Asymmetric and negative return-volatility relationship: The case of the VKOSPI

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ABSTRACT

KOSPI 200 index options are the most actively traded derivative contracts in the world. And, unlike most other active option markets, trading is dominated by individual investors. This paper examines the short-term relationship between stock market returns and implied volatility in the Korean financial market using high frequency data on the recently introduced volatility index (VKOPSI) implied by the KOSPI 200 options. We find a strong asymmetric and negative return-volatility relationship both at the daily and intraday level, which cannot be explained by either leverage or volatility feedback hypotheses on the asymmetric volatility phenomenon. We also find that the asymmetric relationship is more pronounced for extremely negative stock market returns. We conjecture that behavioral factors better explain the observed asymmetric return-volatility relationship. .

1. INTRODUCTION

The relationship between stock market returns and volatility has been the subject of a number of studies in the finance literature. These studies provide evidence of a negative and asymmetric relationship, which indicates that a negative return is generally associated with a large increase in volatility whereas the same magnitude of a positive return is associated with a relatively small decrease in volatility. Traditionally, two competing hypotheses, the *leverage hypothesis* and the *volatility feedback hypothesis*, have been widely used to explain this “asymmetric volatility phenomenon”. According to the leverage hypothesis, if the stock price of a firm declines, the relative proportion of equity (debt) value to the firm value decreases (increases), which makes the firm’s stock riskier and increases its volatility as a result (Black, 1976; Christie, 1982; Schwert, 1990; Duffee, 1995). The volatility feedback hypothesis states that the negative change in expected return tends to be intensified whereas the positive change in the expected return tends to be dampened and these effects generate the asymmetric volatility phenomenon (See

French, Schwert, and Stambaugh, 1987; Campbell and Hentschel, 1992). Later studies have examined the two competing hypotheses. For example, Bekaert and Wu (2000) develop a unified framework based on a multivariate GARCH-in-Mean model to examine both hypotheses. They argue that the volatility feedback effect is largely responsible for the observed asymmetric volatility phenomenon in the Japanese stock market. The model of Wu (2001) also allows for both the leverage and volatility feedback effects. However, unlike Bekaert and Wu (2000), he claims that both effects are related to the asymmetric volatility phenomenon.

Many previous studies have reported the asymmetric and negative return-volatility relationship using low frequency (i.e. weekly or monthly) data and claimed that the leverage effect and/or the volatility feedback effect is the cause of the relationship. However, the two hypotheses may not be appropriate to explain the return-volatility relationship at a higher frequency (i.e. daily or intraday) level in that the leverage and volatility feedback effects are related to changes in the fundamental factors of firms, and thus may only be reflected in the long run. Another limitation of the previous studies is that they base their research on either historical or realized volatilities, which contain little information on the future state of the market and investor sentiments. With these considerations in mind, we adopt the framework of Hibbert, Daigler, and Dupoyet (2008), and investigate the short-term dynamic relationship between stock market returns and implied volatility using high frequency data from the Korean market. More specifically, we analyze the potential asymmetric volatility using daily and intraday data of VKOSPI (Volatility Index of the KOSPI 200). VKOSPI is implied by the KOSPI 200 index options and has been designated as the official implied volatility index by the Korea Exchange (KRX).

Motivations for using the VKOSPI to examine the short-term return-volatility relationship originate from the unique traits of the KOSPI 200 options market and the desirable properties of the VKOSPI as a market volatility indicator. First, the KOSPI 200 options are the single most actively traded derivatives in the world. The liquidity of the KOSPI 200 options market is extremely plentiful and this makes the volatility index quite credible and meaningful. The high level of trading volume of the options market also reflects the abundant interest and concerns of global and local investors. As a result, the options-implied volatility index, the VKOSPI, presumably contains rich information about the opinions and expectations of these investors. Second, the KOSPI 200 options market is known to be highly speculative and very efficient in the sense that new information arrived at the market is instantaneously incorporated into the options prices (Ahn, Kang, and Ryu, 2008, 2010). This means that changes in the VKOSPI not only reflect the arrival of new information but also any variation in market sentiment. Third, unlike derivatives markets in more developed countries, domestic individual investors are the most active group in the KOSPI 200 options market. If domestic individuals also tend to be easily affected by market sentiments and other behavioral biases, and if the options market reflects information shocks and noise shocks very quickly, then the VKOSPI provides an ideal vehicle to examine whether behavioral biases of market participants impact the short-term asymmetric return-volatility relationship. Fourth, in spite of the large trading volume of the KOSPI200 options, most previous studies focus on the US and European options markets. To our knowledge, not a single academic paper investigates the intraday properties of the VKOSPI. This study helps to fill that gap. Fifth, this study will benefit regulators and market practitioners alike if new VKOSPI-related derivatives such as VKOPSI futures and options are introduced. Market practitioners and regulators expect that professional investors will likely actively trade these new derivatives on the volatility index and use these securities for implementing intraday trading strategies such as day-trading or intraday program trading.[1] Consequently, understanding, the high frequency properties of the VKOSPI is important.

