The WMR Fix and its Impact on Currency Markets

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Abstract

One of the most widely used benchmarks for FX trading is the so-called London WMR 4 pm Fix. This study empirically examines intraday liquidity as well as the returns-flows relationship around the London 4 pm Fix and for other intraday points in time using 4 years of high-frequency data for multiple currencies for both the spot and the futures market. Our results indicate that the behaviour of liquidity and prices around the London 4 pm Fix are quite unlike that observed at other points in time. One major finding of this study is that inter-dealer order flow is completely uninformative for spot returns at the Fix window.

Preliminary and Incomplete

Keywords: Currency Markets; Exchange Rates; WMR Fix; Market Microstructure; Order Flow.

JEL Classification: F31; F33; G12; G15.

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1 Introduction

In the summer of 2013, the London WMR 4pm Fix moved from the fine print of foreign exchange contracts to the headlines of newspapers. The London WMR 4 pm Fix (or just the "Fix" hereafter) is a key reference rate in the spot foreign exchange market used extensively by market participants[1]. Given the high degree of reliance that investors place on benchmarks, the 2013 news reports revealing widespread manipulation of the Fix threatened the integrity of this benchmark and resulted in a large-scale investigation from various regulatory bodies from numerous countries worldwide (US, UK, EU, Switzerland and Hong Kong among others). According to regulators, traders at some of the world's largest banks colluded in manipulating the spot benchmark rates on a large scale over a period of at least five years. These investigations resulted in fines in excess of $11bn for the banks involved in the story[2].

Apart from questioning our belief that the more liquid a market[3] the less susceptible it is to manipulation, this incident also revealed that our understanding of forex trading around the Fix, the most important institutional characteristic of the FX market, is not well understood and "price dynamics around fixes are not well accounted for in existing microstructure models" (Melvin and Prins (2015), Osler and Turnbull (2016)). Our paper contributes towards this end by examining the institutional details of the Fix and the price and liquidity dynamics around the Fix. It further extends the literature by incorporating inter-dealer order flow into the analysis and by simultaneously considering the spot and the futures market, as a large number of derivatives products are contractually linked to the spot price at the Fix.

More specifically, in this study we empirically examine the intraday foreign exchange rates and inter-dealer order flow relationship around the Fix for

[1]Other extensively used FX benchmark rates include the 1:15 London local time ECB benchmark rate and the 10 am JST Tokyo fixing (GMT 1:00).

[2]More details can be found in Appendix B.

[3]The global FX market is the world's largest financial market with an estimated average daily turnover of approximately 5.1 trillion U.S. dollars in 2016 (Bank of International Settlements (2016)). However, this figure is down from 5.4 trillion U.S. dollars in 2013.

both spot and futures markets for various currencies by using 4 years of high-frequency data. We further compare and contrast intraday liquidity and price behavior with other fixing points, such as 3 pm London fix and the ECB fix, as well as with other major intraday points in time, such as the 9:30 am London time when macroeconomic indicators are published. Our analysis indicates that benchmark rates play an important role in the workings of currency markets, especially the London 4 pm Fix where the behavior of prices and flows around this time is quite unlike that observed at other points in time.

Our main findings are summarized as follows: (1) During the 60 second calculation window of the Fix, there is an extreme concentration of trading activity not present during any other point in time of the day, as measured by the average number of trades per minute of trading activity, generating price and order flow spikes for both the spot and the futures markets (2) Order flow is uninformative for spot returns during the Fix in the spot market with a zero price impact but not for the futures market (3) There is price reversal in one minute after the Fix but not during other fixing points for both markets (4) Price discovery temporarily migrates from the spot to futures markets at the Fix (5) Less concentration of uninformed order flow in other fixing periods that we observe at the Fix (6) Based on our results, we can infer that trading around the Fix seems not to be information-driven.

On theoretical grounds, the introduction of a benchmark rate in a relatively opaque financial market is associated with information-related and liquidity-related benefits for market participants. The introduction of a benchmark can lead to a reduction of asymmetric information regarding the value of the underlying traded financial instrument and an increase in transparency. For example, with the publication of a reliable benchmark rate investors can more effectively judge whether the rates offered by dealers are competitive or not to verify dealers' claims of good trade execution on behalf of their customers. In absence of a benchmark rate, intermediaries can take greater advantage of market opaqueness and of the cost to customers of searching for alternative rates. Moreover, reliable benchmark rates in highly fragmented or bilateral over-the-counter markets characterized by the absence of a centralized exchange, can increase matching efficiency, decrease search costs and increase participation by less-informed or less-sophisticated investors (Duffie and Stein (2015)).

