there is information within the curves that is mitigated by TSOV, so the effect on the skewness on the OTM and ITM sides of the curves is unknown, ex-ante. For brevity, only the results of small jumps are reported. Results are provided both with and without TSOV in the models.

For market crashes, the predictive power of the implied volatilities for put options is not supported by a preponderance of the evidence for the longer maturity structures. The statistically significant positive coefficients reported for each definition of skewness in the 10–30-day maturity options are not statistically significant for the 31–60-day or the 61–90-day maturity bins, regardless of whether the TSOV variable is included in the specification. The evidence suggests that the put skew is not more negative (positive) in forecasting future crashes (upward spikes) at longer maturities. This supports the conclusion that investors' fears of a possible crash are not reflected in longer maturity options as compared to 10–30-day options. The additional time to recover from a market crash seems to reduce the skewness in the put curve. The call option skew is uninformative for market crashes, but retains some statistical power for market jumps at 31–60 day maturities with the inclusion of the TSOV variable. However, the coefficients for the call skew variable are insignificant at 61–90 day maturities.

The evidence for the longer-term maturities supports the claim in Hypothesis 3 that the predictive ability of the skew weakens as maturity length increases. Although it is well documented that jumps and volatility are related, it is interesting that the information within the shape of the skew is mitigated with an increase in option maturity, but the level of volatility generally is not, especially when TSOV is the model. This may be related to the volatility risk premium versus the jump premium. As noted by Das and Sundaram (1999) and Doran and Ronn (2005), the volatility risk premium is a long-term effect, whereas the jump premium is a short-term phenomenon. Thus, this could explain some of the deterioration in the information content of the implied volatility curves over time.

The TSOV coefficient is positive and significant for 31–60-day maturity options, consistent with ex-ante expectations. For puts, the TSOV coefficient is positive and significant at the 5% level in put option regressions, for both positive and negative jumps. For call options, the TSOV coefficient is only significant for positive jumps. Interestingly, the TSOV coefficient is insignificant at the 61–90 maturities for all specifications, suggesting that jumps are short-term phenomena.

The results suggest that when looking at longer maturity options, it is necessary to account for TSOV effects because jumps and volatility are related. Multiple authors have attempted to dissect the effect of volatility and jump premiums with limited success.[14] Currently, there is much debate about the appropriate method; although we make no qualitative statement about the correct methodology, it appears that cross-sectional and time-series data has to be jointly incorporated in estimation.

LM Jumps

To account for the effect of volatility and downward jumps, we retest the models outlined in Equations (9) through (12) using LM jumps that, by definition, should account for overall volatility. We expect that the skew variables should retain their significance in forecasting market crashes, but the overall volatility should be insignificant. The results are shown in Table VII.

Consistent with the prior findings, the coefficients on the put and BKM skew variables retain the strong positive significance in forecasting negative jumps in the short-term. There is significance in the $\Delta\sigma^{P}_{do,i}$ coefficient at the 31–60-day maturity, but none at the 61–90 day maturity.[15] The call coefficients are insignificant at all maturities. As expected, the level of volatility is unrelated or negatively related to forecasting a negative jump. This suggests that the skew is informative for large negative price movements irrespective of volatility levels, and as such, indicative of a jump premium separate from volatility.[16] The strong negative significance for the coefficient on the percentage bid-ask spread suggests that spreads are positively related to volatility levels, and have little predictive content for forecasting jumps. The other control variables have similar signs and significance as in the prior regressions.

Robustness Checks: Alternative Specifications

Option's Delta

The initial specification defined moneyness using the option's strike price divided by the forward price of the underlying asset. Although using this measure of moneyness is fairly intuitive, it ignores the fact

[14]Pan (2002), Eraker (2004), Doran (2005), and others have estimated parametric models by using both option and underlying prices to estimate multiple risk premia. As Broadie, Chernov, and Johannes (2006) point out, arriving at precise estimates is a quantitative challenge because authors need to restrict either time-series or cross-sectional observations because the data is computationally intensive.