The empirical results of this study show that there exists a strong negative and asymmetric relationship between the stock market return (KOSPI 200 index return) and the change of the implied volatility index (VKOSPI) at both daily and intraday levels. Neither the leverage hypothesis nor the volatility feedback hypothesis adequately explains these results. Indeed, the daily and intraday estimation results for the model coefficients are inconsistent with the leverage and volatility feedback hypotheses. Our results also suggest that negative returns have greater power for explaining the return-volatility relationship than positive returns and that, among negative returns, extremely negative returns play a dominant role in explaining the observed asymmetric volatility and the return-volatility relationship.

Given that Avramov, Chordia, and Goyal (2006) claim that uninformed individual trading can generate asymmetric and negative return-volatility relationship and that Hibbert, et al. (2008) suggest the positive association between the asymmetric volatility and investors' behavioral biases, one potential explanation for the observed asymmetric volatility phenomenon is the dominance of individuals in KOSPI 200 options trading. This assumes, of course, that individual KOSPI 200 options traders are easily affected by the behavioral biases and perceived changes in market sentiment. It should be noted that our intraday results are consistent with the existence of extrapolation bias from which small individual investors often suffer (Barberis, Shleifer, and Vishny, 1998; Frieder; 2008) as well as the phenomenon of investors' quickly forgetting bad news.

The rest of this study is organized as follows. Section 2 describes the KOSPI 200 options market, the

[1] It is widely known that the strategic intraday trading for the short-term profits prevails in the Korea's derivatives market due to its low transaction costs and abundant liquidity (Ryu, 2012a, 2012b; Kim and Ryu, 2012).

VKOSPI, and the sample data. Section 3 explains the regression models and discusses the empirical results. Section 4 concludes the paper.

2. KOSPI 200 OPTIONS AND VKOPSI

Since its introduction in 1997, the trading volume of the KOSPI 200 options has sharply increased and, as noted above, is currently the single most actively traded derivative security in the world. Table 1 depicts the ten most actively traded index derivatives in the world.[2] The table reports the names of the contracts, their corresponding exchanges, index multipliers, and trading volumes which are measured by the number of contracts traded and/or cleared in 2010. It shows that the trading volume of KOSPI 200 options dominates those of other derivatives. The total trading volume of the KOSPI 200 options is greater than the sum of the trading volumes of other derivatives contracts listed top 10. Its high trading volume reflects the great interest of worldwide investors and market practitioners in this options market.

In addition to its ample liquidity, the KOSPI 200 options market has other unique characteristics. First, in contrast to the other financial markets of developed countries, the domestic individual investors are the major market players in the KOSPI 200 options market. Table 2 presents the trading volume (measured by the number of contracts) by three investor types, which are domestic individuals, domestic institutions, and foreign investors, for the period between January 2003 and December 2010.[3] The table shows that the domestic individuals are the most active trader group in stark contrast with options markets in other developed countries. Unlike institutional investors who participate in the options markets mostly for hedging purposes or broad portfolio management reasons, individuals are largely speculators who seek short-term profits and trade options to enjoy the high leverage option trading provides. This means that option prices are potentially more easily affected by behavioral biases and market sentiments of individual traders who account for the vast bulk of option trading volume in the KOSPI 200 options market. Second, the relatively high concentration of investors in the out-of-the-money (OTM) and deep-OTM options markets suggests that the KOSPI 200 options market is highly speculative, considering that these options have negligible expected values and are rarely exercised (Ahn, et al., 2008; Kim and Ryu, 2012). Third, because of the presence of many professional investors and day traders who try to make short-term profits, the KOSPI 200 option prices can reflect market information and investors' expectation very quickly (Ahn, et al., 2010; Ryu, 2011).

VIX is a widely used indicator to measure expected market volatility, market sentiment, and investors'

[2] Source: Futures Industry Association (www.futuresindustry.org).

[3] The trading activities of government and government-owned firms are excluded because they account for only a small portion of total trading volume.

fear in the U.S. market. Eyeing the crucial roles of the VIX as the market indicator, the Korean government and the KRX have recognized the necessity of a volatility index which can represent and summarize the opinions of investors investing in the Korean financial market. However, despite the great success and influence of the KOSPI 200 options market, the KRX only recently introduced the volatility index implied by the KOSPI 200 option prices and named it VKOSPI. Further, though the VKOSPI is the product of thorough research and preparation by experts in the academic community and the financial industry, there is extremely little research investigating the VKOSPI in the finance literature.