Once a reliable and publishable benchmark is established, concentration of trading activity is then expected to take place due to the following two types of effects. Firstly, market participants face a strong incentive to reap the information-related benefits from the introduction of the benchmark and in order to achieve these benefits, investors must choose to trade at the benchmark rate. Secondly, this concentration of trading activity is usually associated with higher liquidity, i.e. smaller spreads, increased depth, faster execution and, potentially lower price impact for larger trades. These benefits could potentially further attract trades as there is an incentive to substitute from less-actively traded instruments towards instruments that reference the benchmark.

In the FX market, such a benchmark rate was introduced in 1994 by the World Markets Reuters (WMR) Company, a joint venture between The WM Company and Thomson Reuters as a means of providing a transparent benchmark that correctly reflects the market at the time at which the rate is calculated. It covers 155 currencies and the forward market providing forward rates for 80 currencies. The rates are intended to cover the currencies for those countries that are included in a global or regional stock market index or where there is sufficient liquidity in the currency market to provide accurate fixings. The benchmark rate is calculated on a daily basis at an hourly frequency (half-hourly rates are provided for the most heavily traded currencies). Over a one-minute fix period, bids and offers of actual trades executed for each currency pair are sampled every second from 30 seconds before to 30 seconds after the fixing point (e.g. 4 pm London time) and median bid and offer rates are calculated[4]. Publication of the fixing rate takes place 15 minutes after the fix time. From those hourly fixes, the most widely used by market participants is the one calculated at 4 pm London time. The reason for the popularity of the 4 pm Fix can partially be explained by the fact

[4]On February 15, 2015, WMR adopted a five-minute window to calculate currency benchmark rates (i.e., a five minute window from +/- 2.5 minutes either side of the fix), in an attempt to discourage further dealer misconduct. For a more detailed discussion of the calculation methodology, please refer to Appendix A.

that the foreign exchange market activity is mostly concentrated around the overlap of US and European business hours and partly because it may be seen, in a sense, as the end of the European trading day.

The Fix is used for constructing indices comprising international securities (e.g. the MSCI stock index, the Barclays Global Bond Index and Markit's credit index), to compute the returns on portfolios that contain foreign currency denominated securities (e.g. country tracking funds and ETFs) as well as the value of foreign exchange securities held in custodial accounts (Evans (2016)). Melvin and Prins (2015) show that trading activity in the spot market is particularly high around the time of the Fix, especially at the month-end. This is because fund managers often rebalance their portfolios at the end of the month to ensure that their currency exposure is in line with their benchmark indices. Because the same rate is also used for the benchmark index the fund manager is measured against, the manager's currency risk is eliminated. Moreover, multinational companies may have an interest in valuing their currency holding using a common reference rate. Trading at the currency Fix rate is often seen as transparent, because the transactions is executed at an official reference rate. It also saves companies from putting resources into monitoring the market and enables them to eliminate the currency risk relative to internal benchmarks that use the Fix rate. Both commercial and financial players thus have an interest in linking orders to currency fixes. This generates large orders and extensive transactions for banks ahead of the times the reference rate are set.

In relation to the manipulation story, two key feature that gave traders an opportunity as well as a strong incentive to manipulate benchmark rates are the high concentration of trading activity over a 60-second interval and the existence of so-called *fill-at-fix orders*.

The desire of market participants to trade at the benchmark rate results in concentration of trading activity. While such concentration is beneficial for market liquidity, it also gives birth to an incentive for market manipulation. For example, the deep and liquid foreign exchange derivatives markets can accommodate extremely large derivatives positions. A trader with a sufficiently large position can profit significantly from even tiny price distortions, on the order of one basis point. Precisely because everybody prefers to be in the high-liquidity club, there is a coordination problem. No individual actor may be willing to switch to an alternative benchmark, even if a world in which many switched would be less vulnerable to manipulation and offer investors a menu of reference rates with a better fit for purpose (Duffie and Stein (2015)).

