The Supply and Demand of S&P 500 Put Options

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Abstract

We model the supply of at-the-money (ATM) and out-of-the-money (OTM) S&P 500 index put options by risk-averse market makers and their demand by risk-averse customers who hold the index and a risk free asset and buy puts as downside-risk protection. In equilibrium market makers are net sellers and customers are net buyers of index puts. Consistent with the data, the model-implied net buy of puts by customers is decreasing in the risk and put prices because the shift to the left of the supply curve dominates the shift to the right of the demand curve. The observed time series of the net buy of ATM and OTM puts are consistent with their model-implied counterparts.

Keywords: S&P 500 options; net buy; option supply and demand; market makers

JEL classification: G11, G12, G23

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1 Introduction

Market makers serve a crucial role in option markets as net sellers of S&P 500 puts. However little is known about changes in their supply of puts and their impact on put prices. This is of particular interest to both policymakers and practitioners. The key innovation in our paper is the study of the endogenous supply shifts by market makers, in addition to demand shifts by customers, in the market for S&P 500 put options.

We model the demand of at-the-money (ATM) and out-of-the-money (OTM) S&P 500 European index put options by risk-averse customers who hold the index and a risk free asset and buy puts as downside-risk protection. We model the supply of these options by risk-averse agents that are the residual writers of puts. We loosely refer to these residual put writers as "market makers" even though it is understood that actual market makers typically hedge by offloading their risk exposure to other agents such as hedge funds. Equilibrium delivers the ATM and OTM put prices and their net buy by customers. The monthly volatility and disaster risk of the index are time-varying and are inferred by matching the model-implied ATM and OTM put prices (as Black-Scholes implied volatilities) with their observed counterparts.

We define the observed net buy of ATM or OTM puts by public customers in a month as the average daily executed total buy orders by public customers minus their daily executed total sell orders. The OTM and ATM puts are defined as puts with moneyness (strike price/index price) ranges 0.8-0.9 and 0.97-1.03, respectively. In the model market makers write "overpriced" index puts to customers who buy puts to hedge against the downside risk in their equity portfolios.

Figure 1 presents the time series of the monthly net buy of OTM and ATM puts and figure 2 presents the three-month average net buy of OTM and ATM puts. The net buy of ATM and OTM puts is mostly positive throughout our sample period from January 1996 to April 2016. The time-series pattern of ATM puts is similar to the pattern of OTM puts. These patterns are consistent with the basic premise of the model that customers buy puts as insurance while market makers write puts for profit. The net buy of OTM puts is slightly negative when the variance is relatively high, such as in some months around 1999, 2002 (dot-com bubble), and after the 2008 financial crisis and very negative during some months of 2014. Speculation may partly explain

this pattern and we leave it to future research to extend the model to include speculators. The net buy of puts sharply decreases to almost zero during the 2008 financial crisis when customers are expected to demand more puts to insure against downside risk. In contrast the net buy of puts, especially OTM puts, rises from 2003 to 2007 when the variance is historically low and the customers' net buy is much higher than the net buy during the financial crisis.

[Figures 1 and 2 here]

The model explains a novel set of observations regarding the net buy of puts. When the volatility and/or the disaster risk increase the model implies that the demand curve shifts to the right and the supply curve shifts to the left but the shift of the supply curve is the dominant effect. Consistent with the data, the model-implied net buy of ATM and OTM puts decrease when the volatility and/or the disaster risk increase.

When the volatility and/or the disaster risk increase the model implies that the price of ATM and OTM puts increase and the net buy of OTM and ATM puts decrease. The model and the data both imply that the net buy of OTM and ATM puts is decreasing in the put price. The intuition is the same as above. When the volatility and/or the disaster risk increase the demand curve shifts to the right and the supply curve shifts to the left but the shift of the supply curve is the dominant effect.

The most direct validation of the model is the finding that the model-implied monthly time series of the net buy of ATM and OTM puts are consistent with the observed net buy of ATM and OTM puts.

Gârleanu, Pedersen, and Poteshman (2009) introduce the demand pressure hypothesis where supply shifts in options by market makers are endogenous while demand in options by customers is exogenous. Therefore the equilibrium net buy equals the exogenous customer demand and the paper does not provide testable implications regarding the net buy response to risk and option prices. The key innovation in our paper is the introduction of endogenous demand shifts by customers in addition to endogenous supply shifts by market makers in the market for S&P 500 put options. Therefore our paper provides testable implications regarding the net buy response to risk and option prices, implications which are empirically verified.

Our paper relates to several other strands in the literature. Bates (2003) highlights institutional difficulties for the risk-sharing assumptions underlying representative agent models of options. Bollen and Whaley (2004) examine the relation between the net buying pressure of index options and find that the *IV* of index options is directly related to the buying pressure of index puts, particularly OTM puts. Etula (2013) models a commodities market with risk-averse producers and consumers and risk-neutral broker-dealers who are subject to a VaR constraint and finds empirical support for the prediction that the broker-dealers' risk-bearing capacity forecasts energy returns. Chen, Joslin, and Ni (2016) proxy the variation of the financial intermediary constraint with the net buy of deep OTM puts and show that this measure explains the variance risk premium embedded in puts and predicts the future excess returns of a variety of assets. Fournier and Jacobs (2016) model the supply and demand for options and find that most of the variance risk premium for index options is due to inventory risk. Muravyev (2016) shows that inventory risk faced by market makers has a first-order effect on option order flow and option prices.

Our paper also relates to the extensive literature on stochastic dominance violations by option prices. Constantinides, Czerwonko, Jackwerth, and Perrakis (2011), Constantinides, Czerwonko, and Perrakis (2017), and Constantinides, Jackwerth, and Perrakis (2009) show that OTM European calls on the S&P 500 index and OTM American calls on the S&P 500 index futures frequently imply stochastic dominance violations: any risk-averse investor who invests in a portfolio of the index and the risk-free asset increases her expected utility by writing OTM "overpriced" calls. By contrast these papers find that OTM puts on the S&P 500 index and the index futures rarely imply stochastic dominance violations: a risk-averse investor who invests in a portfolio of the index and the risk-free asset rarely increases her expected utility by writing OTM "overpriced" puts. These findings motivate our focus on OTM puts, as opposed to OTM calls. In our paper we model investors as buyers, as opposed to sellers, of OTM puts to hedge the downside risk of their market portfolio. This modelling choice is consistent with the above findings on stochastic dominance.

Finally our paper relates to the literature that addresses the cross-sectional variation in index option returns. Examples include Buraschi and Jackwerth (2001), Cao and Huang (2008), Carverhill, Dyrting, and Cheuk (2009), Constantinides, Jackwerth, and Savov (2013), and Jones (2006). Specifically Constantinides, Jackwerth, and Savov (2013) demonstrate that any one of

crisis-related factors incorporating price jumps, volatility jumps, and liquidity, along with the market, explains the cross-sectional variation in index option returns. These findings motivate our focus on disaster risk, in addition to market volatility.

The paper is organized as follows. In Section 2 we describe the data. In Section 3 we present the model and its calibration. In Section 4 we discuss the model predictions on the net buy by public customers and relate them to the empirical evidence. In Section 5 we discuss extensions of the model and conclude.

2   Description of the Data and Summary Statistics

2.1   Definition of Net Buy

We define the model-implied net buy of ATM and OTM puts as the model-implied number of put contracts purchased by customers at the beginning of the one-month period. Equivalently the model-implied net buy of puts is the model-implied number of put contracts written by market makers at the beginning of the period.