[15]Other skew variables are not included because results are similar.

[16]Whether this is true for positive jumps is unknown because we do not estimate for positive jumps due to the small number of observations.

TABLE VII

Probit Model Estimation Results for All Maturity Windows Using LM Jumps

	10–30-day maturities			*31–60-day maturities*			*61–90-day maturities*		
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
$\Delta\sigma^{P}_{do,i}$	**3.68**			**7.53**			**1.98**		
	(2.88)**			**(3.34)****			**(0.67)**		
$\Delta\sigma^{C}_{do,i}$		**0.45**			**−5.34**			**−10.44**	
		(0.37)			**(1.12)**			**(0.60)**	
BKM			**−0.32**			**−0.02**			**0.03**
			(3.47)**			**(0.36)**			**(0.48)**
σ_a	–1.58	–3.82	1.87	–4.09	–3.87	–1.91	–4.35	–7.53	–4.37
	(1.12)	(2.00)*	(1.23)	(3.65)**	(2.80)**	(1.94)	(4.66)**	(4.84)**	(4.92)**
BA_o	–14.99	–10.89	–17.83	–16.01	–11.50	–12.98	–28.70	–25.75	–26.12
	(5.84)**	(2.67)**	(5.91)**	(8.87)**	(4.53)**	(6.48)**	(11.94)**	(8.19)**	(10.02)**
V_o	1.86	27.23	4.43	12.72	22.25	12.40	–61.65	–39.30	–22.17
	(0.24)	(2.65)**	(0.55)	(0.74)	(0.73)	(0.70)	(1.10)	(1.19)	(0.44)
OI_o	–15.55	–12.85	–13.72	–14.75	–0.78	–5.30	–10.51	–9.46	–15.51
	(7.80)**	(2.34)*	(6.31)**	(2.45)*	(0.16)	(0.89)	(1.16)	(1.80)	(1.35)
TS	–35.05	–69.96	–43.80	–28.50	–39.87	–30.42	–36.99	–43.28	–36.56
	(5.81)**	(9.13)**	(4.72)**	(9.08)**	(12.53)**	(8.35)**	(12.06)**	(13.84)**	(9.97)**
$TSOV_a$				5.65	2.39	1.04	2.15	4.01	1.20
				(3.13)**	(0.91)	(0.48)	(1.38)	(2.17)*	(0.69)
α	0.14	0.55	–0.93	0.44	0.33	0.19	1.78	2.13	1.84
	(0.32)	(0.69)	(1.96)*	(1.24)	(0.79)	(0.55)	(5.12)**	(4.74)**	(5.23)**
OBS	2376	1314	1844	2534	1954	1874	2480	1987	1966

Note. The results shown in this table are the parameter estimates for the three maturity bins for both put and call options. The put results come from the probit regression of Equations (9) and (11); the call results are from Equations (10) and (12). The dependent variable in this case is the LM jump downward defined in Equations (8a, 8b). Standard errors are corrected by Newey-West procedures. The reported parameter values for $\Delta\sigma^{P}_{do,i}$ represents the coefficient for the difference between the implied volatility of DOTM (deep-out-of-the-money) puts and ITM (in-the money) puts. $\Delta\sigma^{C}_{do,i}$ represents the coefficient for the difference between the implied volatility of DOTM calls and ITM. BKM is the value calculated from Equation (7). σ_a represents the coefficients for implied volatility of ATM (at-the-money) put and call options. BA_o represents the coefficients for the OTM (out-of-the-money) percentage bid/ask spreads. V_o represent the coefficients for the volume of OTM options, expressed in 100,000s. OI_o represent the coefficients for the open interest of OTM options, expressed in 100,000s. TS represents the coefficients of the difference between the 10-year U.S. Treasury Bond rate and the 1-year U.S. Treasury Note rate. $TSOV_a$ represents the coefficients of the difference between the ATM 30-day and 60-day and 90-day implied volatility. OBS is the number of observations. Put specific variables are used in regressions 1,3,4,6,7 and 9. Call specific variables are used in 2,5, and 8. Absolute values of *z*-scores for the parameter estimates are reported in parentheses.

