International Review of Economics and Finance 85 (2023) 647–663

Contents lists available at ScienceDirect

International Review of Economics and Finance

journal homepage: www.elsevier.com/locate/iref

Is there an expiration effect in the bitcoin market?

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ARTICLE INFO

Keywords:
Expiration effect
Bitcoin
Futures
Exchanges

ABSTRACT

This paper studies the monthly expiration effect in the bitcoin markets. The emergence of trading in bitcoin futures in regulated markets is an ideal occasion to test this effect on an asset with singular characteristics. Our results with intraday data show that around the time of maturity there are significant changes in the trading volume, volatility and return of bitcoin, an asset that is traded in many exchanges simultaneously. Therefore, there is a clear expiration effect related to bitcoin futures. The closer to the expiration time (shortly beforehand or afterwards), the more intense these effects are. However, in spite of these general results, the expiration effect is not homogeneous across exchanges and depends on the characteristics of the futures contract in question. Robustness tests are also applied to confirm the results. The increasing participation of institutional investors is consistent with our findings, particularly in relation to the expiration effects of cash-settled futures, as these contracts are more appealing for sophisticated investors who could be interested in arbitrage or speculative processes.

1. Introduction

Since the 1980s, after the definitive setting up of the derivatives market and the emergence of the first studies detecting the expiration effect, there has been extensive financial literature analysing this alleged anomaly. The expiration effect is defined as the spot market anomalies detected shortly before or after the maturity date of the related derivatives. The explanations traditionally proposed for such effect are based on the different types of investors' behaviour, the characteristics of the settlement systems or the variety of underlying assets and derivative contracts, among others.

The irruption of crypto-currencies in the economy and the development of regulated bitcoin futures markets offer a challenging opportunity to further advance the understanding of this phenomenon. In December 2017, CME and CBOE started to trade futures on bitcoin with the particularity that the underlying asset was not traded in a formally regulated market, as it is usually understood. This situation provides an incentive to test our objective, which is to analyze whether bitcoin trading volume, volatility and return behave differently on the expiration date of bitcoin futures as compared to non-expiration times.

This study contributes to the empirical literature in several ways. It is the first paper, as far as we know, that analyses this anomaly in the bitcoin market. Bitcoin has singular features that make its study particularly attractive. It does not rely on central banks or any

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https://doi.org/10.1016/j.iref.2023.02.013
Received 25 April 2021; Received in revised form 17 April 2022; Accepted 19 February 2023
Available online 20 February 2023

other institution regulating money supply or serving as an intermediary, it enables almost anonymous transactions, which are irreversible, and it can even be divided into small parts and can be purchased easily on appropriate 24/7 exchanges that allow traditional currencies to be exchanged for bitcoins and vice versa. Moreover, spot bitcoin is traded in many non-formally regulated exchanges simultaneously, without a clear theoretical model conceptualizing how to determine its value. These characteristics distinguish bitcoin from other assets previously studied in the literature of the expiration effect, and therefore its study may offer valuable additions to existing knowledge. Secondly, given the fragmentation of the bitcoin spot market, we study the expiration effect on seven significant but very different individual markets. This analysis allows us to observe possible differences among spot markets according to their different running procedures and characteristics. Thirdly, we study the expiration of bitcoin futures traded on three representative and popular regulated markets offering different contract specifications, settlement systems and expiration dates, which can help to understand the reasons behind the maturity effect. Fourthly, we use intraday data. Since in both spot bitcoin exchanges and regulated bitcoin futures markets several features converge that can drive the effect in opposite directions, the use of daily data can mask the results. Intraday data allow a more in-depth analysis round about the precise time of expiration. Fifthly, depending on the results obtained, we could try to infer the behaviour of the different groups of investors who negotiate in these markets. Finally, the work gives some pointers for market supervisors and regulators. If anomalies do not reflect new information in the market, regulators should seek ways to mitigate them so that markets will work more efficiently. Identifying whether such an anomaly occurs is the first step in that process.

The remainder of the paper is structured as follows. The second section provides the literature review, the third section describes the database, the fourth section shows the methodology and the results, and the fifth and final section sets out the discussion and the main conclusions of the paper.

2. The expiration effect: literature review

2.1. Previous empirical literature

The expiration effect is an anomaly observed in prices, trading volume and volatility around the expiration date of a derivatives contract. The first study to analyze the expiration effect dates back to 1974 when the Nathan Report examined it and did not find any abnormal behavior. As pioneering works, we mention Klemkosky (1978), Cinar and Vu (1987) or Vu and Cinar (1988) that find negative returns in the dates previous to the expiration, reverting to positive returns after that date. Stoll and Whaley (1987 and 1991) also analyze the behavior of trading volume and volatility and observe increases on the maturity date. Pope and Yadav (1992) find increases in trading volume but not in volatility. There are also some papers that analyze the joint expiration of several derivative assets, which is known as the “witching hour”. Chamberlain et al. (1989) or Chen and Williams (1994) analyze this phenomenon without finding conclusive results. Alkebäck and Hagelin (2004) summarize the main initial works describing the market under study, the corresponding underlying asset and the results obtained.

Following this pioneering research, the literature on the expiration effect is extensive, analyzing the American markets as well as other markets worldwide. The analyses focus on the behavior of the three usual variables (trading volume, volatility and price), but the results are not unanimous due to the differences among assets, markets and periods analysed as well as the techniques applied. Some examples are the papers by Bollen and Whaley (1999), Chow et al. (2003), Chung and Hseu (2008), Corredor et al. (2001), Karolyi (1996), Lien and Yang (2003 and 2005) and Vipul (2005), among others. More recently, Xu (2014) studied this effect around the quadruple witching Friday, and Batrinca et al. (2020) extended the analysis of the effect to the Pan-European equity markets.

The reasons for the expiration effect can be primarily found in the fact that, in the derivatives markets, speculators, hedgers and arbitrageurs trade together. Their actions can affect the information flow due to arbitrage, speculative and manipulative processes between the spot and the derivatives markets. These strategies might play a relevant role on the maturity date. However, the existence of transaction costs gives some market participants an advantage over others. Investors may act differently, even neutralizing each other’s actions. This means that, a priori, the aggregate observable effect is not obvious.

Stoll and Whaley (1987) suggest that arbitrageurs in the stock market, who can incur the lowest transaction costs, may unwind their spot positions in the same direction when the expiration date arrives. If this unwinding is not anticipated, temporary mismatches between buy and sell orders can occur, putting pressure on the price of the underlying asset and leading to unusually large price swings which will potentially reverse on the following day. Fung and Yung (2009) indicate that the settlement procedure affects the unwinding of spot-futures arbitrage positions. For example, if the settlement value is obtained with an average price calculated at 5-min intervals, arbitrageurs will focus on buying or selling the spot around the 5-min time marks.

Speculators may also find the expiration time to be the ideal moment to develop strategies to act on prices, assuming the existence of agents who may occasionally alter prices (Klemkosky, 1978). These investors have uncovered positions and try to influence the price by buying or selling the underlying asset in the spot market around the key times to settle the derivatives contract at a price favorable to their position (Fung & Yung, 2009).

On the expiration date, there is also the possibility of establishing profitable manipulation strategies (Kumar & Seppi, 1992). For example, “capping” strategies and the opposite practice, “pegging”, manipulate prices by selling (buying) large amounts of a commodity or security close to the expiration date of its options to prevent a rise (decline) in the underlying’s price (Pope & Yadav, 1992). Other practices such as option pinning, which is the tendency of stock prices to run close to the strike price of heavily traded options on the days of expiration, or investors’ preference for stock price clustering in round numbers, may also force stock prices to deviate from their fair value (Ni et al., 2005). Although these practices are found in the option markets, they can also affect related markets such as the futures markets (Golez & Jackwerth, 2012) when market makers rebalance their delta hedging near maturity.

These practices can be reflected in the trading volume. If arbitrageurs, speculators and manipulators use the expiration date to trade more intensively, an abnormal volume will be observed. Since trading volume is closely related to volatility, significant movements in volume can consistently result in noticeable volatility changes. Both variables convey the information flow available in the markets. Their variations will depend on investors' behaviour that, in turn, will also generate new information flows.

Lien and Tse (2006) show in an exhaustive review that the manner of delivery, physical or cash, can cause the expiration effect, and Xu (2014) summarizes different settlement procedures in worldwide markets that could affect the identification of the anomaly. Chay et al. (2013) describe different procedures established worldwide to determine the settlement price of index derivatives in order to try to minimize the maturity effect. They find that the expected settlement price calculated continuously during a final 10-min call auction and immediately disclosed mitigates the effect. However, there is no clear evidence that a call auction procedure during a period is systematically effective in decreasing the maturity effect (Chay & Ryu, 2006). Other changes in the settlement systems did not have more successful results. Switching from taking the closing price to taking the opening price moves the effect to the next day, but does not remove it (Stoll & Whaley, 1991). Other authors such as Chow et al. (2003) suggest that using the average price over a specific period rather than the price at a specific time mitigates the effect. If the pricing period is longer, arbitrageurs are expected to extend their operations for a longer time to ensure their arbitrage profits. Despite the inconclusive results, authors such as Agarwalla and Pandey (2013) emphasize the importance of the settlement procedure in the expiration effect in more traditional financial markets.

2.2. *Bitcoin futures*

In traditional markets, the introduction of derivatives complements the spot market and creates new opportunities for risk transfer. Traders can negotiate in the spot and/or in the derivative markets and the information will be visible in the market chosen for trading in the first instance and can subsequently affect transactions made in the other market. The introduction of regulated bitcoin futures has increased bitcoin's popularity and allows increasing the range of assets to trade and cover the risk, bringing in new participants in a market hitherto dominated by retail investors. The existence of these derivatives is expected to gain the attention of institutional investors, which will increase market liquidity. Traders can take advantage of the bitcoin movements without the need of trading on the spot. Furthermore, regulated bitcoin futures enable traders to trade in jurisdictions that have prohibited crypto-assets.

Should we expect an expiration effect in the bitcoin market? As outlined above, bitcoin markets have some characteristics that can affect market variables in opposite directions and with different intensity. The final effect will depend on the aggregated result. Therefore, the identification of the expiration effect is an empirical question. In fact, if an expiration effect is detected, the results can help to identify those bitcoin market characteristics playing a major role in it.

On the one hand, it is worth noting that bitcoin futures markets, being of recent creation, still have relatively very small trading volumes despite the attractiveness for institutional investors. Perhaps lower than usual liquidity levels, wide spreads or fear of trading halts mechanisms in response to high volatility are the causes of their still limited participation. If the futures trading volume is low, we should not expect any effect on spot bitcoin prices at futures maturity.