We proxy the net buy of puts in a given month by the average daily *executed* total buy orders by public customers minus their daily *executed* total sell orders net buy of S&P 500 put contracts by customers in the given month. The daily observed net buy of a given option on a given trading day is the sum of the open buy and close buy contracts minus the sum of open sell and close sell contracts on that day by customers. We calculate the monthly net buy of options for two moneyness ranges, OTM (0.8-0.9) and ATM (0.97-1.03), and maturity 15-60 days. We next compute the monthly net buy for a given moneyness and maturity as the average of the daily net buy across all trading days of the given calendar month of all options with the targeted moneyness and maturity range.

As a robustness check regarding the definition of the net buy we also calculate each month the net buy of puts in the first 15 days of the month. The top panel in figure 3 displays the time series of the one-month ATM net buy (blue) and the 15-day ATM net buy (red); their correlation is 75%. The bottom panel in the figure displays the time series of the one-month OTM net buy

(blue) and the 15-day OTM net buy (red); their correlation is 66%. Hereafter we use the definition of the net buy over one-month as it is less noisy.

[Figure 3 here]

The CBOE provides three categories of traders: public customers, proprietary traders, and market makers. We investigate whether proprietary traders should be classified as customers or as market makers. The top panel in figure 4 displays the net buy of ATM puts by public customers (blue) and proprietary traders (red). The bottom panel in figure 4 displays the net buy of OTM puts by public customers (blue) and proprietary traders (red). The net buy by public customers and proprietary traders are negatively correlated and therefore proprietary traders behave like market makers rather than public customers, as was earlier pointed out by Gârleanu, Pedersen, and Poteshman (2009). Hereafter we exclude proprietary traders in the definition of net buy.

[Figure 4 here]

2.2   Data on the Net Buy

The data for computing the net buy is obtained from the Chicago Board Options Exchange (CBOE) from January 1996 to April 2016. The data consists of a daily record of traded contract volumes on open-buy, open-sell, close-buy, and close-sell for each option by three types of public customers plus proprietary firms. Public customers are classified as small, medium, or large depending on the order size. An order greater than 200 contracts is classified as an order by a large customer, an order between 101-200 contracts is classified as an order by a medium customer, and an order less than 100 contracts is classified as an order by a small customer. Small customers on S&P 500 options are not necessarily retail traders. Chen, Goslin, and Ni (2014) show that small customers who sell deep OTM S&P 500 puts are institutional traders. Each trading day we compute the net buy as the total number of open buy and close buy orders by large, medium, and small customers, minus the total number of open sell and close sell orders.

2.3 Data on Option Prices

Intraday trades and bid-ask quotes of the S&P 500 options are obtained from the CBOE. We select the last pair of bid-ask quotes at or before 14:45 CDT and match these quotes with the tick-level index price at the same minute. We stop at 14:45 CDT because the market closes at 15:15 CDT and we wish to avoid contamination related to last-minute trading. The minute-level data of the S&P 500 index price is from Tick Data Inc. The recorded underlying S&P 500 index price for each option is the index price at the same minute when the option bid-ask quote is recorded. Therefore the data is synchronous up to a minute. The dividend yield of S&P 500 index is provided by OptionMetrics. For a given option we extract the implied interest rate from the put-call parity as in Constantinides, Jackwerth, and Savov (2013).

2.4 Summary Statistics

Figure 1 presents the time series of the monthly net buy of OTM and ATM puts and figure 2 presents the three-month average buy of OTM and ATM puts. In Table 1 we report summary statistics of the monthly net buy of OTM and ATM puts by public customers and the *IV* of OTM and ATM puts over the period from January 1996 to April 2016. The mean and median of the net buy of both OTM and ATM puts are positive. This is consistent with the conventional view that market makers are net sellers of S&P 500 index puts. The correlation between the monthly net buy of OTM and ATM puts is 0.001. The correlation between the 3-month net buy of OTM and ATM puts is 0.04.

[Table 1 here]

3   A Model of the Supply and Demand for Index Puts

This section addresses the observed relationship between put prices and their net buy in the context of a simple one-period model of the supply of ATM and OTM index puts by market makers and the demand for puts by two classes of customers.

3.1 Securities

We consider a one-period model of length one month. Customers and market makers trade at the beginning of the month and consume at the end of the month. There are four assets: risk free bonds, the market index (stock), one-month ATM index puts, and one month OTM index puts.

Bonds are perfectly elastically supplied. Each bond pays one unit of the consumption good at the end of the month. The bond price is the numeraire at the beginning of the period. Therefore the risk free rate is zero without loss of generality and fairly consistent with the current environment.

Whereas there is speculation in the stock and option markets we wish to focus on the hedging motive for trade and therefore assume that agents have homogeneous information. Shares of stock are perfectly elastically supplied. The stock price at the beginning of the month is exogenous and normalized to one. A share of stock pays S units of the consumption good at the end of the month. A disaster occurs during the month with probability p, $0 < p < 1$. In the no-disaster state, $S = e^{\mu + \sigma z}$ and in the disaster state $S = e^{\mu_J + \sigma_J z}$, where z has a standard normal distribution. We assume that the expected equity premium is positive, $(1-p)e^{\mu + \sigma^2/2} + pe^{\mu_J + \sigma_J^2/2} - 1 > 0$. The parameters $\mu, \mu_J,$ and σ_J are fixed across months. The parameters σ and p vary from month to month. We make no assumptions about the time-series processes of σ and p but infer them from the observed monthly put prices.

We introduce put options in the model because we wish to address the demand for index puts by portfolio managers and individuals who hold the market portfolio and buy puts as downside risk protection. An ATM put option has strike one, pays $[1-S]^+$ units of the consumption good at the end of the month, and has price P_{ATM}. An OTM put option has strike K, pays $[K-S]^+$ units of the consumption good at the end of the month, and has price P_{OTM}. Options are in zero net supply.

We do not introduce in-the-money index puts in the model because they are less liquid and have lower volume of trade than ATM and OTM index puts. We also do not introduce index calls because, in addition to hedging, investors trade calls for reasons that are different from their

trading in puts: investors may buy calls for leveraged speculation and write calls against the box to enhance the average performance of their portfolio.

3.2 Market Makers

We consider a representative market maker (MM) who has endowment W, writes $-m_{OTM}$ OTM puts, writes $-m_{ATM}$ ATM puts, and invests $W - m_{OTM}P_{OTM} - m_{ATM}P_{ATM}$ in the risk free asset. The endowment W is exogenous. Consistent with observation, the MM does not delta hedge with the stock. The MM maximizes expected utility of wealth at the end of the month:

$$\max_{m_{OTM}, m_{ATM}} E\left[\begin{array}{c} W - m_{OTM}P_{OTM} - m_{ATM}P_{ATM} + m_{OTM}\left[K - S\right]^{+} + m_{ATM}\left[1 - S\right]^{+} \\ -\dfrac{A}{2}\left(W - m_{OTM}P_{OTM} - m_{ATM}P_{ATM} + m_{OTM}\left[K - S\right]^{+} + m_{ATM}\left[1 - S\right]^{+}\right)^{2} \end{array}\right], \quad (1)$$

where A is a preference parameter, constant across months. We specify the utility as quadratic merely for computational convenience. In equilibrium the market maker writes both OTM and ATM puts, consistent with observation.