*Significant at 5%. **Significant at 1%.

that the likelihood of the option being exercised relies not only on the volatility, but the time to maturity as well. Although we have accounted for the time to maturity aspect by separating the implied volatility into maturity bins, using an option's delta will allow all options to be grouped together. An option's delta accounts for both volatility and time to maturity. As Bollen and Whaley (2004) point out, an option's delta can be interpreted as the risk-neutral probability that the option will be exercised.

We adopt the five moneyness definitions given in Bollen and Whaley (2004) and show the descriptive statistics for each delta bin in Table VIII. Because most of the trading activity takes place between the DOTM options and ATM options, three measures of put skewness (Δ^{P}_{SKEW}) are defined using these new moneyness categories. These are the differences between the implied volatility of:

$\Delta_{do,o}$ DOTM and OTM options

$\Delta_{o,a}$ OTM and ATM options

$\Delta_{do,a}$ DOTM and ATM options

Given our prior findings of a strong positive relationship between the shape of the put skew and a negative jump, we restrict our attention to the use of put options. The revised probit model in Equation (9) includes one of the three variables defined above or the BKM variable. The new model is then estimated using the same definition of a jump used previously as well as the LM jump downward. The results are reported in Table IX.

TABLE VIII

Descriptive Statistics of Volatility Skew Using Delta Bins

Option	*Moneyness*	*Label*	*Δ Range*	*IV*	*BA*	*V*	*OI*
Call	Deep in-the-money	DITM	$.875 < \Delta \leq .98$	40.71%	2.26%	37	227
	In-the-money	ITM	$.625 < \Delta \leq .875$	24.85%	3.71%	139	757
	At-the money	ATM	$.375 < \Delta \leq .625$	20.33%	5.68%	546	1507
	Out-the-money	OTM	$.125 < \Delta \leq .375$	18.00%	9.87%	677	1936
	Deep out-the-money	DOTM	$.02 < \Delta \leq .125$	16.92%	28.72%	650	2655
Put	Deep in-the-money	DITM	$-.98 < \Delta \leq -.875$	29.46%	2.88%	33	106
	In-the-money	ITM	$-.875 < \Delta \leq -.625$	20.13%	4.20%	125	446
	At-the money	ATM	$-.625 < \Delta \leq -.372$	20.70%	5.40%	560	1327
	Out-the-money	OTM	$-.375 < \Delta \leq -.125$	24.11%	8.32%	565	1930
	Deep out-the-money	DOTM	$-.125 < \Delta \leq -.02$	29.71%	20.32%	528	2741

Note. This table reports the summary statistics for the five delta bins for calls and puts. The table reports the means for implied volatility (IV), the average option percentage bid-ask spread (BA), volume (V), and open interest (OI) for each maturity/implied volatility bin over the 1984–2006 period.

TABLE IX

Probit Model Results for Negative Jumps using Option Deltas

$$\text{Put Model}:\text{Prob}(D_{j,t\rightarrow t+r}=1)=\Phi(\alpha+\beta_1\Delta^P_{SKEW,t}+\beta_2\sigma^P_{a,t}+\beta_3BA^P_{o,t}+\beta_4V^P_{o,t}+\beta_5OI^P_{o,t}+\beta_6TS_t)+e_t$$