A fill-at-fix order is an order placed by investors to banks to buy or sell a given amount of currency at the fix rate, which is unknown at the time the order is placed. Typically, clients place orders before the 4pm Fix[5] to buy or sell a specified volume of a currency pair at the Fix rate and banks' spot desks guarantee that the customer receives the agreed volume of the currency pair at the yet unknown and to be determined Fix rate. Thus currency risk has now been transferred from the customer to the bank as the bank is exposed to rate movements at the Fix. The bank needs to hedge its own currency risk and can achieve that by buying (or selling) the currency needed ahead of the actual Fix from other market participants. This is because it is extremely difficult in practice to trade a large amount of currency at a single price at exactly the time of the Fix. The bank will make a profit if the average rate at which it buys the currency pair in the market is lower than the Fix rate at which it sells to the client. In isolation, the bank's purchase of the quantity needed will serve to push up the value of the currency, which means that a fill-at-fix order can affect pricing in the period to the Fix. This mechanism implies that the bank's and the customer's interests may not necessarily aligned towards moving the price in the same direction in the period to the Fix. For example, the customer wants to buy as cheap as possible and has an interest in the currency appreciating as little as possible. On the other hand, the bank wants to make a profit on the order (as well as to hedge its own exposure) and thus has an interest in the currency strengthening. In this case, it becomes more likely that the bank will be able to sell the currency to the customer at a higher price than the bank paid for them. Thus in the 15 minutes period before the Fix we could argue that bank's spot trading desks role shifts from that of a risk-neutral market-maker to a mix between

[5] According to Melvin and Prins (2015) and Evans (2016), market practices dictate that fill-at-fix orders must be submitted to dealer banks before 3:45 pm London time.

an informed trader about order flow and a market-maker, given also that dealers shared information during this period according to the manipulation story.

It is exactly these two characteristics that distinguish and affect market dynamics around fixing periods and, although the Fix is the most important institutional feature of the FX market, these dynamics were disregarded in academic literature up until recently. In this paper we examine intraday forex trading patterns around fixes and we contribute towards a better understanding of the role of fixes in the operations of the FX market.

In our paper, we do not only focus on the spot market but we also consider currency futures trading. In futures markets, speculators and hedgers exhibit different trading purposes, behaviors, and performance. Hedgers use the futures market to transfer spot price risk, and their hedging pressure tends to drive futures prices up or down, relative to the expected value of the spot price, such that it generates a bias in futures prices. Speculators take the opposite side of futures contracts and bear the risk of trading with informed investors, such that they earn compensation from a positive expected profit in their position. As the presence of speculative activities leads the futures price to change gradually and approach the true implicit value of the underlying asset given that futures contracts are contractually linked to the underlying spot rate at the fix, spot market dynamics around fixes could also potentially relate and impact currency futures trading behaviour.

The paper is structured as follows. In section 2, we present the various strands of the literature with which our study could be linked and place our contribution within this context. In section 3, we describe our data. In section 4, we describe our empirical approach and we present and discuss our results. Section 5 concludes and summarizes the study.

2 Literature Review

Our paper relates to three strands of literature on foreign exchange market microstructure, and especially to the literature on the effects of benchmark rates on foreign exchange market activity. The first and the older strand is that of focusing on order flow's impact on currency returns going back to Lyons (1995) and Evans and Lyons (2002). They provide the first estimate of the foreign exchange market's response to interdealer order flow by regressing the base currency's daily return on order flow as well as on macroeconomic variables (they used interest differentials as a proxy for macroeconomic fundamentals). Their results reveal a strong and statistically significant positive relationship between order flow and contemporaneous currency returns with an extraordinary explanatory power (40-60 percent), as compared to the low explanatory power (1-2 percent R-squared) from regressions of currency returns on macroeconomic fundamentals alone.

Evans and Lyons (2002) argue that the importance of order flow in the determination of spot foreign exchange rates is attributable to the information it conveys about (non-dealer) customer trades. At the start of each day, uncertain public demand for each currency pair is realized (stemming from shocks to hedging demands, liquidity demands as well as speculative demands). These demand realizations produce orders (i.e. each trader receives a number of orders from his/her customers) that are not publicly available, so any information they convey must be aggregated through inter-dealer order flow. Even though each trader has a private signal of the currency's payoff, information is not concentrated, but rather it is dispersed among a large number of separate dealers. Order flow is therefore the proximate determinant of exchange rates as it is the transmission mechanism through which all the dispersed pieces of information in the economy are aggregated and incorporated into price.