The VKOSPI has been publicly reported by the KRX since April 19, 2009. However, the historical VKOSPI series before the official publication date can be constructed by using the "fair variance swap" method that is used to calculate the VKOSPI and the VIX.[4] Consequently, the daily VKOSPI and underlying KOSPI 200 index price data in this study can cover the period from January 2003 to December 2010. Table 3 presents summary statistics for daily stock index price and return and for daily VKOSPI level and its change. S_t denotes the daily closing price of KOSPI200 index. R_t is the log-return of the KOSPI 200 index price and $|R_t|$ denotes its absolute value. $VKOSPI_t$ and $\Delta VKOSPI_t$ represent the level and first-difference of the implied volatility index, respectively. We also obtain the intraday (1-minute interval) VKOSPI and the index price data from the KRX from March 3, 2008 to May, 13, 2010.[5] We carry out the analysis using daily (January 2003 – December 2010) and intraday (March 2008 – May 2010) data.

3. MODELS AND EMPIRICAL RESULTS

3.1 Daily Results

Following Hibbert, et al. (2008), we run the following five regression models to investigate the daily and intraday return-volatility relationship.[6]

$$M1: \Delta V_t=\alpha+\beta_0 R_t+\beta_{-1}R_{t-1}+\beta_{-2}R_{t-2}+\beta_{-3}R_{t-3}+\beta_1 R_{t+1}+\beta_2 R_{t+2}+\beta_{v,-1}\Delta V_{t-1}+\beta_{v,-2}\Delta V_{t-2}+\beta_{v,-3}\Delta V_{t-3}+\beta_{rv}\Delta RV_t+\beta_0^{abs}|R_t|+\varepsilon_t$$

$$M2: \Delta V_t=\alpha+\beta_0 R_t+\beta_{-1}R_{t-1}+\beta_{-2}R_{t-2}+\beta_{-3}R_{t-3}+\beta_{v,-1}\Delta V_{t-1}+\beta_{v,-2}\Delta V_{t-2}+\beta_{v,-3}\Delta V_{t-3}+\beta_{rv}\Delta RV_t+\varepsilon_t$$

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4 The KRX recently starts to release the historical daily VKOSPI series before its official publication date.

5 In principle, the KRX does not sell the historical intraday VKOSPI data to individuals. However, we w ere able to buy the intraday data from the KRX to conduct this research.

6 We allow for a more general structure for the M1 model by incorporating the two lead returns (R_{t+1} and R_{t+2}) and the absolute value of contemporaneous stock return ($|R_{t+1}|$). We do not consider the ATM implied volatility because the VKOSPI is known to perform better than the Black-Scholes (BS) implied volatility derived from the ATM or OTM option prices and the BS-implied volatilities generally contain many biases.

M3: $\Delta V_t = \alpha + \beta_0 R_t + \beta_{-1} R_{t-1} + \beta_{-2} R_{t-2} + \beta_1 R_{t+1} + \beta_2 R_{t+2} + \beta_0^{abs} |R_t| + \varepsilon_t$

M4: $\Delta V_t = \alpha + \beta_0 R_t + \varepsilon_t$

M5: $\Delta V_t = \alpha + \beta_0 R_t + \beta_{22} R_t^2 + \varepsilon_t$

In the above regression equations, V_t denotes the level of the VKOSPI at time t; ΔV_t ($=V_t - V_{t-1}$) means the change in the VKOSPI from time t-1 to time t; R_t is the log-return of the KOSPI 200 index at time t; ε_t is an error term; and β is the regression coefficient to be estimated. RV_t denotes the realized volatility at time t. This daily realized volatility is calculated from the 5-minute intraday KOSPI 200 prices (P_i). Namely, RV_t is equal to $\sum_i [ln(P_i) - ln(P_{i-1})]^2$, where i covers all intraday 5-min interval per each trading day.

Model M1 is the most complicated model and contains all lead and lag return terms (R_{t-1}, R_{t-2}, R_{t-3}, R_{t+1}, R_{t+2}) capturing the intertemporal return-volatility relationship, absolute contemporaneous return ($|R_t|$) capturing the asymmetric effect of current return to volatility, lagged implied volatility index changes (ΔV_{t-1}, ΔV_{t-2}, ΔV_{t-3}), and the realized volatility changes (ΔRV_t). Models M2, M3, and M4 are reduced versions of the model M1. Model M4 is the simplest model of which the only explanatory variable is the contemporaneous return. M5 is also a simple model. In model M5, volatility is measured by squared returns. Based on the adjusted-R^2 values, we can measure the explanatory power of each model. By comparing the size and significance of the β coefficients in each regression model, we are able to determine which factor has more power in explaining the change of volatility.