On the other hand, bitcoin spot markets are relatively small too, illiquid and not very deep (compared to traditional markets). In this scenario, any strategy carried out by arbitrageurs and speculators may have a greater impact on prices. The small size can also make the spot market more susceptible to manipulation. Furthermore, the bitcoin spot market is a fragmented market. This means that strategies can be carried out in several exchanges. If there were lead-lag effects or temporal price discrepancies between exchanges, arbitrage operations would be easier to implement for those traders who incur low transaction costs. In addition, speculators and price manipulators can operate by buying or selling in those exchanges that are more attractive from the point of view of achieving their objectives. Accordingly, a significant expiration effect is to be expected if arbitrageurs, speculators or price manipulators decide to intervene.

The settlement system also requires consideration for its possible involvement in the expiration effect. Futures markets such as CME and CBOE follow a cash settlement system that, a priori, would affect the spot prices to a minor degree since the delivery of the underlying asset is not necessary. Although sharing this common pattern, the reference rate for settlement in CME is based on bitcoin prices traded in several exchanges whereas CBOE takes an auction-based settlement price from only one exchange. However, according to the previous literature, cash settlement would lead to a small effect when the maturity date is due. In turn, other markets such as the Bakkt platform supervised by Intercontinental Exchange (ICE) follow a settlement system by physical delivery and do not require pricing data from the spot market. If differences in the settlement system were to lead to a significant effect on the spot market at maturity, it would be observed differently in those spot exchanges involved in each settlement system.

It should also be taken into account that some significant exchanges such as Binance, Bitfinex and Kraken also trade bitcoin futures, although not regulated by traditional institutions, as is the case of CME, CBOE or ICE. These futures contracts may have different specifications but some expiration dates may coincide with those offered by, for example, CME. In these cases, if any expiration effect were detected, it would not be possible to determine the magnitude of the expiration effect attributable to each contract. Nevertheless, this coincidence is unimportant given that the largest share by far of derivatives futures traded in unregulated markets are perpetual futures (De Blasis & Webb, 2022) which do not have a specific maturity date and, therefore, cannot originate an expiration effect.

Finally, it is worth remembering that institutional investors' trading can play a decisive role in the period around expiration dates, since they are more sophisticated investors that can take advantage of some of the difficulties individual investors face to find profit opportunities. As institutional investors' participation increases, the possibility of finding an expiration effect increases too.

3. Database

This paper focuses on the monthly expiration effect on seven popular bitcoin exchanges that represent a significant trading volume but also exhibit some differences in characteristics that can be helpful for finding robust results. Five of these are constituent exchanges providing pricing data to calculate reference rates and spot price indexes of the underlying asset in some futures contracts: Bitstamp, Coinbase, Itbit, Kraken and Gemini. We also include two other bitcoin reference markets in the analysis: Binance and Bitfinex. Binance is usually considered the biggest cryptocurrency market by volume, but all seven are in the top 10% of bitcoin exchanges. All are centralized exchanges, private companies offering trading platforms that require their clients' registration and identification, providing higher volume and liquidity than decentralized exchanges (direct peer-to-peer transactions, without intermediation) and attracting professional and institutional investors.

We use daily and intraday data provided by CryptoDataDownload. Intraday data constitute the base of our analysis whereas daily data are used for descriptive purposes and in robustness tests. Intraday data are hourly records and contain open, close, high and low prices of the period and trading volume in BTC. The total period covers the beginning of the futures contracts in December 2017 (we take December 31, 2017 as the initial date) until November 20, 2020. The total number of observations is 25,305 for each variable and exchange.

For bitcoin futures, we have considered three regulated alternative markets for monthly expiration dates. Regulated futures present some advantages over unregulated futures for our analysis. On the one hand, having robust traditional security measures (e.g. rulebooks that clearly define how they handle possible defaults without mutualizing losses), the regulated markets attract institutional investors, who are supposed to make educated and informed decisions and contribute to market efficiency. On the other hand, some transparency issues related to faked volume reported by unregulated markets (Cong et al., 2021) lead us to opt for regulated markets to obtain the most accurate possible results.

Although CBOE was the first market to trade futures on bitcoin on 10th December, the contracts offered by the CME on 17th December, one week later, triggered the trading in futures. CME futures trading is currently active, but CBOE released its last bitcoin futures contract in March 2019 to expire on 19th June 2019.

Both contracts are expressed in US dollars and their delivery is made by cash settlement. However, both the size of the contract and the reference for the settlement price differ from each other. The multiplier of the futures contract traded in CBOE was 1 bitcoin and the final settlement value of an expiring futures contract was the official auction price for bitcoin in U.S. dollars determined at 4:00 p.m. Eastern Time (NY Time) on the final settlement date by the Gemini Exchange Auction. The final settlement day takes place two business days (usually a Wednesday) prior to the third Friday of the expiration month.

The multiplier of the bitcoin futures contract traded in CME is 5 bitcoins and the final settlement price is equal to the CME Bitcoin Reference Rate (BRR) at 4:00 p.m. London time on the last Friday of the contract month. BRR is the index composed of the bitcoin quotes from several constituent exchanges. These exchanges are Bitstamp, Coinbase, ItBit and Kraken (since December 2017) and Gemini (since 30 August 2019).

On September 23rd, 2019, the ICE introduced a new regulated future on bitcoin. This contract is negotiated in Bakkt and differs from the two previous contracts in that it is physically settled. The contract size is 1 bitcoin quoted in US dollars and the expiration date is the third Friday of the month. Trading in the expiring contract month ceases at 2:30 p.m. NY time on the business day prior to the delivery day for the contract month.

We have considered Unix time as the reference to unify the time information of all the markets under analysis, as it is widely used in operating systems and file formats because technically it does not change whatever the location on the globe. Daylight saving times have also been taken into account.

Table 1 shows some descriptive statistics of the bitcoin exchanges. Mean daily returns and volatility measures are very similar in all the exchanges. However, the daily trading volume of BTC does not have a similar pattern across the exchanges. Binance stands out as the exchange with the highest volume and Itibit, with a volume 20 times smaller, has the lowest volume, closely followed by Gemini.

During the coexistence period of CBOE futures with CME futures, the CME monthly volume varied from being less than 20% of the monthly volume traded in CBOE to being more than five times greater. During the coexistence period of CME with Bakkt, the CME monthly volume, on average, was 14 times greater than the monthly volume traded in Bakkt,[1] although the physical delivery of Bakkt has become more and more significant and open interest has increased noticeably in this market.

4. Methodology and results

We have run time series regressions to explore the expiration effect. All the models include as independent variables the appropriate number of lags of the dependent variable to control autocorrelation and the dummy variables for the days of the week from Monday to Saturday to avoid the presence of possible seasonality effects from interfering with the expiration date. We denominated D_M, D_{Tu}, D_W, D_{Th}, D_{Fr} and D_{Sat} these dummy variables related to the days of the week.[2] The models also incorporate a dummy variable designed to detect the effect during the period around expiration. D_{Exp} is the generic expression for this variable that captures the

[1] According to the information provided by https://www.theblockcrypto.com/data/crypto-markets/futures and https://es.investing.com/crypto/bitcoin/bitcoin-futures-historical-data on 13th January 2021.

[2] Although some hourly patterns may have been observed in traditional markets with fixed trading hours, bitcoin exchanges operate 24/7 in various time-zones, therefore hourly effects are unlikely.

Table 1
Descriptive daily statistics.

	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken
A. Trading volume BTC							
Mean	45,110	17,716	9065	12,887	3001	2004	6148
Std.Dev.	31,068	19,928	7006	10,487	3032	2582	4634
Max	402,202	189,674	70,961	117,495	29,967	36,419	45,111
Min	–	–	–	–	–	–	–
B. Volatility							
Mean	0.03366	0.03354	0.03416	0.03361	0.03348	0.03473	0.03492
Std.Dev.	0.02670	0.02517	0.02593	0.02654	0.02622	0.05191	0.02823
Max	0.30709	0.26914	0.29845	0.29759	0.28826	1.25368	0.28754
Min	–	–	–	–	–	–	–
C. Returns							
Mean	0.00026	0.00026	0.00025	0.00026	0.00024	0.00028	0.00025
Std.Dev.	0.04081	0.04088	0.04145	0.04128	0.04143	0.04088	0.04122
Max	0.15868	0.15941	0.16935	0.16966	0.17005	0.16887	0.16966
Min	−0.50261	−0.49190	−0.49397	−0.49123	−0.49641	−0.45199	−0.49335

Note: This table shows the main descriptive statistics of daily data: trading volume, Garman-Klass volatility measure and returns for spot markets. Columns show the results for the different exchanges, Binance, Bitfinex, Bitstamp, Coinbase, Gemini, Itbit and Kraken, respectively.

cumulative hourly effect of expiration for a specific futures contract.

We create expiration dummy variables (D_{Exp}) in the following way. The first one, D_1, takes a value of 1 at the hour of the expiration and 0 otherwise. Subsequently D_2 takes a value of 1 both at the hour of expiration and 1 h beforehand and 0 otherwise, D_3 takes the value 1 at the hour of expiration and 2 h beforehand and 0 otherwise and so on until D_{24} identifies the hour of expiration and 23 h beforehand. Some of the dummy variables may even correspond to the day before expiration depending on the time-zones. Similarly, we create 24 dummy variables that identify the sequential cumulative effect of the 24 h after the expiration time and take the value 0 otherwise (from D_{1post}, 1 h after expiration, to D_{24post}, up to 24 h after expiration). These 48 measures to detect the cumulative hourly effect around expiration are based on those used in previous daily studies such as Corredor et al. (2001).

We have considered the expiration dates of CME, CBOE and Bakkt separately as well as the joint effect of all of them (taking into account all the expiration dates in all the contracts involved), with the purpose of finding possible differences among them, if any, and the dominant global effect.

Thus, we have finally run 576 models, using 48 alternative cumulative hourly dummies, on 3 variables of analysis (volume, volatility and return), for 4 different references of expiration dates depending on the futures market studied (CME, CBOE and Bakkt separately and the joint effect).