3.3 Customers

Investors trade options for a variety of reasons, including speculation and relative mispricing such as potential violations of the put-call parity, but we focus on the demand for index puts by portfolio managers and individuals who hold the market portfolio and buy puts as downside risk protection. Thus we address only a subset of the reasons why investors trade in index puts and we expect the model to explain only portion of the observed variation of the net buy of index puts. Nevertheless we show that this simple model explains a large portion of the observed variation.

There are two classes of customers, customers "I" and customers "II". The representative customer I has initial endowment W, buys α_{I} shares of stock, buys β_{I} ATM puts, and invests $W_{c} - \alpha_{I} - \beta_{I}P_{ATM}$ units of the numeraire in bonds. She maximizes expected utility of wealth at the end of the month:

$$\max_{\alpha_I,\beta_I} E\left[W - \alpha_I - \beta_I P_{ATM} + \alpha_I S + \beta_I [1-S]^+ - \frac{A}{2}\left(W - \alpha_I - \beta_I P_{ATM} + \alpha_I S + \beta_I [1-S]^+ \right)^2 \right], \quad (2)$$

The representative customer II has initial endowment W, buys α_{II} shares of stock, buys β_{II} ATM puts, and invests $W - \alpha_{II} - \beta_{II} P_{OTM}$ units of the numeraire in bonds. He maximizes expected utility of wealth at the end of the month:

$$\max_{\alpha_{II},\beta_{II}} E\left[W - \alpha_{II} - \beta_{II} P_{OTM} + \alpha_{II} S + \beta_{II} [K-S]^+ - \frac{A}{2}\left(W - \alpha_{II} - \beta_{II} P_{OTM} + \alpha_{II} S + \beta_{II} [K-S]^+ \right)^2 \right],$$
$$(3)$$

Note that we deliberately keep the model simple by setting the endowment and preference parameter of the MM and the two classes of customers equal.

The division of customers into two classes, those who buy only ATM puts and those who buy only OTM puts requires explanation. We experimented with an alternative model with only one class of customers who trade in both ATM and OTM puts. The alternative model counterfactually implies that customers buy ATM puts and write OTM puts. It also counterfactually implies negative correlation between the model-implied net buy and the observed net buy of OTM puts. We therefore suppress these counterfactual implications by restricting customers to trade either in ATM puts or OTM puts, but not in both. This restriction is consistent with our goal of modelling the purchase of puts as portfolio insurance and suppressing the motive of customers to engage in complex trades of puts and calls of different moneyness. Given that the model explains a large portion of the observed variation of the net buy of one-month index puts, this justifies ex post our modelling choice. In a different context this is in the spirit of He and Krishnamurthy (2013) who assume that at every date each specialist is randomly matched with a household.

3.4   Equilibrium

In every month equilibrium is defined by option prices P_{ATM} and P_{OTM} such that the option markets clear:

$$m_{ATM} + \beta_I = 0 \text{ and } m_{OTM} + \beta_{II} = 0. \tag{4}$$

Equilibrium is calculated numerically and yields the monthly time series of prices and net buy of ATM and OTM puts.

3.5 Model Implications

Recall that the parameters μ, μ_J, and σ_J are fixed across months. We set $\mu = 0.005$ corresponding to annual equity premium with mean 6% in the no-disaster state; and $\mu_J = -0.04$ and $\sigma_J = 0.80/\sqrt{12}$, corresponding to annual volatility 80% of the equity premium in the disaster state. For this range of parameters the annual equity risk premium ranges from 2.86% to 17.04% and the annual volatility ranges from 7.38% to 45.01% consistent with the observed equity premium and volatility of the S&P 500 index. We set the customers' and market maker's initial wealth at $W = 500$ and their preference parameter at $A = 0.001$ thereby matching the average model-implied net buy of ATM and OTM puts with the average observed counterparts.[1]

In figure 5 we plot the ATM price (as IV, red) and the OTM price (as IV, green) as functions of the parameters p and σ. The ATM IV closely approximates the parameter σ. The model captures the implied volatility skew: the OTM IV is always higher than the ATM IV. The slope of the skew (the OTM IV minus the ATM IV) decreases as σ increases because the difference in moneyness between the two types of options becomes less important as a percentage of the parameter σ.

[Figure 5 here]

4 Empirical Evidence

In this section we test the implications of the model regarding the net buy of puts. Recall that the parameters σ and p may vary from month to month. Every month we infer the values of these

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[1] This can always be achieved by scaling: if we scale up the endowments by a factor h to hW and scale down the preference parameters to A/h the same equilibrium obtains except that the net buy of ATM and OTM puts scale up by the factor h.

parameters by matching the model-implied volatility of ATM and OTM puts with their observed counterparts. The inferred time series of these parameters are shown in figure 6.

[Figure 6 here]

Figure 7 shows the close correspondence between the model-implied ATM and OTM net buy (red) and the observed ATM and OTM net buy (blue) as functions of the ATM IV. In Table 2 we present regressions of the model-implied and observed monthly net buy of ATM and OTM puts on the volatility (σ) and disaster probability (p) from 01/1996 to 04/2016. Both the model-implied and observed monthly net buy of ATM and OTM puts are decreasing in the volatility and disaster probability and the regression coefficients are highly significant thereby validating the first implication of the model. As to be expected the R-squares of the regressions of the observed net buy are lower than the corresponding regressions of the model-implied net buy.

[Figure 7 and Table 2 here]

In Table 3 we present regressions of the model-implied and observed monthly net buy of ATM and OTM puts on the corresponding put prices from 01/1996 to 04/2016. Put prices are expressed as Black-Scholes implied volatilities. Both the model-implied and observed monthly net buy of ATM and OTM puts are decreasing in the put prices and the regression coefficients are highly significant thereby validating the second implication of the model. As to be expected the R-squares of the regressions of the observed net buy are lower than the corresponding regressions of the model-implied net buy.

[Table 3 here]

Figure 1 presents the time series of the monthly net buy of OTM and ATM puts and figure 2 presents the three-month average net buy of OTM and ATM puts. The model-implied time series closely track their observed counterparts. In Table 4 we present regressions of the observed net buy of ATM puts on the model-implied net buy of ATM puts and of the observed net buy of OTM puts on the model-implied net buy of OTM puts over the full period from 01/1996 to 04/2016 and over subperiods. All the regression coefficients are positive and statistically significant. Note that the model captures only the hedging motive of customers in buying index puts and it is therefore not surprising that the R^2s are low. We conclude that the model-implied monthly time series of the net buy of ATM and OTM puts are consistent with the observed net buy of ATM and OTM puts.

[Table 4 here]

5   Concluding Remarks

Our paper fills a theoretical gap in modelling the net buy of index put options by introducing the endogenous demand for put options by public customers, in addition to the supply of put options by market makers. The model captures the scenario in which market makers write "overpriced" puts while the risk-averse public customers buy the index to maximize their utility and hedge their exposure to downside risk by buying index puts. The shift in the supply and demand for S&P 500 put options explains a novel set of observations regarding the net buy and prices of put options.

The model and data consistently imply that the net buy of puts by public customers is decreasing in the market volatility and probability of disaster. The model and data consistently imply that the net buy of ATM puts is positive. As predicted by the model the net buy of OTM puts is mostly positive. However in some periods the observed net buy of OTM puts is negative and this is a telltale sign of speculation. We leave it as a task for future research to superimpose to the model speculative behavior. We stress, however, that even without explicitly modelling speculation, the model does a good job in explaining the time series of the observed net buy. Also the model and data consistently imply that the net buy of ATM puts is decreasing in the price of ATM puts; and the net buy of OTM puts is decreasing in the price of OTM puts.