Table 4 shows the estimation results for the five regression models using daily data. Though the differences of adjusted-R^2 values across the models are not large, the table indicates that the M1 model exhibits greater explanatory power than all the other simple models. On the other hand, another complicated model M2 (which contains both lagged implied volatilities and the realized volatility as explanatory variables) has a lower adjusted-R^2 value than the two simpler models, M3 and M5. This indicates that past implied volatility and current realized volatility do not play a critical role in explaining the current change of the implied volatility index for daily data.[7]

The significantly negative coefficient of the current return (R_t) for all models suggests that there is a

[7] The coefficient of the realized volatility is not significant in the model M2.

contemporaneous negative relationship between the returns and implied volatility changes. Further, the absolute value of its coefficient is much larger than the coefficients of lagged and lead returns (R_{t-1}, R_{t-2}, R_{t-3}, R_{t+1}, R_{t+2}). This indicates that the contemporaneous return is the most important determinant of the change of the VKOSPI. The coefficient of the contemporaneous absolute return, $|R_t|$ in both M1 and M3, is also both significant and positive. The different magnitudes and signs between the two coefficients of returns, R_t and $|R_t|$, indicate an asymmetric volatility response to positive and negative returns at the daily level.

In models M1 and M2, the insignificant coefficients of the lagged returns, R_{t-1} and R_{t-3}, and the positive coefficient of the lagged return, R_{t-2}, provide evidence against the leverage hypothesis. This follows because the positive (negative) shock on "lagged returns" should have a significantly negative (positive) effect on the change of the current volatility under the leverage hypothesis. On the other hand, the statistically significant large absolute values of coefficients of "current returns", R_t and $|R_t|$, indicate that they are likely more deterministic factors that affect the change of the current VKOSPI level than the lagged returns are. These results imply that an alternative explanation, such as a behavioral explanation, might be needed to explain the cause of the asymmetric return-volatility relationship.

3.2 Intraday Results

Table 5 presents the estimation results for the five regression models using the intraday KOSPI 200 index return and the intraday VKOSPI data.[8] As the frequency increases (i.e. from 30-minute to 1-minute), the fitness of each model measured by the adjusted-R^2 generally increases. Unlike the daily estimation results, the explanatory power of the relatively complicated models, M1 and M2, are far greater than those of the simpler models, M3, M4, and M5. Specifically, the adjusted-R^2 values of the M3, M4, and M5 models are all below 16%, while the values of the M1 and M2 models exceed 90% for all intraday intervals.

Although the coefficients of lagged returns are significant in M1 and M2, in absolute value terms, the coefficients of current returns are still far greater than those of lagged and lead returns, which supports potential behavioral explanations rather than the leverage hypothesis. The coefficients of lagged VKOSPI values are also highly significant. This intraday results show contrasts with the daily results and imply that using the information on the intraday serial correlation of the implied volatility index enhances model fitness. This is also consistent with the existence of extrapolation bias. In this case, traders with extrapolation bias would generally expect changes of volatility to maintain a trend in the short-term

[8] For the intraday analysis, the realized variance term is omitted.

(Frieder; 2008; Hibbert, et al., 2008).

The larger and negative coefficient of R_t and the smaller positive coefficient of $|R_t|$ are significant in all models and in all intraday intervals. This indicates that there exists a strong asymmetric and negative return-volatility relationship even at the high frequency intraday level. However, the leverage and volatility feedback hypotheses are not applicable to the intraday results because they are only adequate to explain the long term return-volatility relationship. It is not reasonable to assume that a firm's leverage changes significantly within the course of a single day. Meanwhile, the risk premium assumed in the volatility feedback hypothesis also tends to change within the long-term business cycle rather than within the intraday interval. Along with the dominant role of current stock market returns in explaining the change in volatility, the asymmetric return-volatility relationship more clearly observed with the intraday data strongly indicates the potential presence of behavioral biases.

Further, given that individuals dominate trading in KOSPI 200 options, the behavioral explanation suggested by Hibbert, et al. (2008) or the trading-based explanation by Avramov, et al. (2006) would seem to be more appropriate in explaining the observed asymmetric and negative return-volatility relationship. Avramov, et al. (2006) claim that trades by individual investors can generate the asymmetric volatility phenomenon and Hibbert, et al. (2008) insist that the investors' psychological biases are major factors causing the asymmetric and negative return-volatility relationship. As noted in the Section 2, it is known that there are many uninformed and speculative individual investors in the KOSPI 200 options market who trade frequently on noise, and collectively account for the huge trading volume of KOSPI 200 options. Therefore, we argue that the observed strong asymmetric and negative relationship between the KOSPI 200 return and the VKOSPI, is likely due to the collectively large trading volumes of individual investors who may be more easily affected by behavioral biases compared to their institutional counterparts (Kim and Ryu, 2012).