4.1. *Effects on trading volume*

The model proposed to estimate the effect on the trading volume is the following:

$$TV_{i,t} = \beta_0 + \beta_1 D_M + \beta_2 D_{Tu} + \beta_3 D_W + \beta_4 D_{Th} + \beta_5 D_{Fr} + \beta_6 D_{Sat} + \beta_7 D_{Exp} + \beta_8 Trend + \sum_{j=1}^{5} \beta_{j+8} TV_{i,t-j} + \varepsilon_{i,t} \tag{1}$$

where the TV_{it} dependent variable indicates the trading volume in bitcoins in exchange i and hour t. As is usual in the financial literature, trading volume is measured by taking the natural logarithm of the volume. The use of logarithms stabilizes the variance of the volume, since it is non-negative and tends to be more volatile when volume is high and less volatile when volume is low. The model includes the seasonal and expiration dummy variables as previously defined and five lags of the dependent variable. In addition, this model adds a time trend variable (Trend) that captures the increase in trading volume over time. We have run OLS regressions using Newey-West heteroscedasticity-consistent standard errors and covariance. In all the estimates, the coefficients associated with the lags of the dependent variable and the deterministic trend are significant. Those associated with daily seasonality, with a few exceptions in some exchanges, are also significant. Saturdays stand out as the day with the lowest volume traded.

A summary of the results obtained is shown in Table 2.[3] In the 15 h prior to expiration of the CME bitcoin futures contract, a significant increase in the trading volume is observed in all the exchanges. This effect starts even sooner in several of them. The strongest increases take place in the hours closest to maturity. A significant reverse effect is observed after the expiration time in 5 out of the 7 markets, with significant negative volume changes, and this effect extends to all the exchanges after 14 h. The reverse effect in Gemini and Coinbase, two significant markets for American traders, takes more time to be detected.

The pattern of an increase in trading volume in the hours prior to expiration is also observed when analysing the expiration of the CBOE bitcoin future, although the effect is less intense than in the case of the CME expiration. The general increase in all exchanges

[3] For brevity, each table only shows the results from D_1 to D_{10} and D_{1post} to D_{10post} individually whereas further results are considered to be represented by D_{15}, D_{20} and D_{24} as well as D_{15post}, D_{20post} and D_{24post}, given that each of these variables contains an accumulated effect.

Table 2
Expiration effect on hourly trading volume.

	Expiration of CME bitcoin futures							Expiration of CBOE bitcoin futures						
	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken
D_{24}	0.0155	0.0290	0.0352	0.0379*	0.0241	0.0688*	0.0544**	−0.0133	0.0182	0.0179	0.0258	0.0784*	0.0618	0.0261
D_{20}	0.0364*	0.0609**	0.0619**	0.0411*	0.0116	0.0768*	0.0617**	−0.0140	0.0515	0.0620*	0.0508	0.1301***	0.1000*	0.0562
D_{15}	0.0530**	0.0711**	0.1198***	0.0540**	0.1046***	0.1638***	0.0886***	0.0915**	0.1653***	0.1106***	0.1088***	0.2086***	0.1923***	0.1464***
D_{10}	0.0999***	0.2101***	0.26141**	0.1692***	0.1673**	0.2814***	0.2146***	0.1016*	0.1512**	0.0700	0.2123***	0.3348***	0.2473***	0.1849***
D_9	0.091**	0.1924***	0.2413***	0.1616***	0.1753***	0.3245***	0.2001***	0.1053	0.1145	0.0574	0.2140***	0.3351***	0.2269***	0.1781***
D_8	0.0743*	0.1542***	0.2011***	0.1681***	0.1643***	0.3590***	0.1859***	0.1117	0.1116	0.0527	0.2061***	0.3552***	0.2123**	0.1735***
D_7	0.0915***	0.1515***	0.1904***	0.2026***	0.2069***	0.3254***	0.1963***	0.0639	0.1151	0.0478	0.1996***	0.3627***	0.1884*	0.1563**
D_6	0.1086***	0.1572***	0.1830***	0.2518***	0.2814***	0.3986***	0.2208***	0.0449	0.0991	0.0359	0.1730***	0.3582***	0.1581	0.1449**
D_5	0.1268***	0.1333**	0.1849***	0.2756***	0.3073***	0.4430***	0.2210***	0.0122	0.0995	0.0291	0.1393***	0.3198***	0.1562	0.1086*
D_4	0.1261**	0.1204**	0.1588***	0.2579***	0.3278***	0.4462***	0.2185***	0.0024	0.1072	0.0295	0.1251**	0.3110***	0.1348	0.0929
D_3	0.1269***	0.0802	0.1826***	0.2925***	0.3869***	0.4200***	0.2555***	0.0344	0.1851*	0.0893	0.1502**	0.4122***	0.1432	0.1185
D_2	0.2035***	0.1715*	0.2755***	0.3566***	0.4452***	0.5397***	0.2984***	0.0270	0.2129**	0.0375	0.1618**	0.5957***	0.2087*	0.0948
D_1	**0.1838****	**0.1435**	**0.0710**	**0.2491*****	**0.3001****	**0.3413****	**0.3161*****	**0.0172**	**0.2575***	**0.0134**	**0.0700**	**1.1069*****	**0.3484***	**0.0813**
D_{1post}	−0.1312*	−0.1661	−0.2632**	−0.0643	−0.0250	−0.1202	−0.0761	−0.2584**	−0.3995**	−0.4884***	−0.3157**	−0.8796***	−0.9730***	−0.4098***
D_{2post}	−0.2142***	−0.1737*	−0.2156***	−0.0754	0.0219	−0.1283	−0.1470**	−0.0929	−0.1584*	−0.2025**	−0.1043	−0.4324***	−0.4197***	−0.1364
D_{3post}	−0.2197***	−0.2110***	−0.2267***	−0.0631	0.0419	−0.2134**	−0.1091**	−0.1092*	−0.1284	−0.2187***	−0.1011	−0.3304***	−0.2920***	−0.1527*
D_{4post}	−0.1714***	−0.1812***	−0.1605***	−0.0272	0.0673	−0.1881*	−0.0804**	−0.0862*	−0.1561**	−0.1875***	−0.0962*	−0.2768***	−0.1862**	−0.1525**
D_{5post}	−0.1426***	−0.1442***	−0.1752***	−0.0113	0.1343***	−0.2481***	−0.0562	−0.0519	−0.1165*	−0.1374**	−0.0568	−0.2692***	−0.1067	−0.1351**
D_{6post}	−0.1603***	−0.1192***	−0.2303***	−0.0381	0.0409	−0.4490***	−0.0733**	−0.0347	−0.1365**	−0.1145**	−0.0390	−0.1968**	−0.0994	−0.1477**
D_{7post}	−0.1325***	−0.1290**	−0.2111***	−0.0387	0.0056	−0.4050***	−0.0717*	−0.0237	−0.0964	−0.1119***	−0.0494	−0.1624**	−0.0854	−0.1294**
D_{8post}	−0.1153***	−0.1105**	−0.2163***	−0.0544*	−0.0499	−0.3379***	−0.0772**	−0.0254	−0.1071*	−0.1004**	−0.0676	−0.1297*	−0.0643	−0.1567***
D_{9post}	−0.0909***	−0.0945**	−0.1816***	−0.0505	−0.0763	−0.2553***	−0.0518	−0.0399	−0.1084*	−0.1035**	−0.0910**	−0.1511**	−0.1008	−0.1802***
D_{10post}	−0.0867***	−0.0928**	−0.1603***	−0.0399	−0.0804	−0.2405***	−0.0659*	−0.0489*	−0.1344**	−0.1099***	−0.1337***	−0.1903***	−0.1297**	−0.1706***
D_{15post}	−0.0703***	−0.0786**	−0.1250***	−0.0914***	−0.1087**	−0.2007***	−0.0988***	−0.0028	−0.0524	−0.0331	−0.0900***	−0.0970	−0.0504	−0.0973**
D_{20post}	−0.0443**	−0.0138	−0.0548	−0.0858***	−0.1046***	−0.1680***	−0.0374	0.0165	0.0044	0.0064	−0.0454	−0.0095	0.0195	−0.0058
D_{24post}	−0.0117	0.0214	−0.0287	−0.0233	−0.0221	−0.0995*	−0.0091	0.0016	−0.0042	−0.0081	−0.0053	0.0386	0.0366	−0.0036

	Expiration of Bakkt bitcoin futures							Expiration of all bitcoin futures						
	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken
D_{24}	−0.0071	−0.0383	−0.0339	−0.0118	0.0173	−0.0644	−0.0113	0.0076	0.0173	0.0203	0.0266*	0.0384	0.0424	0.0349*
D_{20}	−0.0028	−0.0638	−0.0485	−0.0286	0.0160	−0.0479	−0.0192	0.0195	0.0386	0.0445**	0.0325**	0.0468*	0.0649**	0.0464**
D_{15}	0.0334	0.0376	0.0669	0.0093	0.0959	−0.0172	0.0657	0.0630***	0.0949***	0.1101***	0.0624***	0.1323***	0.1425***	0.1022***

(*continued on next page*)

Table 2 (*continued*)