The key result is that the model-implied net buy of ATM and OTM puts is consistent with the observed time series of the monthly net buy. In regressions of the observed net buy of ATM puts on the model-implied net buy of ATM puts and of observed net buy of OTM puts on the model-implied net buy of OTM puts, all the regression coefficients are positive and statistically significant.

References

Bollen, N. P. B. and R. E. Whaley. 2004. Does Net Buying Pressure Affect the Shape of Implied Volatility Functions? *Journal of Finance* 59: 711–753.

Buraschi, A. and J. C. Jackwerth. 2001. The Price of a Smile: Hedging and Spanning in Option Markets. *Review of Financial Studies* 14: 495–527.

Cao, C. and J. Huang. 2008. Determinants of S&P 500 Index Option Returns. *Review of Derivatives Research* 10: 1–38.

Carverhill, A. P., S. Dyrting, and T. H. F. Cheuk. 2009. Futures Options: A Linearized Factor Analysis. *Review of Derivatives Research* 12: 109–139.

Chen, H., S. Joslin, and S. Ni. 2016. Demand for Crash Insurance, Intermediary Constraints, and Risk Premia in Financial Markets. Working paper, MIT and NBER.

Constantinides, G. M., M. Czerwonko, J. C. Jackwerth, and S. Perrakis. 2011. Are Options on Index Futures Profitable for Risk Averse Investors? Empirical Evidence. *Journal of Finance* 66: 1407-1437.

Constantinides, G.M., M. Czerwonko, and S. Perrakis. 2017. Mispriced Index Option Portfolios. Working paper, University of Chicago and Concordia University.

Constantinides, G. M., J. C. Jackwerth, and S. Perrakis. 2009. Mispricing of S&P 500 Index Options. *Review of Financial Studie*s 22: 1247-1277.

Constantinides, G. M., J. C. Jackwerth, and A. Z. Savov. 2013. The Puzzle of Index Option Returns. *Review of Asset Pricing Studies* 3: 229–257.

Etula, E. 2013. Broker-Dealer Risk Appetite and Commodity Returns. *Journal of Financial Econometrics* 0: 1-36.

Fournier, M. and K. Jacobs. 2016. Inventory Risk, Market Maker Wealth, and the Variance Risk Premium, Working paper, University of Houston.

Gârleanu, N., L. H. Pedersen, and A. M. Poteshman. 2009. Demand-Based Option Pricing. *Review of Financial Studies* 22: 4259–4299.

He, Z. and A. Krishnamurthy. 2013. Intermediary Asset Pricing. *American Economic Review* 103: 732-770.

Muravyev, D. 2016. Order Flow and Expected Option Returns. *Journal of Finance* 71: 673-707.

Table 1: Summary Statistics, 01/1996-04/2016

The table reports monthly summary statistics of the monthly net buy of ATM and OTM puts, the annualized *IV* of ATM and OTM puts, and the monthly volume of trade of ATM and OTM puts. The variables are defined in Section 2. The ATM puts are S&P 500 puts with moneyness 0.97–1.03 and maturity 15–60 days. The OTM puts are S&P 500 puts with moneyness 0.80–0.90 and maturity 15–60 days.

	Mean	Median	STD	5th Quantile	95th Quantile	AC(1)
ATM *IV*	0.1821	0.1717	0.0724	0.1004	0.3100	0.8647
OTM *IV*	0.3084	0.2934	0.0796	0.2219	0.2240	0.4372
ATM Net Buy	3,255	2590	3,624	-263	9,262	0.1863
OTM Net Buy	1,124	554	4,272	-4980	9,510	0.4965
ATM Volume	42,087	35,143	31,261	11,012	97,549	0.7130
OTM Volume	30,017	15,353	28,630	2,851	83,114	0.8496

Table 2: Regressions of the Model-Implied and Observed Monthly Net Buy of ATM and OTM Puts on the Volatility (σ) and Disaster Probability (p), 01/1996-04/2016

Intercept	Regression Coefficient	R^2
	Model-Implied Net Buy of ATM Puts on Volatility	
4042 (99)	-47,798 (1,806)	0.743
	Observed Net Buy of ATM Puts on Volatility	
6037 (731)	-53,185 (13,301)	0.062
	Model-Implied Net Buy of ATM Puts on Disaster Probability	
1701 (57)	-10,359 (1,348)	0.196
	Observed Net Buy of ATM Puts on Disaster Probability	
3355 (248)	-6,475 (3,355)	0.005
	Model-Implied Net Buy of OTM Puts on Volatility	
3401 (79)	-39,718 (1,446)	0.757
	Observed Net Buy of OTM Puts on Volatility	
3519 (875)	-45,799 (15,919)	0.033
	Model-Implied Net Buy of OTM Puts on Disaster Probability	
1456 (47)	-8,634 (1,106)	0.201
	Observed Net Buy of OTM Puts on Disaster Probability	
1283 (292)	-10,365 (1,283)	0.009

Standard errors are in parentheses. The table indicates that the observed and model-implied regression coefficients for each regressor are statistically significant and of similar order of magnitude.

Table 3: Regressions of the Model-Implied and Observed Monthly Net Buy of ATM Puts on the Price of ATM Puts (as IV) and Regressions of the Model-Implied and Observed 15-Day Monthly Net Buy of ATM Puts (as IV) on the Price of ATM Puts, 01/1996-04/2016

Intercept	Regression Coefficient	R^2
	Model-Implied Net Buy of ATM Puts on ATM Put Price	
3465 (95.5)	-10,560 (487)	0.659
	Observed Net Buy of ATM Puts on ATM Put Price	
5232 (615)	-10,854 (3,143)	0.047
	Model-Implied Net Buy of OTM Puts on OTM Put Price	
3835 (147)	-8,146 (466)	0.557
	Observed Net Buy of OTM Puts on OTM Put Price	
5262 (1193)	-13,421 (3,772)	0.049

Standard errors are in parentheses. The table indicates that the observed and model-implied regression coefficients for each regressor are statistically significant and of similar order of magnitude.

Table 4: Regressions of the Observed Net Buy of ATM Puts on the Model-Implied Net Buy of ATM Puts and of the Observed Net Buy of OTM Puts on the Model-Implied Net Buy of OTM Puts

Intercept	Regression Coefficient	R^2
	ATM, 01/1996-12/2005	
850 (240)	0.764 (0.151)	0.177
	ATM, 01/2006-04/2016	
3420 (775)	0.672 (0.390)	0.024
	ATM, 01/1996-04/2016	
1815 (433)	.933 (0.240)	0.059
	OTM, 01/1996-12/2005	
-795 (281)	1.255 (0.210)	0.233
	OTM, 01/2006-04/2016	
-92 (1015)	1.122 (0.598)	0.028
	OTM, 01/1996-04/2016	
-510 (529)	1.23 (0.346)	0.050
	ATM, 01/1996-04/2016, 3-Month Average	
1961 (289)	0.845 (0.160)	0.104
	ATM, 01/1996-04/2016, 3-Month Average	
-515 (417)	1.245 (0.273)	0.079

Standard errors are in parentheses. The table indicates that the observed and model-implied regression coefficients for each time period and regressor are statistically significant and of similar order of magnitude.