Puts	*Jump* $< -2.73\%$				*Jump* $< -1.65\%$				*LM Jump down*			
$\Delta_{do,o}$	**7.73**				**6.41**				**5.38**			
	(2.59)**				**(1.97)***				**(2.37)***			
$\Delta_{o,a}$		**2.05**				**2.30**				**3.61**		
		(2.33)*				**(2.06)***				**(2.20)***		
$\Delta_{do,a}$			**1.56**				**1.49**				**4.22**	
			(2.57)**				**(2.46)***				**(2.33)***	
BKM				**−0.11**				**−0.34**				**−0.07**
				(2.18)*				**(3.12)****				**(1.96)***
σ^P_a	18.53	19.61	19.86	20.19	7.33	8.14	9.43	8.92	−3.58	−3.77	−4.34	−0.17
	(5.01)**	(5.21)**	(5.40)**	(5.06)**	(6.45)**	(6.77)**	(9.81)**	(9.30)**	(2.19)*	(2.14)*	(2.77)**	−0.1
BA^P_o	2.10	1.98	2.37	0.98	−5.42	−4.82	−4.71	−7.91	−24.25	−24.00	−23.17	−21.99
	(0.46)	(0.47)	(0.54)	(0.21)	(2.60)**	(2.28)*	(2.08)*	(3.30)**	(5.47)**	(5.38)**	(5.21)**	(4.74)**
V^P_o	16.00	18.21	20.39	19.33	31.70	34.60	34.68	35.98	−15.49	−13.69	−10.53	18.80
	(0.87)	(0.97)	(1.04)	(0.83)	(2.41)*	(2.61)**	(2.58)**	(2.51)*	(0.79)	(0.72)	(0.58)	(0.93)
OI^P_o	−21.64	−20.39	−20.26	−18.66	−30.02	−28.86	−26.57	−24.64	−46.22	−46.92	−49.29	−41.16
	(2.95)**	(2.95)**	(3.11)**	(2.79)**	(5.18)**	(5.00)**	(4.66)**	(4.25)**	(4.84)**	(4.93)**	(5.20)**	(4.74)**
TS	−15.32	−14.40	−14.16	−14.68	−14.94	−14.47	−14.29	−14.40	−36.23	−35.92	−36.00	−38.07
	(2.70)**	(2.83)**	(2.90)**	(2.84)**	(3.84)**	(3.75)**	(3.70)**	(3.70)**	(7.74)**	(7.77)**	(7.79)**	(7.36)**
α	−3.83	−3.84	−3.91	−3.49	−2.03	−2.13	−2.20	−1.17	1.42	1.41	1.39	0.76
	(3.36)**	(3.56)**	(3.46)**	(3.12)**	(6.04)**	(6.31)**	(6.11)**	(2.86)**	(2.21)*	(2.20)*	(2.20)*	−1.01
OBS	1961	1961	1961	1960	2328	2328	2328	2324	2546	2546	2546	2541

Note. The results shown in this table are the parameter estimates for negative jumps using put option deltas. The puts results come from the revised probit regression of equation (9) shown below. The dependent variable equals one if the option window contains a daily jump below −1.65%, −2.73%, or a LM jump, zero otherwise. Standard errors are corrected by Newey-West procedures. The reported parameter values for $\Delta_{do,o}$, $\Delta_{o,a}$, or $\Delta_{do,a}$ represent the coefficients for the difference between the implied volatility of DOTM (deep-out-of-the-money) and OTM (out-of-the-money put deltas, OTM and ATM (at-the-money) put deltas, and DOTM and ATM (at-the-money) put deltas, respectively. $\Delta_{a,i}$ represents the coefficient for the difference between the implied volatility of ATM and ITM (in-the money) put deltas. BKM is the value calculated from Equation (1). σ^P_a represents the coefficient for implied volatility of ATM put options. BA^P_o represents the coefficient for the OTM put percentage bid/ask spread. V^P_o represents the coefficient for the volume of OTM put options, expressed in 100,000s. $OI^P{}_o$ represents the coefficient for the open interest of OTM put options, expressed in 100,000s. TS represents the coefficient of the difference between the 10-year U.S. Treasury Bond rate and the 1-year U.S. Treasury Note rate. OBS is the number of observations. Absolute values of z-scores for the parameter estimates are reported in parentheses.

*Significant at 5% . **Significant at 1%.

The findings in Table IX for crashes of −1.65% and −2.73% or greater show a positive relationship between the shape of the put skew and a large negative jump; all three skew coefficients are significant at the 5% level. The BKM variable is negative and significant, which is consistent with a higher degree of negative skewness prior to a market crash. These findings also hold for the LM jump. For the LM jump, however, a major difference is the negative and sometimes significant relationship with the level of volatility. This may suggest some downward bias relationship between LM jumps and volatility. The results suggest that our findings are robust to the definition of moneyness.