	Expiration of Bakkt bitcoin futures							Expiration of all bitcoin futures						
	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken
D_{10}	−0.0111	−0.0280	−0.0438	0.0635	0.1934***	0.1702	0.0822*	0.0786***	0.1475***	0.1463***	0.1599***	0.2195***	0.2498***	0.1795***
D_9	−0.0366	−0.0750	−0.0694	0.0589	0.1772***	0.2174**	0.0634	0.0703***	0.1186***	0.1266***	0.1556***	0.2201***	0.2739***	0.1661***
D_8	−0.0593	−0.1088	−0.0915	0.0672	0.2137***	0.2163*	0.0640	0.0589*	0.0914***	0.0998***	0.1583***	0.2275***	0.2856***	0.1572***
D_7	−0.0426	−0.1053	−0.0748	0.0714	0.2864***	0.3434**	0.0964*	0.0582**	0.0915**	0.0960***	0.1748***	0.2659***	0.2843***	0.1645***
D_6	−0.1035**	−0.1738**	−0.1182*	0.0321	0.2847***	0.2838*	0.0240	0.0491*	0.0756*	0.0803**	0.1843***	0.3021***	0.2996***	0.1587***
D_5	−0.1086**	−0.2136**	−0.1503**	0.0058	0.2546***	0.2187	0.0041	0.0485*	0.0554	0.0728**	0.1817***	0.2984***	0.3088***	0.1445***
D_4	−0.1071*	−0.2607**	−0.1142	0.0079	0.2436***	0.2051	0.0177	0.0465	0.0411	0.0671*	0.1694***	0.3051***	0.3008***	0.1418***
D_3	−0.1481**	−0.2514**	−0.1889**	−0.0678	0.1737*	0.1607	−0.0384	0.0472	0.0439	0.0807*	0.1780***	0.3488***	0.2801***	0.1555***
D_2	−0.2678***	−0.4063***	−0.3637***	−0.1867***	0.0715	0.0513	−0.2139**	0.0109	0.0448	0.0499**	0.0380**	0.0537*	0.0827**	0.0518**
D_1	**−0.2493*****	**−0.2536****	**−0.2948*****	**−0.1304***	**0.0594**	**−0.0506**	**−0.1435**	**0.0508**	**0.0959**	**−0.0229**	**0.1208****	**0.4686*****	**0.2563****	**0.1545***
D_{1post}	−0.0296	0.1318	0.0101	−0.0104	0.1055	0.0843	−0.0015	−0.1351**	−0.1621*	−0.2642***	−0.1190**	−0.2306***	−0.3348***	−0.1503**
D_{2post}	−0.0290	0.0798	0.0229	0.0404	0.1195	0.0725	0.0559	−0.1324***	−0.1110	−0.1582***	−0.0563	−0.0829	−0.1833**	−0.1008**
D_{3post}	−0.1277**	−0.1850	−0.1168	−0.0301	0.0478	−0.3559*	−0.0236	−0.1613***	−0.1778***	−0.1978***	−0.0643**	−0.0612	−0.2724***	−0.1029***
D_{4post}	−0.1164**	−0.1422	−0.1442*	−0.0356	0.0445	−0.4297**	−0.0692	−0.1277***	−0.1604***	−0.1614***	−0.0459*	−0.0346	−0.2390***	−0.0975***
D_{5post}	−0.0941**	−0.1575*	−0.1786**	−0.0483	−0.2910**	−0.3736**	−0.0961	−0.0987***	−0.1343***	−0.1624***	−0.0296	−0.0690	−0.2340***	−0.0860***
D_{6post}	−0.0779*	−0.1497*	−0.1565**	−0.0411	−0.4099***	−0.2607**	−0.0820	−0.1005***	−0.1268***	−0.1808***	−0.0370	−0.1213**	−0.3136***	−0.0961***
D_{7post}	−0.0784**	−0.1120	−0.1515**	−0.0501	−0.2574**	−0.2798**	−0.0831	−0.0842***	−0.1134***	−0.1700***	−0.0424*	−0.0962**	−0.2900***	−0.0910***
D_{8post}	−0.0542	−0.0969	−0.1284*	−0.0368	−0.2078**	−0.2608**	−0.0723	−0.0713***	−0.1042***	−0.1649***	−0.0529**	−0.1049***	−0.2441**	−0.0994***
D_{9post}	−0.0639*	−0.1209**	−0.1707***	−0.0539	−0.2022**	−0.2844**	−0.1130*	−0.0655***	−0.1019***	−0.1572***	−0.0613***	−0.1238***	−0.2157***	−0.1016***
D_{10post}	−0.0436	−0.1011*	−0.1279**	−0.0364	−0.1806**	−0.2901***	−0.1206**	−0.0620***	−0.1042***	−0.1391***	−0.0642***	−0.1307***	−0.2168***	−0.1076***
D_{15post}	0.0096	0.0178	−0.0052	−0.0643*	−0.1835***	−0.2597***	−0.0629	−0.0310**	−0.0494*	−0.0720***	−0.0847***	−0.1169***	−0.1626***	−0.0908***
D_{20post}	0.0105	0.0038	0.0052	−0.0263	−0.1073*	−0.1751**	−0.0288	−0.0130	−0.0028	−0.0225	−0.0611***	−0.0730***	−0.1071***	−0.0253
D_{24post}	0.0001	−0.0187	−0.0086	−0.0104	−0.0654	−0.1131	−0.0245	−0.0023	0.0084	−0.0161	−0.0137	−0.0068	−0.0555*	−0.0091

Note: This table contains a summary with the coefficients and statistical significance of the variable of interest to test the expiration effect. All regressions include week-daily dummy variables, trend variable and dependent lags to adjust autocorrelation. Trading volume is the logarithm transformed of bitcoin traded. Columns show the results for the different exchanges, Binance, Bitfinex, Bitstamp, Coinbase, Gemini, Itbit and Kraken, respectively. ***, ** and * denote coefficients significant at the 1, 5 and 10 per cent level, respectively.

Table 3
Expiration effect on hourly volatility.

	Expiration of CME bitcoin futures							Expiration of CBOE bitcoin futures						
	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken
D_{24}	0.0028	0.0023	0.0039	0.0054	0.0023	0.0135	−0.0111	0.0525	0.0433	0.0402	0.0440	0.0408	0.0637*	0.0951
D_{20}	0.0177	0.0175	0.0156	0.0166	0.0143	0.0144	−0.0087	0.0514	0.0524*	0.0546*	0.0453	0.0521	0.0612	0.1003
D_{15}	0.0123	0.0171	0.0155	0.0147	0.0134	0.0163	−0.0155	0.1005***	0.099***	0.0989**	0.0998**	0.1018**	0.1151**	0.1543**
D_{10}	0.0555**	0.0608**	0.0634***	0.0609**	0.0568**	0.0744**	0.0388	0.1266***	0.0951**	0.1058**	0.1210**	0.1250**	0.1365**	0.1991**
D_9	0.0636***	0.0659**	0.068***	0.0692**	0.0663**	0.0853***	0.0521	0.1302***	0.0888**	0.0975**	0.1131**	0.1177**	0.1285**	0.1928**
D_8	0.0594**	0.0572*	0.0633**	0.0670**	0.0610**	0.0796**	0.0549	0.1431**	0.0972**	0.1071*	0.1200*	0.1287**	0.1396**	0.2019**
D_7	0.0542**	0.00518	0.0598*	0.0637*	0.0565*	0.0720*	0.0512	0.1412**	0.1034*	0.1136*	0.1189*	0.1258**	0.1476**	0.2087**
D_6	0.0601**	0.0610	0.0647*	0.0696*	0.0653*	0.0868**	0.0634	0.1490**	0.1119**	0.1153*	0.1192*	0.1321**	0.1651**	0.2160**
D_5	0.0697**	0.0748*	0.0707*	0.0768*	0.0726*	0.0907*	0.0786	0.1132*	0.0976*	0.0988*	0.0990**	0.1025**	0.1328**	0.2001**
D_4	0.0525	0.0594	0.0532	0.0575	0.0538	0.0756	0.0586	0.0783	0.0738	0.0647	0.0787	0.0678	0.1088	0.1630
D_3	0.0637	0.0703	0.0597	0.0665	0.0689	0.0956	0.0656	0.1880*	0.1587*	0.1521*	0.1614*	0.1603*	0.1738*	0.2513*
D_2	0.1392*	0.1578	0.1426	0.1472	0.1463	0.1894*	0.1398	0.1744**	0.1417**	0.1133*	0.1286*	0.1336**	0.1914*	0.2201*
D_1	**0.228***	**0.2452**	**0.2201**	**0.2514**	**0.2419**	**0.3418***	**0.2686**	**0.0645**	**0.0510**	**0.0036**	**0.0475**	**0.0148**	**0.0825**	**0.1266**
D_{1post}	−0.0887	−0.0941	−0.1135*	−0.1130	−0.1072	−0.1192*	−0.0753	−0.0178	−0.0821	−0.1769	−0.1833	−0.1637	−0.0423	−0.1169
D_{2post}	−0.1618***	−0.1260***	−0.1440***	−0.1431***	−0.1384***	−0.1579***	−0.1159**	−0.0158	−0.0411	−0.0671	−0.0966	−0.0534	−0.0207	0.0077
D_{3post}	−0.1504***	−0.1306***	−0.1316***	−0.1268***	−0.1256***	−0.1497***	−0.1204***	−0.0733	−0.0554	−0.0871	−0.1137	−0.1006	−0.0410	−0.0276
D_{4post}	−0.1121***	−0.1114***	−0.1062***	−0.0945***	−0.0996***	−0.1251***	−0.1101***	−0.0779	−0.0699	−0.0686	−0.1007	−0.0721	−0.0422	−0.0227
D_{5post}	−0.0835***	−0.0912***	−0.0798***	−0.0698**	−0.0694***	−0.0854***	−0.1082***	−0.0864**	−0.0725*	−0.0751*	−0.0977**	−0.0833*	−0.0577	−0.0270
D_{6post}	−0.0728**	−0.0702**	−0.0719**	−0.0655**	−0.0624**	−0.0723**	−0.1188***	−0.0690*	−0.0615	−0.0674	−0.0828*	−0.0695	−0.0535	−0.0245
D_{7post}	−0.0311	−0.0345	−0.0350	−0.0334	−0.0284	−0.0400	−0.0876**	−0.0570	−0.0539	−0.0671*	−0.0747*	−0.0647*	−0.0478	−0.0207
D_{8post}	−0.0303	−0.0323	−0.0392	−0.0378	−0.0264	−0.0437	−0.0800**	−0.0507	−0.0470	−0.0652*	−0.0665*	−0.0562	−0.0466	−0.0202
D_{9post}	−0.0116	−0.0197	−0.0201	−0.0015	−0.0026	−0.0217	−0.0568	−0.0578*	−0.0537*	−0.0699**	−000731**	−0.0673**	−0.0542	−0.0335
D_{10post}	−0.0163	0.0011	−0.0056	0.0040	0.0168	−0.0010	−0.0282	−0.0657**	−0.0587**	−0.0698**	−0.0732**	−0.0687**	−0.0527	−0.0416
D_{15post}	−0.0292	−0.0175	−0.0234	−0.0223	−0.0140	−0.0229	−0.0396	−0.0160	−0.0117	−0.0199	−0.0280	−0.0210	−0.0069	0.0090
D_{20post}	−0.0110	−0.0040	−0.0051	−0.0069	−0.0047	−0.0034	−0.0235	0.0037	0.0122	−0.0009	−0.0111	−0.0001	0.0151	0.0298
D_{24post}	−0.0041	−0.0013	−0.0012	−0.0012	−0.0008	0.0005	−0.0126	−0.0027	0.0027	−0.0044	−0.0096	−0.0011	0.0077	0.0283

	Expiration of Bakkt bitcoin futures							Expiration of all bitcoin futures						
	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken
D_{24}	−0.0136	−0.0126	−0.0109	−0.0110	−0.0067	−0.0031	0.0240	0.0114	0.0075	0.0086	0.0119	0.0092	0.0164	0.0203
D_{20}	−0.0333	−0.0305	−0.0244	−0.0287	−0.0242	−0.0222	−0.0007	0.0155	0.0150	0.0166	0.0150	0.0157	0.0159	0.0163
D_{15}	−0.0078	−0.0019	0.0004	−0.0040	0.0019	0.0052	0.0360	0.0315**	0.0338**	0.0343**	0.0346**	0.0347**	0.0356	0.0387*

(*continued on next page*)

Table 3 (*continued*)