ATM Net Buy

OTM Net Buy
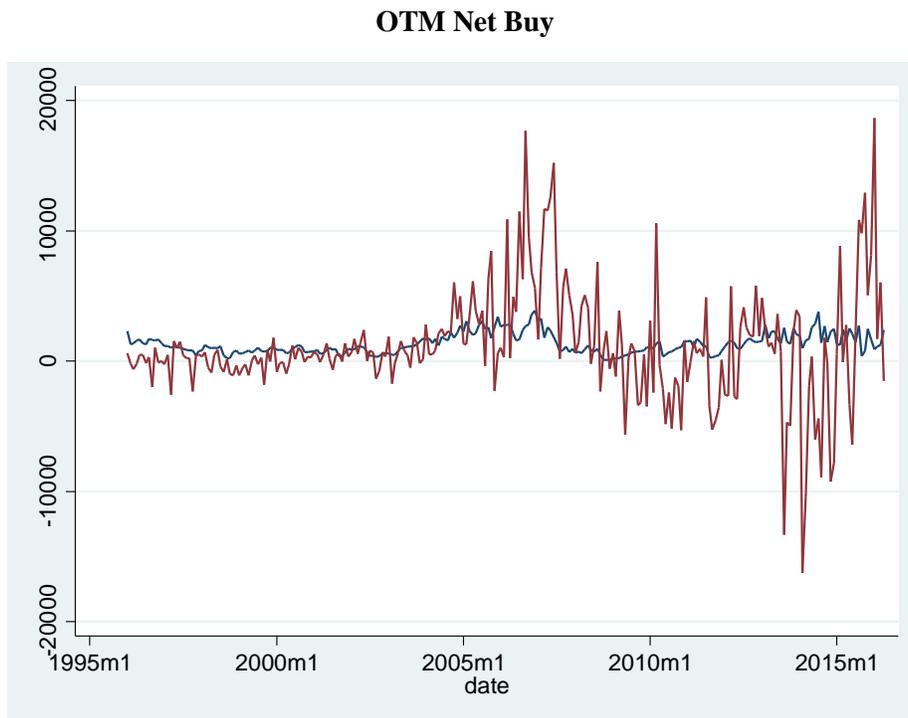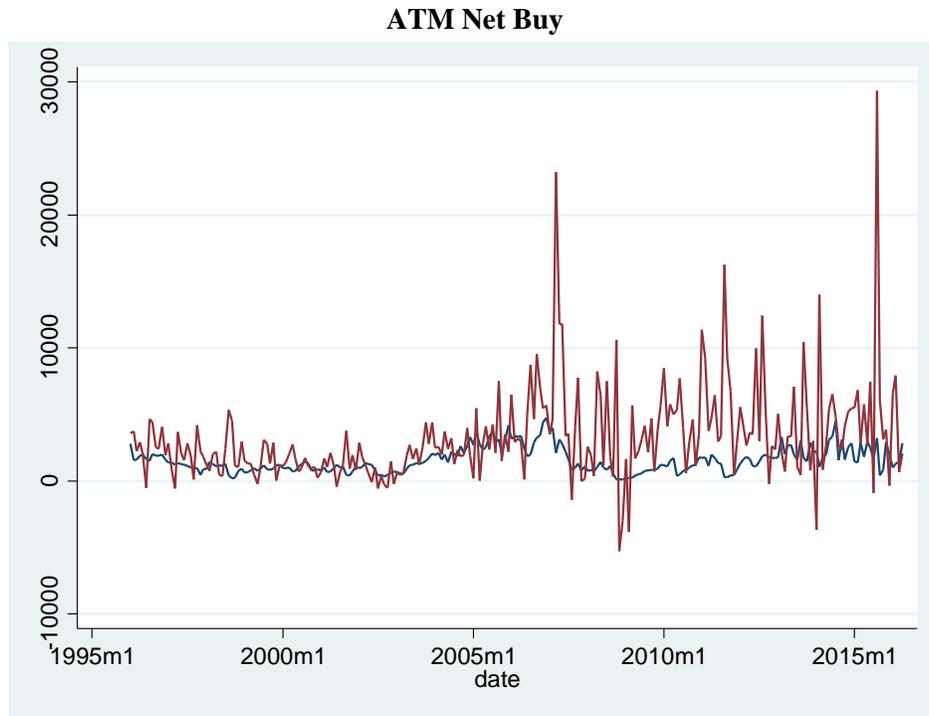
Figure 1: Time Series of the Observed Net Buy (Red) and Model-Implied Net Buy (Blue), 01/1996-04/2016

The figures indicate that the model-implied net buy tracks the observed net buy but with significantly lower volatility.

ATM Net Buy
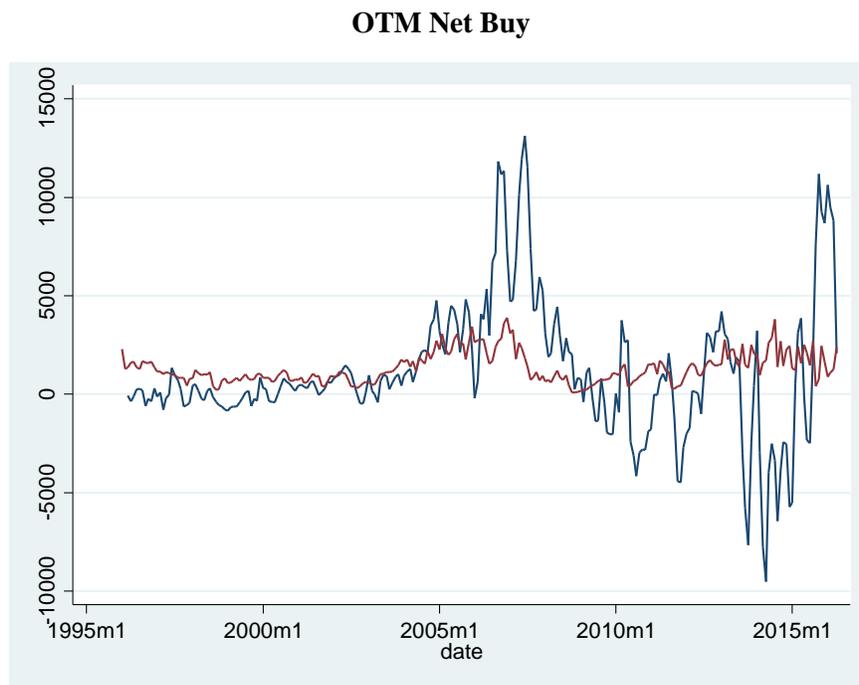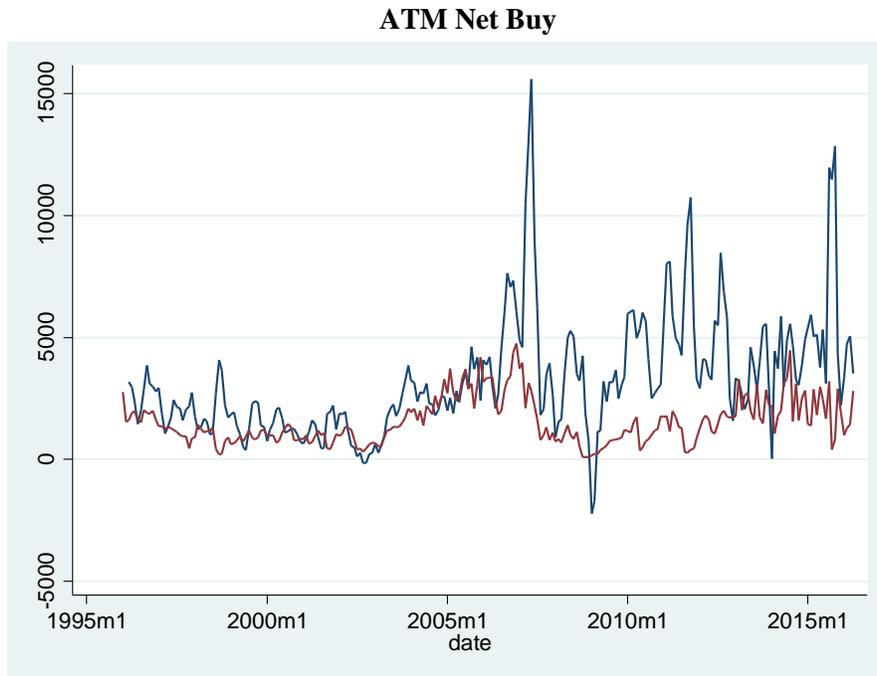
OTM Net Buy