Probability of a Crash or Spike Upward

To test the implications our findings, the probability of a crash or spike upward is assessed using the marginal coefficients from the put and call probit model specified in Equations (9) and (10) on both small negative and positive jumps and LM jumps.[17] The put skew variable, $\Delta\sigma^{P}_{do,i}$, is allowed to vary between −1% and 14%, which is equal to one standard deviation either side of the mean value. Additionally, the ATM implied volatility level varies between 13% and 27%, while all other variables are kept at their mean values. To assess the probability of a spike upwards, the call skew variable, $\Delta\sigma^{C}_{do,i}$, is varied between −16% and −6%. The probabilities of a crash or spike upward are reported in Table X.

The results show the informative nature of the put skew relative to the call skew, conditional on the level of implied volatility. As shown in Panel A, at a 13% level of ATM implied volatility, the probability of a crash increases 6.32% when $\Delta\sigma^{P}_{do,i} = -1\%$ and increases to $\Delta\sigma^{P}_{do,i} = 14\%$. At 27% ATM implied volatility, the probability increase is 13.91%. This suggests that a negative jump is proportional not only to level of volatility, but also to the shape of the volatility skew. However, the result for the LM crash, shown in Panel C, implies an even greater effect for the shape of the skew. This is due to removing volatility from the jump effect. An increase from −1% to 14% in $\Delta\sigma^{P}_{do,i}$ increases the probability of a forthcoming crash approximately 39.18%, as shown in the first column.

The probabilities for the spikes upward using the call skew, shown in Panel B, are only marginally informative when the ATM implied volatility is at 27%. However, even the probabilities of a spike upward in the extreme case, $\Delta\sigma^{P}_{do,i} = -6\%$, is only 21.81%. This is approximately 40% of the probability of the put skew counterpart for the downward crash. Even though we document some significant positive power for predicting a

TABLE X
Probability of a Crash or Spike Upward

	ATM Implied volatility		
	13%	20%	27%
Panel A: Put skew		*Probability of crash*	
−1%	7.24%	17.88%	35.12%
2%	8.28%	19.81%	37.81%
5%	9.43%	21.86%	40.56%
8%	10.69%	24.03%	43.35%
11%	12.06%	26.31%	46.18%
14%	13.56%	28.69%	49.03%
Panel B: Call skew		*Probability of spike upward*	
−16%	0.01%	0.40%	5.40%
−14%	0.02%	0.64%	7.47%
−12%	0.04%	1.01%	10.10%
−10%	0.07%	1.55%	13.34%
−8%	0.12%	2.32%	17.25%
−6%	0.20%	3.40%	21.81%
Panel C: Put skew		*Probability of LM crash*	
−1%	15.70%	13.18%	10.96%
2%	21.74%	18.62%	15.80%
5%	28.94%	25.27%	21.86%
8%	37.10%	33.00%	29.09%
11%	45.89%	41.52%	37.26%
14%	54.88%	50.47%	46.05%

Note. This table reports the predicted probability of a crash given the level of ATM (at-the-money) implied volatility and the difference in implied volatility between a DOTM (deep-out-of-the-money) and ITM (in-the money) option, as defined in Table I, for both put and call options. The mean value for all other variables including the bid-ask spread, open interest, volume, and term-structure, are used. The probabilities are inferred from multiplying the coefficients from a marginal effects probit regression, given the same specification as in Equations (9) and (10), to the given values of the variables. The dependent variable uses the −1.65% crash definition for the put skew results in Panel A, a 1.72% spike upward definition for the call skew results in Panel B, and an LM jump definition for the put skew results in Panel C.

market spike upward, the marginal effect of this prediction is small. This result is consistent with the one-sided notion that market fears and/or liquidity constraints about future precipitous price drops are reflected in higher implied volatility in OTM puts.