	Expiration of Bakkt bitcoin futures							Expiration of all bitcoin futures						
	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken
D_{10}	−0.0275	−0.0182	−0.0177	−0.0170	−0.0125	−0.0024	0.0922	0.0562***	0.0511**	0.0564***	0.0611***	0.0596***	0.0828**	0.0734***
D_9	−0.0331	−0.0234	−0.0193	−0.0209	−0.0140	−0.0067	0.1028	0.0600***	0.0506**	0.0556***	0.0620***	0.0618***	0.0887**	0.0752***
D_8	−0.0513	−0.0427	−0.0345	−0.0390	−0.0283	−0.0223	0.0917	0.0572**	0.0441*	0.0523**	0.0586**	0.0589**	0.0894**	0.0717**
D_7	−0.0360	−0.0278	−0.0239	−0.0248	−0.0146	−0.0069	0.1235	0.0568**	0.0459*	0.0543**	0.0592**	0.0582**	0.0942*	0.0728**
D_6	−0.0558	−0.0494	−0.0438	−0.0454	−0.0332	−0.0216	−0.0753	0.0577**	0.0486*	0.0534*	0.0581*	0.0609**	0.0637	0.0825**
D_5	−0.0043	−0.0493	−0.0414	−0.0451	−0.0275	−0.0273	−0.0569	0.0530**	0.0516*	0.0524*	0.0563**	0.0574**	0.0732*	0.0746**
D_4	−0.0413	−0.0278	−0.0254	−0.0329	−0.0164	0.0006	−0.0229	0.0377	0.0420	0.0377	0.0437	0.0409	0.0576	0.0665*
D_3	−0.0434	−0.0402	−0.0416	−0.0443	−0.0220	−0.0150	−0.0107	0.0726*	0.0682	0.0620	0.0687	0.0728	0.0869	0.0923*
D_2	−0.2275***	−0.2272***	−0.2353***	−0.2281***	−0.1977***	−0.2143***	−0.1657**	0.0218	0.0220	0.0216	0.0194	0.0208	0.0224	0.0239
$\mathbf{D_1}$	**−0.2032***	**−0.2143***	**−0.1939***	**−0.1856***	**−0.1787***	**−0.1941***	**−0.1400**	**0.0910**	**0.0927**	**0.0706**	**0.1035**	**0.0868**	**0.1449**	**0.1560**
D_{1post}	−0.1397**	−0.1406**	−0.089**	−0.1146**	−0.1256**	−0.1289**	−0.1538**	−0.0749	−0.1003**	−0.1291***	−0.1327**	−0.1257**	−0.1040*	−0.1066*
D_{2post}	−0.0371	−0.0298	−0.0051	−0.0154	−0.0277	−0.0304	−0.0815	−0.0948**	−0.0853**	−0.0979***	−0.1059***	−0.0931***	−0.0769*	−0.1026**
D_{3post}	−0.0520	−0.0630	−0.0492	−0.0485	−0.0583	−0.0605	−0.1172	−0.1100***	−0.0992***	−0.1057***	−0.1091***	−0.1065***	−0.0995***	−0.1093***
D_{4post}	−0.0535	−0.0514	−0.0491	−0.0451	−0.0502	−0.0598*	−0.1147*	−0.0916***	−0.0903***	−0.0868***	−0.0875***	−0.0835***	−0.0907***	−0.0955***
D_{5post}	−0.0400	−0.0421	−0.0358	−0.0364	−0.0618*	−0.0468	−0.1018	−0.0760***	−0.0783***	−0.0719***	−0.0718***	−0.0731***	−0.0878***	−0.0762***
D_{6post}	−0.0323	−0.0371	−0.0322	−0.0280	−0.0703**	−0.0333	−0.0879	−0.0645***	−0.0636***	−0.0649***	−0.0637***	−0.0678***	−0.0898***	−0.0653***
D_{7post}	−0.041*	−0.0447*	−0.0411*	−0.0372	−0.0624**	−0.0421	−0.0960	−0.0421**	−0.0450**	−0.0479**	−0.0470**	−0.0475**	−0.0745**	−0.0489**
D_{8post}	−0.0233	−0.0310	−0.0223	−0.0201	−0.0365	−0.0288	−0.0736	−0.0360**	−0.0389**	−0.0454**	−0.0431**	−0.0384*	−0.0657**	−0.0474**
D_{9post}	−0.0371	−0.0441*	−0.0388	−0.0361	−0.049**	−0.0424	−0.0890	−0.0314*	−0.0371**	−0.0402**	−0.0366**	−0.0316*	−0.0607**	−0.0408**
D_{10post}	−0.0304	−0.0367	−0.0337	−0.0300	−0.0420*	−0.0376	−0.1007*	−0.0348**	−0.0261	−0.0315*	−0.0253	−0.0203	−0.0502	−0.0287
D_{15post}	−0.0056	−0.0112	−0.0122	−0.0156	−0.0161	−0.0189	−0.0790	−0.0224*	−0.0168	−0.0215	−0.0228	−0.0168	−0.0364	−0.0224
D_{20post}	−0.0096	−0.0134	−0.0101	−0.0164	−0.0175	−0.0193	−0.0760	−0.0080	−0.0033	−0.0060	−0.0098	−0.0062	−0.0215	−0.0056
D_{24post}	−0.0150	−0.0186	−0.0172	−0.0219	−0.0225	−0.0265	−0.0801	−0.0075	−0.0057	−0.0065	−0.0075	−0.0055	−0.0169	−0.0072

Note: This table contains a summary with the coefficients and statistical significance of the variable of interest to test the expiration effect. Coefficients are multiplied by 10^2. All regressions include weekdaily dummy variables and dependent lags to adjust autocorrelation. Columns show the results for the different exchanges, Binance, Bitfinex, Bitstamp, Coinbase, Gemini, Itbit and Kraken, respectively. ***, ** and * denote coefficients significant at the 1, 5 and 10 per cent level, respectively.

Table 4
Expiration effect on hourly returns.

	Expiration of CME bitcoin futures							Expiration of CBOE bitcoin futures						
	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken
D_{24}	0.0000	0.0002	0.0089	0.0070	0.0029	0.0271	0.0063	0.0020	−0.0107	0.0180	0.0210	0.0206	0.0207	0.0056
D_{20}	−0.0110	−0.0099	−0.0053	−0.0086	−0.0126	0.0210	−0.0103	−0.0178	−0.0385	−0.0044	−0.0026	−0.0016	0.0026	−0.0123
D_{15}	0.2825***	0.3065***	0.2744***	0.2989***	0.3139***	0.3756***	0.3124***	−0.0288	−0.0597*	−0.0042	−0.0034	−0.0003	0.0012	−0.0185
D_{10}	0.0142	0.0357	0.0317*	0.0324*	0.0243	0.0427*	0.0353	−0.0142	−0.0400	−0.0055	−0.0039	0.0097	−0.0009	−0.0175
D_{9}	0.0060	0.0261	0.0327*	0.031*	0.0215	0.0478**	0.0355	−0.0632*	−0.0896***	−0.0493*	−0.0466	−0.0287	−0.0401	−0.0638**
D_{8}	0.0334	0.0543**	0.0673***	0.0634***	0.0491**	0.0636**	0.0699***	−0.0406	−0.0736**	−0.0206	−0.0167	−0.0028	−0.0133	−0.0382
D_{7}	0.0107	0.0254	0.0407**	0.0393**	0.0333*	0.0441*	0.0464**	−0.0373	−0.0593	−0.0218	−0.0209	−0.0080	−0.0138	−0.0348
D_{6}	0.0281	0.0504**	0.0593***	0.0477**	0.0412**	0.0609**	0.058**	−0.0386	−0.0520	−0.0415	−0.0487	−0.0354	−0.0553	−0.0344
D_{5}	0.1206***	0.1828***	0.1947***	0.1747***	0.1741***	0.1616***	0.1856***	−0.0201	−0.0396	−0.0178	−0.0183	−0.0100	−0.0231	−0.0233
D_{4}	0.098**	0.1356***	0.1565***	0.1182***	0.1259***	0.1305***	0.1407***	−0.0565	−0.0768	−0.0630	−0.0576	−0.0465	−0.0584	−0.0629
D_{3}	0.1396***	0.2029***	0.1970***	0.1651***	0.2004***	0.1973***	0.2066***	−0.0926*	−0.1191**	−0.0901*	−0.1012*	−0.0891	−0.0942*	−0.0966*
D_{2}	0.3496***	0.4927***	0.5221***	0.4637***	0.4584***	0.3740***	0.4717***	−0.0280	0.0233	0.0375	0.0396	0.0064	0.0501	0.0359
$\mathbf{D_{1}}$	**0.2825*** **	**0.3065*** **	**0.2744*** **	**0.2989*** **	**0.3139*** **	**0.3756*** **	**0.3124*** **	**−0.0218**	**0.0910**	**0.0257**	**0.0705**	**0.0698**	**0.0629**	**0.0624**
D_{1post}	0.1178	0.1907**	0.1750**	0.2047***	0.1884***	0.1607	0.2177***	0.1842	0.1929	0.1857	0.0593	0.0262	0.0119	−0.0042
D_{2post}	0.0455	0.0888	0.0230	0.0288	0.0976	0.0622	0.0863	0.0614	0.2712	0.0413	0.1444	0.0059	0.2113	0.0396
D_{3post}	0.0158	0.0352	0.0061	0.0153	0.0278	0.0477	0.0310	0.1037	0.0903	0.1103	0.1124	0.1105	0.1363	0.0249
D_{4post}	0.0259	0.0551	0.0485	0.0308	0.0558	−0.0012	0.0302	0.0574	0.1391	0.0811	0.1259	0.0468	0.0504	0.0521
D_{5post}	0.0521	0.0569	0.0423	0.0280	0.0609	0.0752	0.0695	0.0634	−0.0054	0.0878	0.0132	0.0958	−0.0143	0.0165
D_{6post}	0.0549	0.0922*	0.0429	0.0803	0.1020	0.1237*	0.0939*	0.0663	0.1184	0.1210	0.0560	0.0651	0.1133	0.0824
D_{7post}	0.0559*	0.0680**	0.0491	0.0636*	0.0569*	0.0765**	0.0731**	0.0057	0.0553	0.0358	0.0687	0.0694	0.1136	0.0556
D_{8post}	0.0658*	0.0072**	0.0624*	0.0696**	0.0646**	0.0882***	0.0844***	0.0369	0.0269	0.0283	0.0558	0.0549	−0.0294	0.0827
D_{9post}	0.0553*	0.0556**	0.0449	0.0528*	0.0452	0.0667**	0.0637**	−0.0039	−0.0039	0.0336	0.0524	0.0110	0.1089	0.0621
D_{10post}	0.0411	0.0455	0.0372	0.0399	0.0532*	0.0005*	0.0505*	0.0432	0.0068	0.0085	0.0208	0.0123	0.0781	0.0068
D_{15post}	0.0459*	0.0433*	0.0405	0.0439	0.0425	0.0410	0.0488*	0.0478	0.0343	0.0089	0.0076	−0.0063	−0.0083	0.0344
D_{20post}	0.0041	0.0102	0.0086	0.0075	0.0082	0.0055	0.0113	0.0329	0.0013	0.0163	0.0206	0.0488	−0.0346	0.0398
D_{24post}	−0.0032	0.0033	−0.0007	−0.0009	0.0052	−0.0201	0.0000	−0.0149	0.0362	0.0024	0.0098	0.0397	−0.0053	0.0275