Figure 2: Time Series of the Observed 3-Month Average Net Buy (Red) and Model-Implied Net Buy (Blue), 01/1996-04/2016

The figures indicate that the model-implied net buy tracks the observed net buy but with significantly lower volatility.
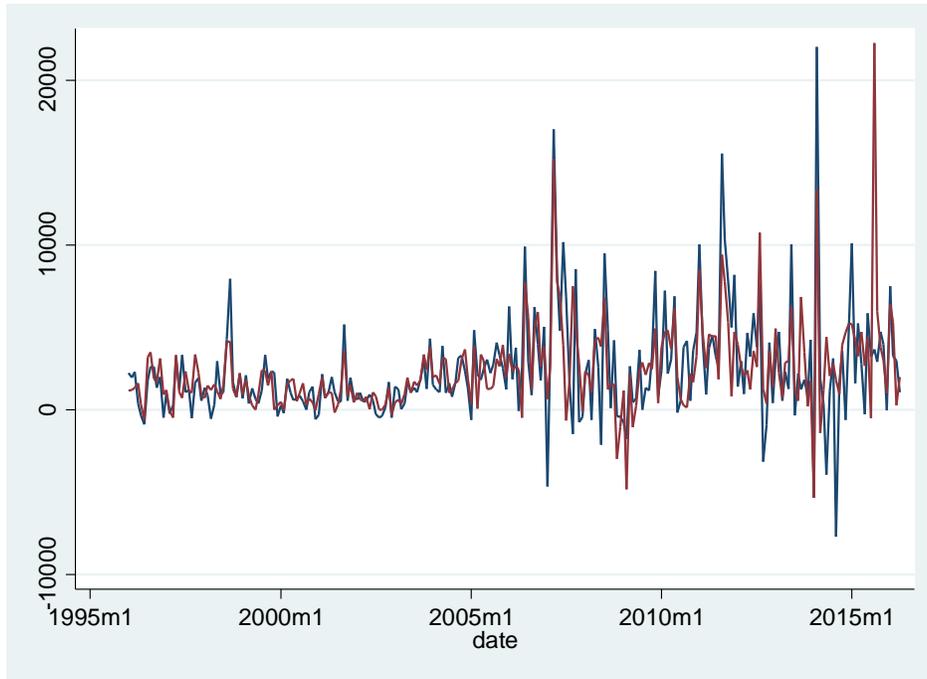
ATM Net Buy

OTM Net Buy
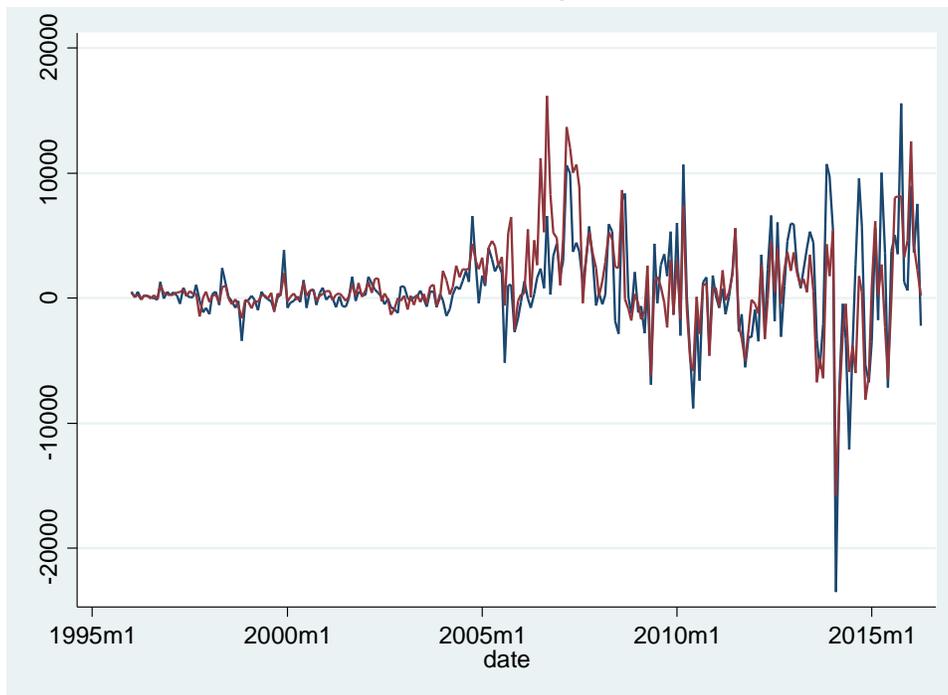
Figure 3: Time Series of the Observed One-Month Net Buy (Blue) and 15-Day Net Buy (Red), 01/1996-04/2016

The figures indicate that the 15-day net buy closely tracks the one-month net buy.