Since then, an-ever growing literature has further tested the original hypothesis with longer or more recent datasets, covering more currencies, at daily and higher frequencies, with brokered, interdealer as well as customer trades (e.g. Evans and Lyons (2005a); Evans and Lyons (2005b); Marsh and O'Rourke (2005); Killeen et al. (2006); Danielsson and Love (2006); Berger et al. (2008)). The estimated coefficients for order flow are always statistically significant providing substantial empirical support for the validity of the contemporaneous relationship between inter-dealer order flow and exchange rate returns.

The second strand is that of time-of-day patterns in foreign exchange markets. The foreign exchange market is in operation on a 24/7 basis and could be considered as the closest analogue to the concept of a continuous time global market. The underlying assumption of these studies is that each hour of the day and each currency pair may exhibit different trading characteristics based on which global markets are actively trading at that time. Admati and Pfleiderer (1988) develop a theoretical model in which concentrated intraday trading and high volatility in particular hours in a day arise endogenously as a result of the strategic behaviour of liquidity traders and informed traders. Among other findings, they relate their theoretical results to the U-shaped pattern of volume and variance observed in New York Stock Exchange and they also predicted that the spreads should be lowest at the beginning of the day.

When intra-daily data of trading activity became available, a large number of studies emerged examining intraday seasonalities of trading activity. In relation to trading volume in the spot market, a number of studies (e.g. Bollerslev and Domowitz (1993), Hartmann (1999), Ito and Hashimoto (2006)) report trading activity and bid-ask spreads of some major currency pairs (such as GBP/USD, EUR/USD and USD/CHF) increases during London and/or New York opening hours and that trading volume and volatility is highest during the overlap period i.e., when both New York and London are open as well as that trading activity picks up after midnight as the Tokyo and Sydney markets open with subsequent activity in Singapore and Hong Kong. Moreover, a U-shaped pattern of quote revision frequency and trading volume is found for both Tokyo and London participants, but no daily U-shaped patterns for New York participants.

With respect to volatility, a number of studies (Baillie and Bollerslev (1991), Andersen and Bollerslev (1997), and Andersen and Bollerslev (1998)) document the existence of a distinct U-shaped pattern in return volatility over the trading day i.e. volatility is high at the open and close of trading and low in the middle of the day. In addition, they report intraday volatilty calendar effects, Daylight Saving Time, Tokyo Opening effects and Tokyo Lunch time effects, and then proceeded to examine the dynamics of intraday volatility clustering and other properties. Harvey and Huang (1991) report similar results for the currency futures market. It is not clear, however, whether large volumes and volatilities are caused by efficient processing of fundamentals or other factors, such as noise trading.

An important contribution within this strand of literature made by Ito et al. (1998) and Covrig and Melvin (2002). They analyzed foreign exchange market activity during Asian business hours for the periods before and after the lunchtime trading and found evidence consistent with the presence of significant private information in the foreign exchange market. A particularly important piece of evidence in their study was that there is a U-shape of volatility of yen/dollar exchange rate returns in the Tokyo morning when the lunchtime closing occurs that disappears once lunchtime trading begins. This is consistent with models of private information where the informed traders must exploit their informational advantage prior to the market closing so that a compressed trading time results in a faster revelation of the private information.

In relation to returns, a well established empirical regularity is the tendency for the foreign currency to rise during U.S. trading hours, with the majority of that rise occurring in the first and last 2 hours of trading as well as a significant tendency to fall outside U.S. trading hours (Cornett et al. (1995); Ranaldo (2009). These studies also report a statistically significant tendency for the domestic currency to depreciate in its own trading hours. Breedon and Ranaldo (2013), extend the analysis and examine order flow intraday seasonalities in relation to returns and report a strong relationship between average order flow and average returns implying that intraday order flow follows similar intraday patterns as those observed for intraday returns and that it is the timing of trades that is largely responsible for the intraday pattern in returns.