	Expiration of Bakkt bitcoin futures							Expiration of all bitcoin futures						
	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken
D_{24}	−0.0695***	−0.0443	−0.0326	−0.0396	−0.0277	−0.0360	−0.0311	−0.0061	−0.0022	0.0065	0.0044	0.0044	0.0025	0.0113
D_{20}	−0.0721*	−0.0665	−0.0170	−0.0683*	−0.0298	−0.0621	−0.0644*	−0.0177	−0.0182	−0.0069	−0.0092	−0.0108	−0.0127	0.0018
D_{15}	−0.0238	0.0188	−0.0037	−0.0200	−0.0195	−0.0100	−0.0116	0.1616***	0.1825***	0.1632***	0.1719***	0.1777***	0.1722***	0.2118***

(*continued on next page*)

Table 4 (*continued*)

	Expiration of Bakkt bitcoin futures							Expiration of all bitcoin futures						
	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken	Binance	Bitfinex	Bitstamp	Coinbase	Gemini	Itbit	Kraken
D_{10}	0.0086	0.0380	0.0509	0.0051	0.0296	0.0080	0.0492	0.0116	0.0073	0.0249	0.0246	0.0258	0.0216	0.0212
D_9	0.0363	0.0260	0.0220	0.0141	0.0304	0.0320	0.0425	−0.0033	0.0009	0.0127	0.0110	0.0134	0.0075	0.0115
D_8	−0.0027	0.0084	0.0485	−0.0061	0.0227	0.0038	−0.0019	0.0138	0.0174	0.0314*	0.0302*	0.0307*	0.0265	0.0285
D_7	0.0092	0.0082	0.0155	0.0117	0.0190	0.0190	−0.0065	0.0022	0.0023	0.0219	0.0208	0.0241	0.0205	0.0177
D_6	−0.0005	0.0717	0.0368	0.0694	0.0567	0.0675	0.0124	0.0131	0.0281	0.0292*	0.0201	0.0216	0.0275	0.0227
D_5	0.0148	0.0158	0.0155	0.0326	0.0417	0.0631	0.0371	0.0535*	0.067***	0.0791***	0.0699***	0.0771***	0.0739***	0.0686**
D_4	0.0375	0.0007	0.0353	−0.0084	0.0020	0.0364	−0.0164	0.0286	0.0292	0.0432	0.0319	0.0419	0.0372	0.0365
D_3	0.0165	0.0140	0.0412	0.0022	0.0439	0.0363	0.0269	0.0299	0.0367	0.0475	0.0284	0.0515*	0.0457	0.0471
D_2	0.0734	0.0194	0.0944	0.0469	0.0842	0.0961	0.0778	0.1221**	0.1504***	0.1914***	0.1451***	0.1672***	0.1676***	0.1203**
D_1	**0.1246**	**0.0926**	**0.0640**	**0.0647**	**0.1051**	**0.0940**	**0.0668**	**0.1616*****	**0.1825*****	**0.1632*****	**0.1719*****	**0.1777*****	**0.1722*****	**0.2118*****
D_{1post}	0.0411	0.0610	0.0584	0.0982	0.0993	0.0408	0.0744	0.1197	0.1417*	0.1643**	0.1433**	0.1379**	0.1363**	0.0490
D_{2post}	−00045	−0.0789	−0.0361	−0.0452	−0.0333	−0.0452	−0.0437	0.0744	0.0032	0.0198	0.0908	0.1483*	0.0934	0.0718
D_{3post}	0.0051	−0.0376	0.0051	0.0253	−0.0292	0.0185	0.0000	0.0054	0.0273	0.0517	0.0194	0.0627	0.0575	0.0861
D_{4post}	0.0077	−0.0266	0.0223	0.0128	0.0085	−0.0068	−0.0005	0.0480	0.0656	0.0576	0.0072	0.0569	0.0532	0.0670
D_{5post}	−0.0042	−0.0197	−0.0360	−0.0012	−0.0018	−0.0041	−0.0075	0.0493	0.0157	0.0428	0.0556	0.0550	0.0455	0.0761
D_{6post}	−0.0549	−0.0579	−0.0561	−0.0438	−0.0621	−0.0398	−0.0625	0.0253	0.0653	0.0063	0.0599	0.0578	0.0690	0.0783
D_{7post}	−0.0577	−0.0503	−0.0662*	−0.0693*	−0.0673*	−0.0375	−0.0733*	0.0400	0.0392	0.0288	0.0349	0.0336	0.0372	0.0371
D_{8post}	−0.0525	−0.0572	−0.0623	−0.0648	−0.0719*	−0.0344	−0.0725**	0.0359	0.0285	0.0205	0.0363	0.0226	0.0372	0.0326
D_{9post}	−0.0054	−0.0038	−0.0143	−0.0196	−0.0160	−0.0102	−0.0241	0.0226	0.0250	0.0218	0.0286	0.0188	0.0258	0.0218
D_{10post}	−0.0458	−0.0471	−0.0558*	−0.0549*	−0.0638**	−0.0425	−0.0714***	0.0143	0.0085	0.0099	0.0122	0.0182	0.0149	0.0196
D_{15post}	−0.0108	−0.0176	−0.0143	−0.0193	−0.0240	0.0079	−0.0283	0.0085	0.0099	0.0335	0.0318	0.0204	0.0095	0.0111
D_{20post}	−0.0204	−0.0277	−0.0178	−0.0214	−0.0283	−0.0083	−0.0301	0.0047	0.0069	0.0126	0.0170	−0.0097	0.0167	0.0058
D_{24post}	−0.0164	−0.0283	−0.0167	−0.0109	−0.0243	−0.0046	−0.0277	0.0041	−0.0153	0.0130	−0.0127	−0.0142	0.0088	−0.0087

Note: This table contains a summary with the coefficients and statistical significance of the variable of interest to test the expiration effect. Coefficients are multiplied by 10^2. All regressions include week-daily dummy variables and dependent lags to adjust autocorrelation. Columns show the results for the different exchanges, Binance, Bitfinex, Bitstamp, Coinbase, Gemini, Itbit and Kraken, respectively. ***, ** and * denote coefficients significant at the 1, 5 and 10 per cent level, respectively.

occurs between 10 and 18 h prior to expiration. In addition, Coinbase, Itbit, Gemini and Kraken also show an increase in trading during the hours nearest to expiration. The increase in Gemini (the exchange involved in the settlement system of the CBOE contract) is especially significant since the effect is detected up to 24 h before the time of expiration. In the hour after the expiration, all the exchanges have a significantly lower trading volume and this effect is prolonged for a few more hours, although not as uniformly as in the case of the expiration of the CME nor for as many hours, since after 16 h the volume in all the exchanges becomes normal. In sum, the volume in the Gemini exchange is the most affected by the CBOE expiration effect, but it is also interesting to note that all the exchanges start to significantly decrease their trading volume shortly after this expiration although the opposite effect before expiration is not always detected shortly before maturity.

The results for the expiration dates of the Bakkt bitcoin future do not follow a uniform pattern. In contrast to the clear increase in trading volume observed when the CME or the CBOE bitcoin futures expire, there is a decrease in trading volume in 4 of the 7 exchanges at the time of the Bakkt expiration and in the previous hours (up to 6 h beforehand). This effect is more intense in D_2. Two of the exchanges (Gemini and Itbit) have an increase in trading volume from 5 to 10 h before expiration. A mixed behaviour is observed in Kraken since in the hour preceding expiration the trading decreases, but this follows a significant increase some hours earlier. In the hours immediately following expiration, the trading volume also decreases significantly in almost all the exchanges, the significant effect lasting longest in Gemini and Itbit. Therefore, the only common pattern that can be found in the three cases is the significant decrease in trading volume after futures expiration.

When the joint effect of all maturities is analysed, a result similar to the combination of the significant coefficients of the CME and CBOE maturities is observed, both when looking at the effect in the hours before maturity and in the hours after it. Furthermore, this result suggests that CME is the most influential futures market.

Since the traded volume gathers the activity of all types of market participants, at least in this first approach the variation detected in trading volume around the expiration cannot be directly attributed to a specific investor type.

Finally, our results indicate that volume effects are identified on constituent and non-constituent exchanges. The usual arbitrage strategies among spot exchanges (cash-and-carry arbitrage) or the herding effects among exchanges could help to explain the trading activity around expiration in all exchanges.

4.2. Effects on volatility

The concept of volatility is a controversial one in the financial literature. Since volatility is a latent variable and is not directly observable, its computation can be carried out in different ways depending on the use of real data, expectations or conditional information. Historical, realized, implied or conditional volatilities are some of the measures reflecting these choices. In this paper, we analyze the expiration effect on a historical volatility measure in order to observe the effect on the trading data itself.[4]

We use the Garman and Klass (GK) estimator of unconditional volatility. Range-based volatility estimators are unbiased and highly efficient relative to other volatility measures and robust to certain types of microstructure noise (Brandt & Diebold, 2006). This measure includes maximum (H_t), minimum (L_t), opening (O_t) and closing (C_t) prices in hour t and computes $P_t = \ln (H_t/L_t)$ and $Qt = \ln (C_t/O_t)$. Volatility is obtained as follows:

$$\sigma_{GK,t} = \sqrt{\frac{1}{n}\sum_{t=1}^{n}\left[\frac{1}{2}P_t^{2} - (2\ln 2 - 1)Q_t^2\right]} \tag{2}$$

where n is the number of historical prices used. We use n equal to 1 in our calculation of hourly volatility estimation. As in the case of trading volume, we run OLS regressions with Newey-West heteroscedasticity-consistent standard errors and covariance. The model estimated is the following:

$$\sigma_{GK\,i,t} = \beta_0 + \beta_1 D_M + \beta_2 D_{Tu} + \beta_3 D_W + \beta_4 D_{Th} + \beta_5 D_{Fr} + \beta_6 D_{Sat} + \beta_7 D_{Exp} + \sum_{j=1}^{5}\beta_{j+7}\sigma_{GK\,i,t-j} + \varepsilon_{i,t} \tag{3}$$

where $\sigma_{GKi,t}$ is the GK volatility in the exchange i in hour t. Daily and expiration dummy variables are the same as the ones defined in the previous section. The models also include five lags of the dependent variable to correct autocorrelation, which is significant in all the estimates, and include dummy variables for daily seasonality. Thursday is the day with the highest volatility and Saturday the lowest, but the effect varies depending on the exchange.