Lastly, if we compare the estimation results reported by *Panels A*, *B*, *C*, and *D* of Table 5, we find that, in the models M1 and M2, the lagged coefficients (R_{t-1} and R_{t-2}) of stock market returns are significantly positive for 30-minute (*Panel A*) and 15-minute (*Panel B*) intraday data, but become negative for 5-minute (*Panel C*) and 1-minute (*Panel D*) intraday data. This is quite a different result from those reported in Hibbert, et al. (2008) where all corresponding lagged coefficients are negative. The positive signs of R_{t-1} and R_{t-2} coefficients imply that the KOSPI200 options traders generally are "quicker to forget the bad news" than their U.S. counterparts. Negative return shocks happening 1-minute and 5-minutes ago increase investors' expected volatility, but these effects tend to disappear after 10-minutes, while in the U.S. markets they still affect volatility even after half an hour. This highlights the speculative nature of the KOSPI 200 options traders.

3.3 Positive and Negative Returns

In order to further investigate the asymmetric impact of returns on volatilities, we separate our analysis by using only positive or negative returns. Table 6 reports the daily estimation results separately for positive returns (*Panel A*) and negative returns (*Panel B*).[9] The adjusted-R^2 values indicate that model fitness is significantly higher in the presence of negative returns than positive returns. In all models, compared to the cases of positive returns, the adjusted-R^2 values is more than doubled for the negative returns. The absolute size of the R_t coefficient of each model is about twice the size and more significant in the negative return case than in the positive return case. The lead and lagged returns give a similar interpretation. The lagged VKOSPI changes (ΔV_{t-1}, ΔV_{t-2}, ΔV_{t-3}) also have larger significant explanatory powers in the presence of the negative returns. These evidences show a clear asymmetric volatility relationship. Further, the positive and/or insignificant coefficient estimates of the lagged returns (R_{t-1}, R_{t-2}, R_{t-3}) suggest evidence against the leverage effect hypothesis in each case.

If one compares the negative return case reported in *Panel B* of Table 6 with the results of the Hibbert, et al. (2008), it is immediately apparent that the adjusted-R^2 values are much higher than those in Hibbert, et al. (2008). Further, a comparison between models M1 and M3 reveals that the difference in the explanatory power is mainly due to the lagged implied volatilities. This indicates that the extrapolation bias of individual investors in the KOSPI 200 options market overwhelms other behavioral biases. This is partially supported by a larger proportion of domestic individuals in the KOSPI 200 options market, who are reportedly noise traders (Ahn, et al, 2008; Kim and Ryu, 2012).

To investigate the effect of the negative returns in more detail, we sort the returns based on the absolute size of positive and negative returns, respectively. Table 7 shows the estimation result of the M1 model, which has the best model fitness, for five return quintiles of positive returns (*Panel A*) and negative returns (*Panel B*). In each Panel, the first (fifth) quintile indicates the largest (smallest) return magnitude category. For example, in case of positive returns, the first return quintile has the most extremely positive values whereas the first return quintile has the extremely negative values in the case of negative returns. While we can't find a significant difference of model fitness across return quintiles in case of positive returns, the adjusted-R^2 value of the model is remarkably high at the first quintile of negative returns. In addition, the negative coefficients of R_t for the first quintile in *Panel B* not only has far greater absolute value but also is the only significant R_t coefficient. In general, the evidence in Table 7 shows that the

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[9] Thus, the $|R_t|$ term is naturally excluded for this analysis on positive and negative returns.

asymmetric and negative return-volatility relationship is considerably dependent on the *extreme returns*. One possible explanation for this observed dependency is the high participation and heavy speculative trading volume of individual investors in the KOSPI 200 options market, who are more sensitive to bad news and tend to overreact as a result.

4. CONCLUSION

We examine high frequency data on the KOSPI 200 index and the VKOSPI implied by the market prices of the KOSPI 200options in order to assess the return-volatility relationship. The strong and significant asymmetric and negative short-term relationship observed in our sample suggests that neither the leverage nor the volatility feedback hypotheses satisfactorily explain observed behavior in the Korean financial market. Moreover, the asymmetric and negative relationship is even more pronounced for extremely negative stock market returns. Given that KOSPI 200 options trading is dominated by individuals, one possible explanation for this result is behavioral. That is, if individual investors are more sensitive to bad news than institutional investors, then the greater speculative trading by individuals may result in the asymmetric volatility observed in the KOSPI 200 options market. This is consistent with the conjectures by Avramov et al. (2006) and Hibbert et al. (2008).

To the best of our knowledge, this is the first study that examines the intraday properties of the VKOSPI and should serve as the starting point for further research on the high frequency properties of this volatility index. The behavior of volatility indices, in general, and the VKOSPI, in particular, is a matter of great interest to practitioners and academics, alike. It is also important for derivative exchanges and policy makers as they prepare to launch volatility-related derivatives such as futures and options on various volatility indices..