ATM Net Buy

OTM Net Buy
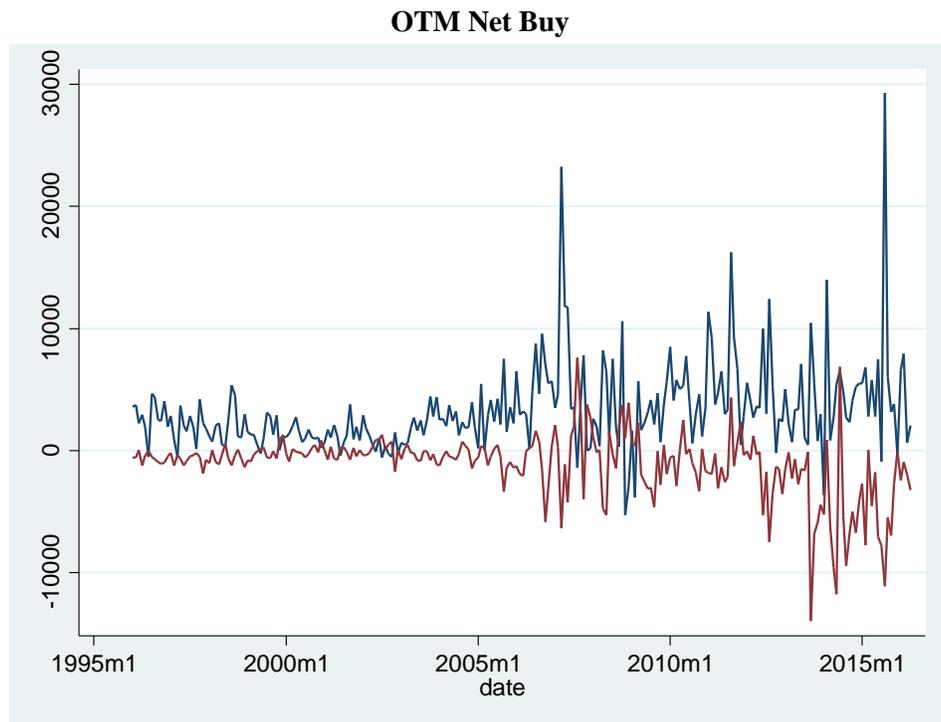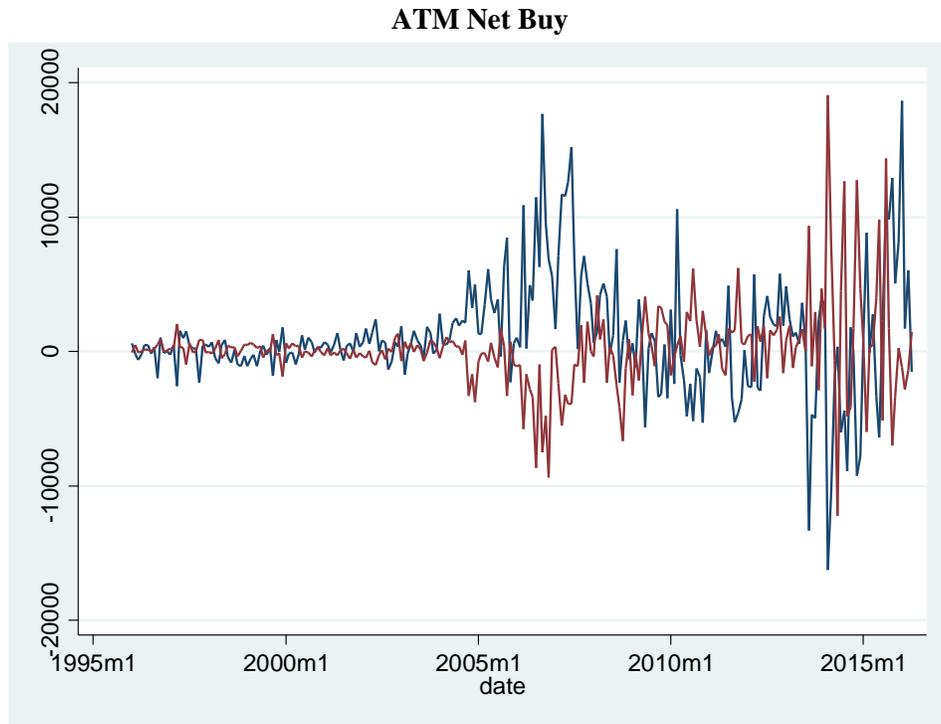
Figure 4: Time Series of the Observed Net Buy by Public Customers (Blue) and Proprietary Traders (Red), 01/1996-04/2016

The figures indicate that the net buy by public customers and proprietary traders are strongly negatively correlated.
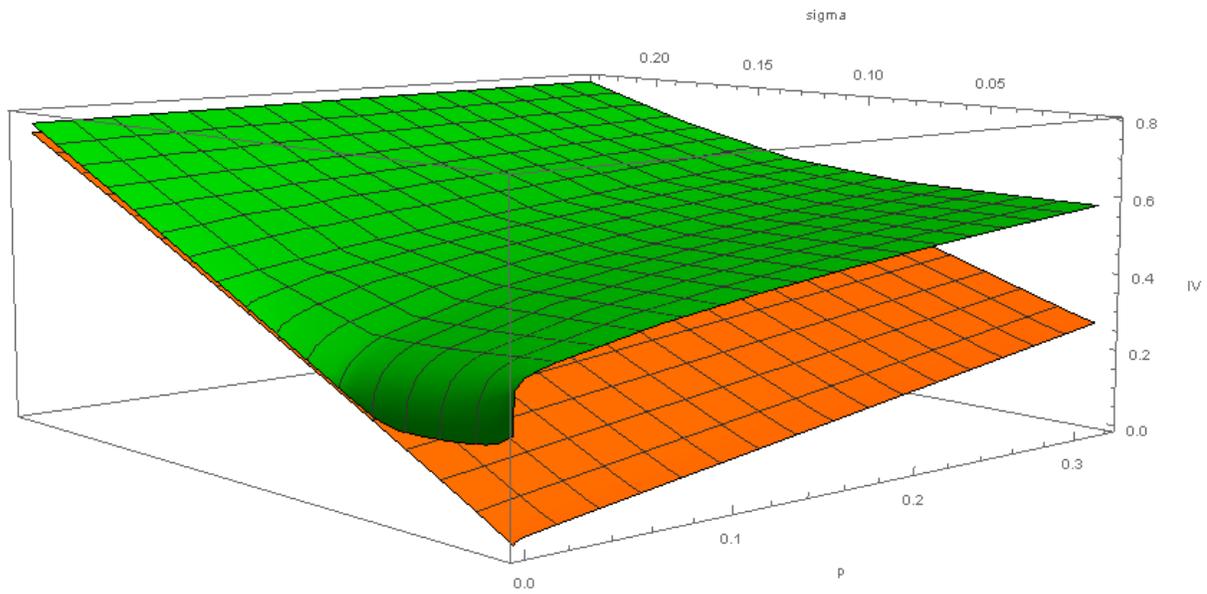
Figure 5: The ATM IV (Red) and the OTM IV (Green) as Functions of the Risk Parameters p and σ