CONCLUSION

Our findings suggest that there is predictive information content within the volatility skew, especially in the short-term. Consistent with prior literature and the notion of a negative jump premium, the put volatility skew has strong predictive power in forecasting short-term market declines. This result is robust to different definitions of moneyness and jump specifications. In addition, there is power in the call skew in predicting upward market spikes in the short-term; however, the magnitude of the prediction is quite small. The predictive power for both declines and increases appears to diminish as the time to maturity increases, even when a term structure of volatility control is included. This general conclusion suggests that different risk premiums exist across time and in the cross-section, and that negative crash concerns are stronger than positive jump concerns.

We do not try to comment upon why there is a negative skew, but we accept that the market prices options with an embedded jump premium or that the skew is the result of market liquidity effects such as the cost of short-selling. However, regardless of the explanation for the skew, the shape of the skew contains information about future market movements. Our results are consistent with the possibility that there is both a positive and negative jump premium embedded in option prices, but the magnitude of the jump premium is much stronger for negative movements. This is interesting as it suggests our current single-price jump factor models are misspecified.

There is information within the volatility curves and this information provides some predictive power in short-term options. We show that the predictive information for market crashes within implied volatility of puts and calls dissipates rather quickly with increases in maturity. Given that it is a short-term phenomenon, and there are liquidity issues such as short-selling constraints, substantial barriers exist that limit the feasibility to dynamically hedge the potential crash or spike upward even if it can be forecast.

If liquidity is not a concern, then our results are of a practical importance, as the hedging implications for investors and companies are ample. If the volatility skew is the harbinger of bad or good news, then market participants can take an active role in protecting their market assets depending on their level of risk-aversion. Additionally, the skew may signal investment opportunities in the short-term for those willing to speculate on future market movements. This is not to say there are arbitrage opportunities, but a change in the volatility skew is more a reflection of a change in jump risk aversion. The traders willing to bear that risk can use the volatility skew ex-ante to profit from investors' increasing or decreasing risk attitudes.

APPENDIX

Expressions for Risk-Neutral Skewness

The model-free estimates of risk-neutral skewness are based on Bakshi, Kapadia, and Madan (2003). Let $R(t,\tau) \equiv \log(S_{t+\tau} - \log(S_t)$ and $\mu(t,\tau) \equiv E^Q\{R(t,\tau)\}$. BKM is defined as:

$$BKM \equiv \frac{E^Q\{(R(t,\tau) - \mu(t,\tau))^3\}}{(E^Q\{(R(t,\tau) - \mu(t,\tau))^2\})^3}$$

$$= \frac{e^{r\tau}W(t,\tau) - 3\mu(t,\tau)e^{r\tau}v(t,\tau) + 3\mu(t,\tau)^2}{(e^{r\tau}v(t,\tau) - \mu(t,\tau)^2)^{\frac{3}{2}}}$$

$$v(t,\tau) = \int_{S_t}^{\infty} \frac{2\left(1 - \log\left[\frac{K}{S_t}\right]\right)}{K^2} C_t(\tau; K)dK + \int_{0}^{S_t} \frac{2\left(1 + \log\left[\frac{S_t}{K}\right]\right)}{K^2} P_t(\tau; K)dK, \qquad \text{(A1)}$$

where

$$W(t,\tau) = \int_{S_t}^{\infty} \frac{6\log\left[\frac{K}{S_t}\right] - 3\left(\log\left[\frac{K}{S_t}\right]\right)^2}{K^2} C_t(\tau; K)dK$$

$$- \int_{0}^{S_t} \frac{6\log\left[\frac{S_t}{K}\right] + 3\left(\log\left[\frac{S_1}{K}\right]\right)^2}{K^2} P_t(\tau; K)dK, \qquad \text{(A2)}$$

and the price of the cubic and quartic contracts are

$$X(t,\tau) = \int_{S_t}^{\infty} \frac{12\left(\log\left[\frac{K}{S_t}\right]\right)^2 - 4\left(\log\left[\frac{K}{S_t}\right]\right)^3}{K^2} C_t(\tau; K)dK$$

$$- \int_{0}^{S_t} \frac{12\left(\log\left[\frac{S_t}{K}\right]\right)^2 + 4\left(\log\left[\frac{S_t}{K}\right]\right)^3}{K^2} P_t(\tau; K)dK. \qquad \text{(A3)}$$