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Table 1: Global top 10 index derivatives contracts at 2010

Rank	Contract	Index Multiplier	Trading Volume
1	KOSPI 200 options, KRX	KRW 100,000	3,525,898,562
2	E-mini S&P 500 index futures, CME	USD 50	555,328,670
3	SPDR S&P 500 ETF options, multiple exchanges	-	456,863,881
4	S&P CNX Nifty index options, NSE (India)	INR 100	529,773,463
5	Euro Stoxx 50 futures, Eurex	EUR 10	372,229,766
6	Euro Stoxx 50 index options, Eurex	EUR 10	284,707,318
7	RTS index futures, RTS	USD 2	224,696,733
8	S&P 500 index options, CBOE	USD 100	175,291,508
9	S&P CNX Nifty index futures, NSE (India)	INR 100	156,351,505
10	Nikkei 225 Mini futures, OSE	JPY 100	125,113,769

Table 2: Trading volume by investor type

Investor Group	# of contracts	Percentage (%)
Domestic individuals	17,912,571,221	40.3
Domestic institutions	17,052,873,390	38.4
Foreigners	9,497,528,152	21.4
Total	44,462,972,763	100.0

Table 3: Summary statistics for the daily data

	S_t	R_t*100	$\|R_t\|$*100	$VKOSPI_t$	$\Delta VKOSPI_t$
Mean	171.035	0.060	1.109	25.647	-0.008
Std	54.561	1.559	1.097	9.783	1.750
Max	282.030	11.540	11.540	89.300	23.000
Min	65.640	-10.903	0.000	14.150	-13.920
Skewness	-0.075	-0.410	2.602	2.418	2.426
Kurtosis	1.931	8.278	15.843	11.266	37.250

Table 4: Daily estimation results for the five regression models

	Const.	R_t	R_{t-1}	R_{t-2}	R_{t-3}	R_{t+1}	R_{t+2}	ΔV_{t-1}	ΔV_{t-2}	ΔV_{t-3}	ΔRV_t	$\|R_t\|$	R_t^2	$Adj\text{-}R^2$
M1	-0.366	-74.716	-2.071	14.464	0.531	11.424	4.994	-0.140	0.015	-0.108	-1.474	34.904		0.487
	(-6.79)	(-31.48)	(-0.67)	(4.67)	(0.17)	(4.91)	(2.14)	(-5.50)	(0.60)	(-4.23)	(-2.03)	(10.05)		
M2	0.037	-76.542	-4.029	10.558	-4.141			-0.119	0.004	-0.124	0.426			0.440
	(0.96)	(-30.94)	(-1.26)	(3.31)	(-1.30)			(-4.50)	(0.15)	(-4.68)	(0.58)			
M3	-0.334	-76.520	8.608	10.584		10.935	3.882					31.914		0.466
	(-6.25)	(-32.26)	(3.61)	(4.47)		(4.64)	(1.65)					(9.47)		
M4	0.040	-79.202												0.418
	(1.03)	(-32.20)												
M5	-0.093	-76.045											517.655	0.454
	(-2.31)	(-31.67)											(9.93)	

Table 5: Intraday estimation results for the five regression models

Panel A. 30-min data

	Const.	R_t	R_{t-1}	R_{t-2}	R_{t-3}	R_{t+1}	R_{t+2}	ΔV_{t-1}	ΔV_{t-2}	ΔV_{t-3}	$\|R_t\|$	R_t^2	*Adj-*R^2
M1	-0.104	-63.742	33.323	7.137	23.115	-0.295	4.393	0.734	0.085	0.166	11.851		0.927
	(-7.76)	(-19.28)	(9.80)	(2.20)	(9.10)	(-0.09)	(1.91)	(43.41)	(4.34)	(10.92)	(10.44)		
M2	-0.003	-59.288	33.678	6.780	21.760			0.745	0.082	0.162			0.925
	(-0.35)	(-25.66)	(9.74)	(2.06)	(8.46)			(43.40)	(4.14)	(10.50)			
M3	-0.545	-65.215	-21.653	-3.697		-0.675	29.862				28.478		0.148
	(-12.14)	(-5.76)	(-1.94)	(-0.44)		(-0.06)	(3.80)				(7.36)		
M4	-0.307	-58.612											0.123
	(-9.67)	(-21.58)											
M5	-0.383	-55.999										570.513	0.134
	(-11.39)	(-20.52)										(6.58)	

Panel B. 15-min data

	Const.	R_t	R_{t-1}	R_{t-2}	R_{t-3}	R_{t+1}	R_{t+2}	ΔV_{t-1}	ΔV_{t-2}	ΔV_{t-3}	$\|R_t\|$	R_t^2	*Adj-*R^2
M1	-0.061	-45.260	9.470	22.851	12.877	1.635	-2.008	0.808	0.131	0.045	6.422		0.947
	(-9.47)	(-21.30)	(4.28)	(10.57)	(7.81)	(0.77)	(-1.32)	(84.18)	(11.01)	(4.82)	(11.68)		
M2	-0.008	-46.603	10.514	23.362	11.887			0.818	0.130	0.038			0.947
	(-1.73)	(-30.05)	(4.73)	(10.73)	(7.17)			(84.93)	(10.87)	(4.11)			
M3	-0.518	-46.060	-22.768	-12.363		4.311	14.937				26.497		0.148
	(-20.46)	(-5.39)	(-2.61)	(-1.92)		(0.51)	(2.44)				(12.08)		
M4	-0.303	-60.696											0.132
	(-16.63)	(-38.79)											
M5	-0.354	-58.654										390.994	0.138
	(-18.61)	(-37.24)										(8.97)	