Table 3 presents the results on volatility. Up to 12 h before maturity of the CME bitcoin future, volatility increases significantly in all the exchanges except Kraken where no effect is observed before maturity. Once the contract negotiation is closed, a significant decrease in the volatility of the spot bitcoin is observed, which lasts for 6 h but does not extend beyond that time (except in Kraken,

[4] We are aware that other alternatives such as conditional volatilities could also be interesting, especially when it has been proven that the errors in the mean equation follow this conditional structure. We tried to estimate the effect on volatility using conditional volatility models. However, daily seasonality variables in the mean and also in the variance led to estimation problems as the models failed to converge. An alternative to achieve convergence could have been to eliminate daily seasonality dummy variables, but this option does not cater for the possible overlap with the expiration day. In order to be consistent with the general model proposed, we consider the use of unconditional volatility more appropriate in this paper.

where the volatility reduction is noticeable for 8 h).

All the exchanges showed significantly increased volatility in the hours leading up to the expiration of the CBOE bitcoin future. The greatest movement in prices is detected during the day of expiration, since the significance is observed in the 15 h prior to maturity. It is noteworthy that the effect is not visible at the final time of maturity, maybe due to the system of settlement by auction. In the hours following the expiration, the exchanges do not react immediately as they take time to significantly reduce their volatility which occurs 5 h later, maintaining this effect for about five more hours. The effect does not last longer. Itbit and Kraken do not change their volatility level after the expiration time.

The effect of the expiration of the Bakkt bitcoin futures, once again, differs from the effects of the CME or CBOE futures expiration. The most relevant factor is that volatility in the spot market decreases significantly at the time of expiration, 1 h before and 1 h later. From that time onwards there is no defined pattern for all the markets. For some exchanges, volatility is significantly lower than the others at some times after maturity, but this effect does not last long. In order to highlight a common pattern for volatility, it can be pointed out that volatility decreases after the expiration time, regardless of the futures contract expiring.

Finally, the aggregation of maturities for the three futures markets offers homogeneous results among exchanges. With some exceptions, from 5 h before to 15 h before the expiration time, volatility increases significantly. After expiration, volatility decreases for 10 h. After that time, the effect vanishes.

The most noticeable effects on volatility generally appear close to the expiration time. These results analysed together with results in trading volume show that the effects are not uniform. The effects of CME and CBOE maturities are similar in volume and volatility, although with different intensity. Both variables increase before maturity and substantially decrease later. In the case of the Bakkt expirations, when there is an effect before maturity, this effect is negative on trading volume and volatility. However, effects after expiration follow the same direction for all three futures contracts. Differences in the delivery procedure may very likely be the cause of the differences in the results. In traditional markets, most physically delivered futures contracts are offset or rolled forward prior to the last trading day, particularly if the delivery process is complex. This practice in the futures markets could be a feasible explanation for the surprising decrease in activity in spot exchanges before the expiration date in futures contracts with physical delivery, presumably used mainly by hedgers. Conversely, speculators and arbitrageurs are potentially more inclined to use cash-settled futures.

4.3. *Effects on returns*

The model proposed to examine the effect on returns is:

$$R_{i,t} = \beta_0 + \beta_1 D_M + \beta_2 D_{Tu} + \beta_3 D_W + \beta_4 D_{Th} + \beta_5 D_{Fr} + \beta_6 D_{Sat} + \beta_7 D_{Exp} + \sum_{j=1}^{2} \beta_{j+7} R_{i,t-j} + \varepsilon_{i,t} \tag{4}$$

where R_{it} is the return of the exchange i in hour t. The other variables are defined previously and ε_{it} follows a distribution $N(0, \sigma_t^2)$

We use Threshold GARCH models with the threshold order equal to 1 to reflect asymmetric conditional volatility. Following this particular choice, the specification for the conditional variance is given by:

$$\sigma_t^2 = \omega_0 + \omega_1 \sigma_{t-1}^2 + \omega_2 \varepsilon_{t-1}^2 + \omega_3 \varepsilon_{t-1}^2 \gamma_{t-1} \tag{5}$$

where $\gamma_t = 1$ if $\varepsilon_t < 0$ and 0 otherwise.

Table 4 shows a summary of these results. Although not shown in the table for reasons of clarity, two return lags have been included in the mean models since they were found helpful to prevent autocorrelation. Both are significant in all the regression estimates. With respect to the daily seasonality, although the pattern is not coincident in all estimations and exchanges, it is observed that Tuesday returns are significantly lower than on the rest of the days. This also occurs on Fridays in some exchanges. As for conditional volatility, all the coefficients are significant, confirming the appropriateness of the estimation procedure. This equally occurs in more traditional markets, where the asymmetry of negative shocks inducing greater volatility stands out.

When we estimate the effect using the expiration dates for the CME bitcoin futures, we appreciate a clear effect on prices at the maturity time and 5 h prior to the expiration time in all the exchanges under analysis. Returns are significantly higher than the mean return at the 1% significance level. The strongest effect is reflected in D_2 and D_1, that is, at the time of the expiration effect and 1 h before. After the expiration time, returns are significantly higher for one more hour in five markets. Furthermore, this effect remains some hours later, although less intensely and at a lower confidence level. Nevertheless, it is noticeable that this significant positive effect is repeated 7, 8 and 9 h after the maturity time, and it can also be perceived 15 h later in some markets. These results can be attributable to the different time zones where the exchanges operate. European locations may be from 5 to 9 h ahead of American sites, and Asian locations between 8 and 17 h ahead. For example, Singapore is 8 h ahead of London, 13 h ahead of New York and 16 h ahead of San Francisco, all cities where the exchanges have their headquarters or main offices. For example, Bitstamp, one of the major platforms for European crypto traders, basically shows the effect prior to the expiration date and shortly after it, with a residual significance in D_{8post}. This finding is compatible with the fact that most of the trading close to this expiration time is European or even Asian, whereas the residual response of late American traders (or even new Asian traders) may be reflected hours later. In fact, the rest of the exchanges under analysis where the effect on returns remains up to D_{15post}, have a significant market share in Asia and America.

The effects in relation to the monthly expiration times of CBOE bitcoin futures are scarce. A negative expiration effect could be detected 3 h before maturity and 9 h before maturity for some exchanges, but not all of them. This minor effect on D_9 may be compatible with European and Asian trading, both for the time and for the exchanges involved (Binance and Bitfinex are strong markets in Asia, Bitstamp and Kraken are major markets for European customers). However, it is worth mentioning that these results are mostly significant at the 10% significance level. In particular, the Gemini exchange, involved in fixing the final settlement price, is not affected by this negative effect. No significant pattern is found after maturity. These results do not allow us to confirm a clear effect of the CBOE futures expiration on returns.

Table 4 also shows the results for the monthly expiration date of the Bakkt bitcoin futures. Neither at the expiration time nor at the nearest hours before and after it can we appreciate significant changes in the bitcoin returns for any of the exchanges in our sample. There are some significant negative results in D_{20} and D_{24} and between D_{7post} and D_{10post}. These scarce significant negative results (most of them only significant at a 10% significance level) may be related to time-zone effects, but there is no clear pattern of the Bakkt expiration effect on returns.

Trying to explain the disparity in the results relating to returns, we have also checked whether the expiration dates with a positive/negative effect were coincidentally framed in periods with positive/negative returns. We calculate the accumulated return 15 days before each expiration date and compare it with the expiration date return. The percentage of coincidences between positive 15-day previous returns and positive expiration date returns is 29.4%, 27.7% and 42.8% for CME, CBOE and Bakkt contracts, respectively. The percentage of coincidences between negative 15-day previous returns and negative expiration date returns is, respectively, 26.4%, 22.2% and 28.5%. These statistics indicate that our results are not a consequence of the state of the market, but something else, supporting the idea of a possible expiration effect on returns.

Finally, we study the global effect taking into account the expiration times for the three futures markets under analysis. The results indicate significant positive returns about 5 h before maturity, and 1 h after maturity (in five out of seven exchanges), showing a similar pattern to the findings for the CME futures.

To sum up, once again the CME contract is the most dominant in terms of the expiration effects on returns. The strongest effects are detected shortly before or after the maturity time, although there may be some smaller earlier or later effects related to trading in different time zones.

Our prevailing result is an abnormal positive return induced by the CME. Although the financial literature does not show a consensus on expiration effects on returns, previous studies have found results in accordance with ours (see, among others, Chamberlain et al., 1989; Chen et al., 2011 or Sadath & Kamaiah, 2011). Typically, this effect is attributed to the unwinding of short arbitrage positions. In the case of bitcoin markets, the unwinding of short arbitrage positions would be possible if the available arbitrage opportunities consisted of selling bitcoin short and buying under-priced futures and, consequently, prices rose at expiration as short arbitrageurs move to unwind their positions and provoke a buy order imbalance. In fact, Lee et al. (2020) report that bitcoin futures underpricing has often been detected at the introduction of futures contracts. Therefore, this could be a feasible explanation for our findings. However, this type of arbitrage strategy is not easily implementable in the bitcoin market: arbitrage operations can be inhibited by price differences constantly changing among constituent exchanges as well as trading frictions (for example, price limits or circuit breakers due to extreme volatility) on the CME futures markets.

On the other hand, we must remember that the spot market is susceptible to price manipulations. Baur and Dimpfl (2019) found that bitcoin spot prices were ahead of CBOE and CME futures prices in terms of price discovery in 2018 because the spot market never closes, whereas the CBOE and CME operate at traditional US trading hours. Speculators (and arbitrageurs) could therefore be interested in determining winning and losing positions on the futures market. Those who buy futures before maturity can try to manipulate spot prices upwards if they are interested in market upturns at maturity (either to liquidate futures at a gain or to avoid negative roll yields when futures markets are in contango[5]). Conversely, speculators (and arbitrageurs) who sell futures before maturity can try to manipulate spot prices downwards if they are interested in market downturns at maturity (either to liquidate futures at a gain or to avoid negative roll yields when futures markets are in backwardation). Contango is more often seen than backwardation. In fact, backwardation appeared during the bearish market conditions in 2018 and the beginning of 2019 (Lee, El Meslmani & Switzer., 2020). Perhaps this fact can help to explain the difference in return results between CBOE maturities and CME maturities. CBOE futures disappeared in the first quarter of 2019, after a bearish market and likely backwardation conditions, whereas a significant contango appeared later as the CME took the definitive leadership in bitcoin futures.