Finally, $\mu(t,\tau) \equiv e^{r\tau} - 1 - \frac{e^{r\tau}}{2}v(t,\tau) - \frac{e^{r\tau}}{6}W(t,\tau) - \frac{e^{r\tau}}{24}X(t,\tau)$. (A4)

BIBLIOGRAPHY

Bakshi, G., Cao, C., & Chen, Z. (1997). Empirical performance of alternate option pricing models. The Journal of Finance, 52(5), 2003–2049.

Bakshi, G., & Kapadia, N. (2003). Delta-hedged gains and the negative market volatility risk premium. Review of Financial Studies, 16(2), 527–566.

Bakshi, G., Kapadia, N., & Madan, D. (2003). Stock return characteristics, skew laws, and differential pricing of individual equity options. Review of Financial Studies, 16(1), 101–143.

Barone-Adesi, G., & Whaley, R. (1987). Efficient analytic approximation of american option values. Journal of Finance, 42, 301–322.

Bates, D. (1991). The crash of '87: Was it expected? The evidence from options markets. The Journal of Finance, 46(3), 1009–1044.

Bates, D. (2000). Post-'87 crash fears in S&P500 futures options. Journal of Econometrics, 94, 181–238.

Black, F., & Scholes, M. (1973). The pricing of options and corporate liabilities. Journal Political Economy, 81, 637–659.

Bollen, N., & Whaley, R. (2004) Does net buying pressure affect the shape of implied volatility functions? The Journal of Finance, 59(2), 711–753.

Broadie, M., Chernov, M., & Johannes, M. (2006). Model specification and risk premiums: Evidence from futures options. Journal of Finance, Forthcoming, June 2007.

Chan, L., Karceski, J., & Lakonishok, J. (1998). The risk and return from factors. The Journal of Financial and Quantitative Analysis, 33, 159–188.

Das, S., & Sundaram, R. (1999). Of smiles and smirks: A term structure perspective. Journal of Financial and Quantitative Analysis, 34(1), 60–72.

Doran, J. (2007). The influence of tracking error on volatility risk premium estimation, Journal of Risk, 9(3), 1–36.

Doran, J., and Ronn, E., (2005) The market rice of volatility risk (working paper). Tallahassee, FL: Florida State University.

Eraker, B. (2004). Do stock prices and volatility jump? Reconciling evidence from spot and option prices, Journal of Finance, 59, 1367–1403.

Evans, R., Geczy, C., Musto, D., & Reed, A. (2005). Failure is an option: Impediments to short selling and options prices (working paper). Chapel Hill, NC: University of North Carolina.

Garleanu, N., Pedersen, L.H., & Poteshman, A. (2006). Demand-based option pricing (working paper). New York: New York University.

George, T., & Longstaff, F. (1993). Bid-ask spreads and trading activity in the S&P 100 index options market. The Journal of Financial and Quantitative Analysis, 28, 381–397.

Hentschel, L. (2003). Errors in implied volatility estimation. The Journal of Financial and Quantitative Analysis, 38, 779–810.

Lee, S., & Mykland, P. (2006). Jumps in real-time financial markets: A new nonparametric test and jump dynamics. Review of Financial Studies, in press.

Manaster, S., & Rendleman R. Jr. (1982). Option prices as predictors of equilibrium stock prices. The Journal of Finance, 37(4), 1043–1057.

Newey, K., & West, K.D. (1987). Hypothesis testing with efficient method of moments estimation. International Economic Review, 28, 777–787.

Pan, J. (2002). The jump-risk premia implicit in options: evidence from an integrated time-series study. Journal of Financial Economics, 63, 3–50.