Panel C. 5-min data

	Const.	R_t	R_{t-1}	R_{t-2}	R_{t-3}	R_{t+1}	R_{t+2}	ΔV_{t-1}	ΔV_{t-2}	ΔV_{t-3}	$\|R_t\|$	R_t^2	*Adj-R²*
M1	-0.028	-20.939	-13.787	6.686	23.710	0.448	2.570	0.748	0.132	0.109	2.662		0.968
	(-10.67)	(-14.80)	(-9.83)	(4.85)	(23.46)	(0.31)	(2.48)	(145.24)	(20.83)	(21.77)	(11.82)		
M2	-0.006	-18.334	-13.710	6.790	23.829			0.752	0.132	0.107			0.968
	(-3.37)	(-18.08)	(-9.75)	(4.91)	(23.53)			(145.76)	(20.77)	(21.39)			
M3	-0.499	-17.725	-25.170	-33.202		-0.264	13.897				26.089		0.153
	(-38.11)	(-2.44)	(-3.51)	(-6.39)		(-0.04)	(2.62)				(22.75)		
M4	-0.291	-62.391											0.136
	(-30.56)	(-75.25)											
M5	-0.342	-60.225										400.591	0.144
	(-34.59)	(-72.21)										(18.11)	

Panel D. 1-min data

	Const.	R_t	R_{t-1}	R_{t-2}	R_{t-3}	R_{t+1}	R_{t+2}	ΔV_{t-1}	ΔV_{t-2}	ΔV_{t-3}	$\|R_t\|$	R_t^2	*Adj-R²*
M1	-0.006	32.308	-18.454	-14.709	14.721	-14.311	-0.248	0.878	0.048	0.069	0.497		0.989
	(-9.80)	(31.40)	(-17.95)	(-14.48)	(22.67)	(-13.97)	(-0.38)	(385.59)	(16.02)	(30.39)	(8.69)		
M2	-0.002	14.859	-15.665	-14.022	14.111			0.878	0.048	0.069			0.989
	(-5.26)	(22.70)	(-15.34)	(-13.79)	(21.73)			(385.31)	(15.90)	(30.39)			
M3	-0.482	22.277	12.913	-87.092		-19.664	10.165				25.352		0.150
	(-86.01)	(2.48)	(1.45)	(-15.30)		(-2.20)	(1.77)				(51.13)		
M4	-0.285	-62.602											0.136
	(-69.32)	(-173.29)											
M5	-0.334	-60.555										398.195	0.144
	(-78.57)	(-166.87)										(41.92)	

Table 6: Estimation results for positive (Panel A) and negative (Panel B) returns

Panel A. Positive contemporaneous returns

	Const.	R_t	R_{t-1}	R_{t-2}	R_{t-3}	R_{t+1}	R_{t+2}	ΔV_{t-1}	ΔV_{t-2}	ΔV_{t-3}	ΔRV_t	R_t^2	*Adj-R²*
M1	-0.109	-53.817	-0.468	2.729	2.165	1.685	-0.352	-0.062	-0.095	-0.095	-0.142		0.207
	(-1.60)	(-11.53)	(-0.13)	(0.74)	(0.59)	(0.52)	(-0.11)	(-1.99)	(-3.14)	(-2.98)	(-0.16)		
M2	-0.110	-53.652	-0.490	2.915	2.162			-0.062	-0.095	-0.095	-0.185		0.208
	(-1.62)	(-11.56)	(-0.14)	(0.79)	(0.60)			(-2.02)	(-3.15)	(-2.97)	(-0.21)		
M3	-0.092	-56.129	4.243	8.320		0.593	-1.751						0.183
	(-1.39)	(-12.37)	(1.55)	(2.95)		(0.18)	(-0.58)						
M4	-0.059	-58.638											0.176
	(-0.90)	(-13.14)											
M5	-0.033	-62.785										80.307	0.175
	(-0.42)	(-7.75)										(0.61)	