In light of our results and previous comments, we suggest that although theoretically speculators' and arbitrageurs' joint participation could produce the expiration effect, it is empirically difficult to distinguish the leading role of each of these actors. However, the difficulties mentioned above in carrying out arbitrage operations make it possible to question the prevalence of this type of market participant and highlight the role of speculators at close-to-expiration times.

4.4. Robustness tests

The empirical models in this paper involve different assumptions such as the computation of the variables, the definition of the estimation model or the nature of the information used that could affect the interpretation of the results. We conduct different robustness checks in order to consider some of these sensitive aspects.[6]

First, we examine the robustness of the results following a different methodology in the estimation process. The results described above have been found for each of the bitcoin exchanges independently. In order to establish the general effect on all the exchanges, we

[5] In this paper, we consider the market is in "contango" when the futures price is above the expected future spot price, and the market is in "backwardation" when the futures price is below the expected future spot price.

[6] For brevity, these results are not included as tables in the paper, but they are available upon request.

have run pool estimations using least squares with fixed effects and robust standard errors. This estimation imposes the condition that the coefficients are equal across all exchanges. The aggregation allows an overall assessment. The effect on trading volume is confirmed with the pooled estimation for the CME and CBOE expirations, showing a general positive impact on the volume at the expiration time and some hours before, and a negative effect after expiration. Likewise, the results for the Bakkt expiration are corroborated, given that the pool shows, on the one hand, the negative effect for D_1 and D_2 and, on the other, a positive effect from D_{11} to D_{14} that is consistent with the above-mentioned effects in Gemini, Itbit and Kraken. The negative effect from D_{6post} to D_{10post} is also proven. The global effect on volatility is confirmed, being positive and concentrated in the few hours before expiration and negative for six or 7 h after maturity for the CME futures, the negative effect concentrated around the Bakkt expiration, and the volatility increasing in the hours previous to the CBOE expiration dates. In the specific case of CME expiration, the results show a significant positive effect on returns in a short time before maturity (about 5 h before expiration, although not in the last hour). No effects are detected after then. The results also confirm that CBOE does not show any significant global influence on returns. However, the results do not coincide in the case of Bakkt. This shows significant positive effects on returns from D_7 to D_{24} and D_{1post} that did not appear in the individual analyses. We emphasize that the only clear impact on returns is caused by the expiration of the CME futures.

We also test the robustness of the results to the historical volatility measure. We propose to re-estimate the models using the Parkinson volatility estimator. This measure merely uses the information of maximum (H_t) and minimum (L_t) prices of bitcoin in hour t through the following indicator

$$\sigma_{P,t} = \frac{1}{2\sqrt{ln\,2}}\sqrt{\frac{1}{n}\sum_{t=1}^{n} P_t^2} \tag{6}$$

where P_t is calculated as previously and n is the number of historical prices used. The results are practically the same as those discussed for GK volatility.

Finally, although this paper does not report the results with daily data, an exhaustive analysis has been made with the daily information considering possible effects during the week before and after expiration. The results do not allow detection of a clear expiration effect on the days around expiration. This finding highlights the relevance of intraday data. Particularly for markets that operate 24/7 worldwide, the exclusive use of daily data can mask the no-longer-than- a-day effect that futures expiration produces on exchanges available in different time zones.

5. Discussion and conclusions

This paper studies the monthly expiration effect in the bitcoin markets. The arrival of trading of bitcoin futures in regulated markets is an ideal occasion to try to test this effect on an asset with singular characteristics.

Our results show that around the time of maturity there are significant changes in the trading volume, volatility and returns of bitcoin, an asset traded in many exchanges simultaneously. Therefore, there is a clear expiration effect related to bitcoin futures. The closer to the expiration time (shortly beforehand or afterwards), the more intense these effects are. The prevailing effect on trading volume is that it increases before the expiration date, at least in the case of cash-settled contracts, and decreases later. The volatility pattern is similar, but more concentrated. The effects on returns do not follow a common pattern. In fact, the only clear expiration effect is caused by the CME expiration time.

The expiration dates of the CME futures cause the most noticeable effects. When all the expiration dates are considered, the global results indicate this dominance. This finding may be due not only to the larger trading volume in this market but also to the fact that the CME is the market with the longest life in our analysis.

For all markets and maturities, volatility changes are aligned with the effect detected in trading volume. Volume increases tend to increase volatility and vice versa. However, the effect on volatility is shorter in time than that detected on volume. Both are noticeable some hours before the beginning of the effect on prices. It should be noted that spot markets trade 24/7 worldwide, but some exchanges concentrate significant market shares in a specific area. For example, Binance and Bitfinex are strong markets in Asia, Bitstamp and Kraken are major markets for European customers, and Gemini, Coinbase and Kraken are currently the main crypto exchanges for U.S based crypto traders. Continuous trading along different time zones may help to explain the extension of the effects on volume that, in turn, can induce later effects on volatility and prices.

The fragmentation of the spot markets allows us to detect some differences across exchanges. Given that different platforms worldwide offer different bitcoin prices, we would also expect some differences in their expiration effects. For example, regarding volume effects, large markets such as Binance are less affected than relatively small markets such as Itbit; or for example, Coinbase, a more retail-consumer oriented platform, is also less affected, probably because institutional investors generally focus on other exchanges. From another perspective, Gemini, as an exchange specifically involved in CBOE futures, shows some differences in the effects on returns and volume compared to other exchanges.

As stated before, the overlapping of possible effects from other unregulated futures with the same maturity dates as those of some of the formally regulated futures under analysis, as well as the expiration of other sophisticated products such as options or futures with daily maturity, may also influence the results obtained in the spot markets. However, as pointed out previously, perpetual futures represent the highest percentage of unregulated futures trading and cannot induce an expiration effect as they do not expire, they are generally marked-to-market every 8 h, and they trade close to the spot price of the underlying cryptocurrency. In addition, regulated futures attract institutional investors, whose robust access to information is likely to sway trading among retail investors and contributes to explaining the expiration effects. Furthermore, the largest unregulated futures market, Binance, was roughly the same size as CME at the end of our sample period in terms of open interest in bitcoin futures ($1095 billion and $1,16 billion, respectively[7]). Considering that much of Binance's turnover involves perpetual futures, our results can be mainly attributed to the regulated maturities at the CME. Finally, other expiration dates such as quarterly expiration dates in Binance are assumed not to cause the monthly reactions detected. At most, some weekly or daily maturities could contribute to our results, but this contribution does not seem to be significant as we do not detect any effect on non-expiry dates at the CME, CBOE or Bakkt that could coincide with more frequent expiration dates in unregulated markets.[8]

It is worth highlighting that the use of intraday data allows detection of the persistence of the changes in the market variables throughout the expiration day or on the previous or subsequent day, knowing that the effect does not last longer than 24 h. This means that tests with daily data would hide much of the information that has been detected in this work. Intraday data provide efficiency to the analysis. Likewise, the analysis of individual exchanges and individual futures contracts is helpful, given the different sensitivities to some variables such as time-zone, market size or crypto-traderś preferences. Joint estimations may also mask particular effects if there is a very heavily traded futures contract and/or bitcoin exchanges are considered as a whole.

The introduction of bitcoin futures contracts in regulated markets leads to an expected increase in institutional investors' trading. The evidence presented in this paper suggests that this has occurred especially because of the CME contracts. According to Arcane Research,[9] as of December 29th' 2020, CME is the largest contributor to the open interest in the BTC futures market. Coinciding with the fact that during the second half of 2020 many institutional investors announced or recommended bitcoin allocations, CME open interest at the end of 2020 was more than 60 times greater than the open interest in Bakkt futures. This may be due to the multiplier associated with the futures contract specifications. In the case of CME, the five bitcoins size versus the 1 bitcoin size of the CBOE or Bakkt contracts may amplify the effect. Institutional investors tend to be sophisticated investors compared with retail investors. This means that institutional traders may find arbitrage and speculation opportunities more often than retail traders. The institutional participation may strengthen the expiration effect. These explanations are also consistent with the fact that CME expirations are dominant.

This study has several implications. We believe that this research throws some light on cryptocurrencies, on some anomalies that cast doubts on market efficiency, and on how bitcoin pricing can be stable. Should bitcoin become a generalized means of payment, it would be of interest to control such pricing anomalies. Regulators must be aware of the bitcoin market fragmentation. If an expiration effect is detected, there may be exploitable anomalies from which some participants can take advantage. Furthermore, effective regulations require consensual actions among the different agents involved in the individual markets, and empirical evidence can help to determine the areas where regulatory action or supervision is required.

Our work brings together two branches of financial literature: the analysis of market anomalies and the study of bitcoin. Although the literature has already reported introduction effects and price discovery processes in bitcoin markets, not very much is known about the peculiar case of the expiration effect on bitcoin. We empirically confirm a clear anomaly in the spot market when the futures expiration date arrives, a phenomenon which is clearly manifested in the hours around the expiration. However, the complex conjunction of many factors involved in the determination of this effect does not allow us to identify the driving causes for it. Although some clues have been suggested in this paper, the peculiarities of the bitcoin markets hinder such an analysis.

The course of time will see future research in this field. One possible line of study could be to observe how the expiration effect changes with the recent introduction of regulated markets of bitcoin options or micro bitcoin futures. Undoubtedly, more extensive periods will enable better analysis of how the expiration effect changes as the bitcoin futures markets grow and become more mature.

Acknowledgements

We sincerely thank the anonymous referee and the editor for their helpful comments and suggestions. We acknowledge the following financial support: Grant PID2019-104304 GB-I00 funded by MCIN/AEI/10.13039/501100011033 https://doi.org/10.13039/501100011033; Grant RTI2018-093483-B-I00 funded by MCIN/AEI/10.13039/501100011033 https://doi.org/10.13039/501100011033 and by ERDF A way of making Europe; Grant S11_20R: Cembe funded by the Government of Aragon and ERDF.

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[7] https://www.coinglass.com/BitcoinOpenInterest, as of December 1st, 2020.

[8] Kraken also has monthly expiration days coinciding with CME monthly expirations, but we estimate that Kraken's open interest for such bitcoin futures is at most 1.5% of the CME monthly futures. Furthermore, Kraken does not show any significant different effects.

[9] Arcane Research weekly update, 2020 summary. Downloadable at https://research.arcane.no/the-weekly-update on 10th January 2021.

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