The figure indicates that the ATM IV closely approximates the parameter σ; the model captures the implied volatility skew; and the slope of the skew decreases as σ increases.
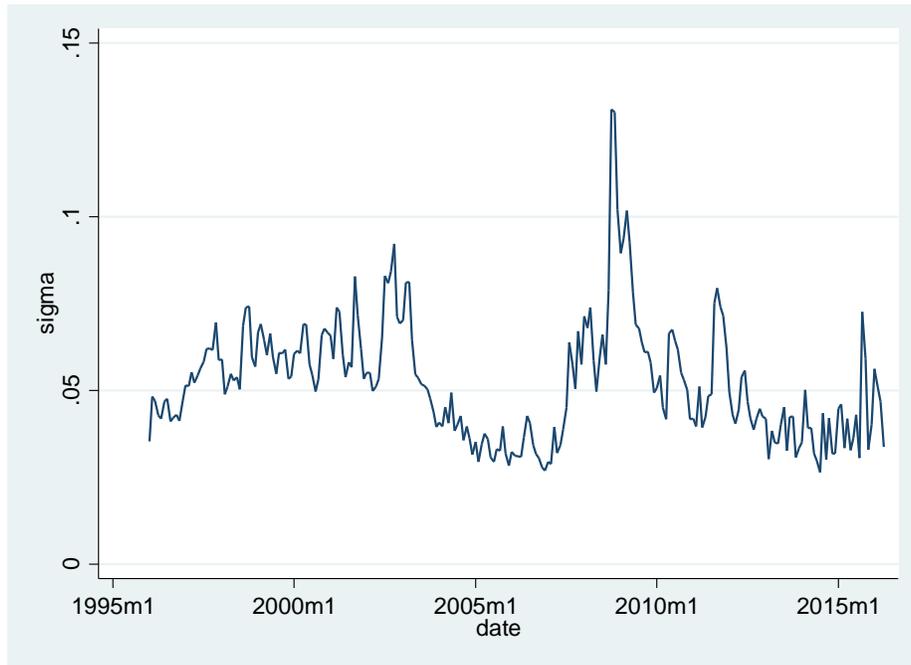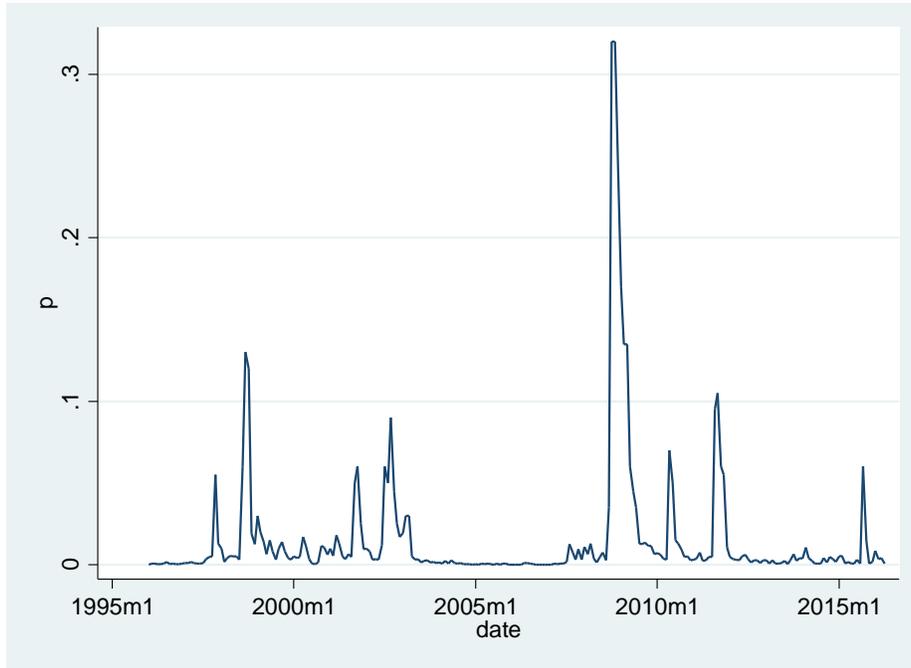
Figure 6: The Time Series of the Calibrated Monthly Probability of Disaster Parameter p and volatility parameter σ, 01/1996-04/2016

The figures indicate that the probability of disaster and, to a lesser extent, the volatility parameter capture periods of financial turmoil.
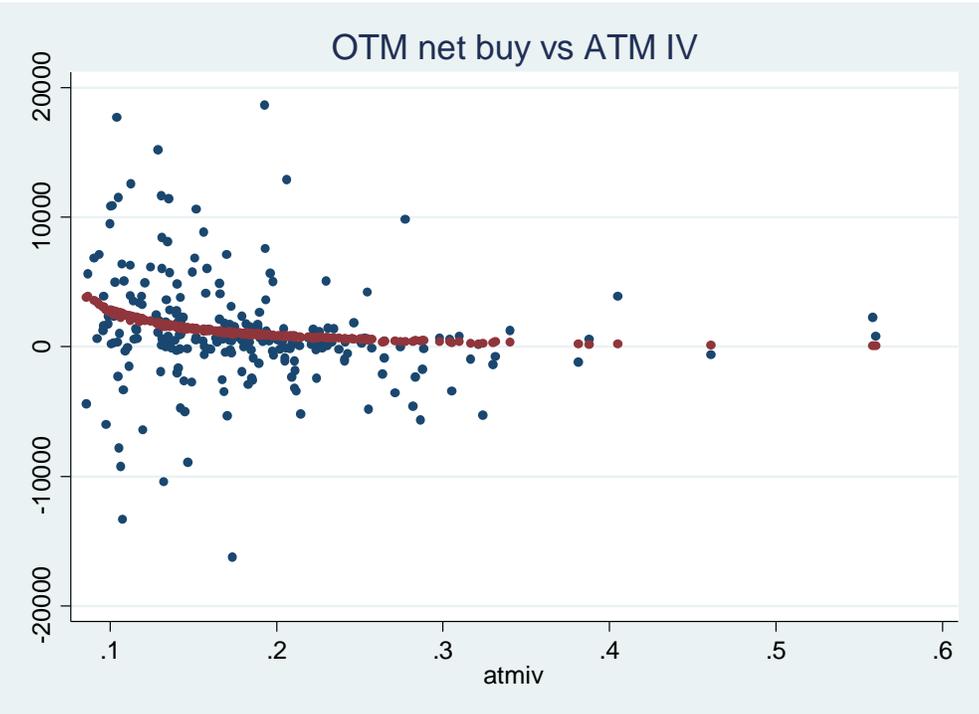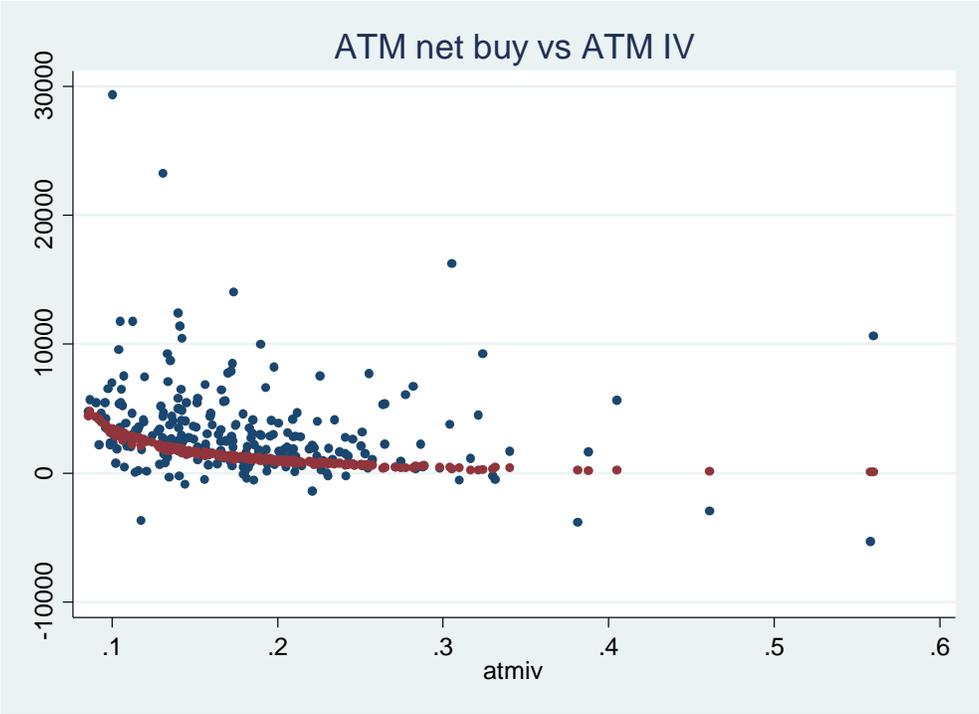
Figure 7: The Model-Implied ATM and OTM Net Buy (Red) and the Observed ATM and OTM Net Buy (Blue) as Functions of the ATM IV, 01/1996-04/2016

The figures indicate the close correspondence between the model-implied ATM and OTM net buy and the observed ATM and OTM net buy as functions of the ATM IV.