Panel B. Negative contemporaneous returns

	Const.	R_t	R_{t-1}	R_{t-2}	R_{t-3}	R_{t+1}	R_{t+2}	ΔV_{t-1}	ΔV_{t-2}	ΔV_{t-3}	ΔRV_t	R_t^2	*Adj-R²*
M1	-0.655	-123.842	2.024	32.899	-0.473	15.197	3.251	-0.192	0.195	-0.151	-2.504		0.548
	(-7.80)	(-23.68)	(0.38)	(6.43)	(-0.09)	(4.51)	(0.90)	(-4.53)	(4.32)	(-3.67)	(-2.17)		
M2	-0.674	-126.039	3.254	35.162	-1.507			-0.183	0.250	-0.164	-2.644		0.534
	(-7.93)	(-23.85)	(0.60)	(6.80)	(-0.28)			(-4.27)	(5.69)	(-4.00)	(-2.27)		
M3	-0.622	-119.943	14.028	16.202		18.757	8.756						0.504
	(-7.30)	(-24.45)	(3.34)	(4.03)		(5.47)	(2.42)						
M4	-0.566	-117.113											0.459
	(-6.45)	(-23.27)											
M5	-0.275	-73.769										752.514	0.479
	(-2.64)	(-7.42)										(5.03)	

Table 7: Estimation Results for positive and negative return quintiles

Panel A. Positive return quintiles

	Const.	R_t	R_{t-1}	R_{t-2}	R_{t-3}	R_{t+1}	R_{t+2}	ΔV_{t-1}	ΔV_{t-2}	ΔV_{t-3}	ΔRV_t	*Adj-*R^2
1st	-0.092	-53.508	-14.354	12.542	-7.871	18.400	7.893	-0.142	-0.094	-0.083	-0.947	0.124
	(-0.21)	(-3.34)	(-1.28)	(1.09)	(-0.66)	(1.63)	(0.78)	(-1.59)	(-1.29)	(-0.91)	(-0.37)	
2nd	0.688	-114.725	-2.649	14.116	15.339	-0.951	-7.364	-0.219	0.112	-0.001	1.073	0.178
	(1.02)	(-2.21)	(-0.31)	(1.60)	(1.70)	(-0.14)	(-1.29)	(-3.61)	(1.32)	(-0.01)	(0.56)	
3rd	-0.455	-20.736	-1.512	-1.940	10.670	2.221	6.912	-0.121	-0.052	-0.172	4.682	0.160
	(-0.78)	(-0.28)	(-0.19)	(-0.31)	(1.75)	(0.41)	(1.24)	(-1.43)	(-0.55)	(-3.42)	(2.59)	
4th	0.166	-98.640	22.905	6.810	-4.335	-7.478	2.298	0.229	0.041	-0.033	1.273	0.089
	(0.57)	(-1.59)	(3.75)	(1.07)	(-0.76)	(-1.53)	(0.48)	(3.26)	(0.57)	(-0.51)	(0.77)	
5th	-0.078	-86.820	1.039	10.186	9.501	-8.752	1.812	0.017	-0.059	-0.034	-1.409	0.108
	(-0.76)	(-1.39)	(0.24)	(1.63)	(1.86)	(-2.05)	(0.37)	(0.28)	(-0.96)	(-0.56)	(-1.02)	

Panel B. Negative return quintiles

	Const.	R_t	R_{t-1}	R_{t-2}	R_{t-3}	R_{t+1}	R_{t+2}	ΔV_{t-1}	ΔV_{t-2}	ΔV_{t-3}	ΔRV_t	*Adj-*R^2
1st	-2.624	-188.823	-15.358	67.627	21.743	21.166	-3.855	-0.286	0.434	0.088	-5.828	0.519
	(-4.39)	(-10.13)	(-0.77)	(4.22)	(1.11)	(2.03)	(-0.34)	(-2.33)	(3.22)	(0.71)	(-1.69)	
2nd	0.344	-34.413	7.110	-0.835	-2.488	-0.026	7.437	0.056	-0.002	-0.136	0.990	0.011
	(0.71)	(-1.07)	(0.84)	(-0.11)	(-0.35)	(-0.01)	(1.51)	(0.67)	(-0.03)	(-1.78)	(0.54)	
3rd	0.099	-26.255	0.424	35.317	4.125	5.602	-0.321	-0.184	0.311	-0.310	1.202	0.476
	(0.21)	(-0.47)	(0.06)	(4.60)	(0.49)	(0.98)	(-0.05)	(-2.35)	(3.62)	(-4.78)	(0.67)	
4th	0.102	-0.598	-22.663	22.080	-2.657	3.915	-8.601	-0.570	0.097	-0.130	2.959	0.424
	(0.31)	(-0.01)	(-2.93)	(2.64)	(-0.34)	(0.71)	(-1.67)	(-8.03)	(0.96)	(-1.53)	(1.78)	
5th	-0.121	-89.714	7.700	22.418	0.376	9.294	-3.856	-0.018	0.125	0.076	1.803	0.125
	(-0.92)	(-1.08)	(1.36)	(3.52)	(0.06)	(2.07)	(-0.83)	(-0.26)	(1.92)	(0.97)	(1.13)	