The third, and the more recent strand, relates to forex trading around the London WMR 4pm Fix. Although the Fix is an important institutional characteristic of the forex market, only a handful of papers focus on the Fix. The majority of these studies stem from the spot rates manipulation scandal[6] and concentrate on empirically examining trading activity around

[6]The aim of this study is to examinie trading behaviour around fixing periods and not to

the Fix during the period of alleged manipulation (e.g. Michelberger and Witte (2016); Evans (2016); Ito and Yamada (2015)). Our paper falls into this category and extends the literature by incorporating order flow to the analysis and simultaneously examining the currency futures market (as several financial contracts are contractually linked to the Fix benchmark rate). A second category of studies of the Fix contains papers which theoretically model trading behaviour around the Fix (e.g. Saakvitne (2016); Osler and Turnbull (2016)).

A common finding of these studies is that market dynamics around the Fix can be distinguished from other times during the day. The fixing period is characterized by high concentration of trading activity and it is believed that market dynamics around the Fix are most probably caused by the compression of a large number of trades into a narrow time window (Michelberger and Witte (2016); Melvin and Prins (2015); Ito and Yamada (2015)). Moreover, the fixing period is associated with increased volatility and there is a significant probability for observing extreme price movements withing the Fixing period, as compared to other trading intervals within a day, consistent across all investigated currency pairs (Michelberger and Witte (2016); Evans (2016)). Ito and Yamada (2015) and Evans (2016) further examine price dynamics around the Fix and provide some evidence of spikes in prices around the fixing window. Evans (2016) provides evidence of negative autocorrelation of the spot rate between the pre- and post-fixing periods, particularly at the end-of-month trading days and identifies very small reversals during the first minute after the Fix (on the order of one basis point) for intra-month days and sizeable reversals in prices in the end-of-month days. Ito and Ya-

establish empirical red flags concerning the alleged manipulation of forex benchmark rates. Thus the work presented here is not directly linked to the literature of the manipulation of security prices. Moreover, much of this literature concentrates on the manipulation of equity prices. There are various differences between equities and forex rates that limit the applicability of existing models to studying manipulation of spot benchmark rates. For example, the literature on closing equity price manipulation applies in settings where trading stops, whereas forex trading takes place continiously. Evans (2016) documents that forex trading between 4pm and 5pm is comparable in terms of volume and liquidity to trading in the hours before the Fix. In addition, the relevance of LIBOR manipulation to the Fix is also limited as LIBOR is based on bank's judgement-based estimate of their borrowing costs, whereas the Fix is determined by the spot prices for actual transactions.

mada (2015) provide evidence that liquidity provision at the fixing time is larger than other times, which makes the price impact of any trade smaller. They also examine trading behaviour around the Tokyo fixing and show that price spikes in the Tokyo fixing are more frequent than in the London fixing.

Furthemore, Melvin and Prins (2015) test the hypothesis that currency hedging trades by international equity portfolio managers, generated by outperformance of a country's equity market over the course of a month, relative to other markets, will lead to selling of that country's currency prior to the last Fix of the month. They report a statistically significant and negative effect suggesting that currency returns in the lead-up to the Fix on the last day of the month are predicted by relative moves in country equity markets. They also provide evidence that equity hedging flows are responsible for higher exchange rate volatility, specifically around the end-of-month Fix.

On theoretical grounds, Saakvitne (2016) motivated by the observation that a dealer with a large Fix order faces an optimal execution problem, explicitly links market manipulation to optimal order execution strategies. Saakvitne (2016) develops an equilibrium model of strategic agents receiving Fix orders, who are "banging the close"[7] and shows that banging the close can naturally occur in practice as the solution to the optimal order execution problem.

Finally, our paper could also potentially be related to the optimal benchmark design literature. The foreign exchange and LIBOR scandals have spurred policy discussions of the appropriate design of financial benchmarks. Given that similar concerns have recently been raised over manipulation of commodity benchmarks and given the important role of these benchmarks in financial markets, reports that they have been systematically manipulated have triggered a regulatory reform process with a view to improving their robustness to manipulation (Duffie and Dworczak (2014)). Our paper can potentially contribute to this discussion. According to a pair of reports commissioned by the Financial Stability Board on designing benchmark rates in a way that leans against manipulation suggested that benchmark rates should be based

[7]According to the definition by Saakvitne (2016), a trader who bangs the close is buying or selling large volumes exactly when a benchmark price is determined, in order to affect this price and profit on an even larger pre-existing position.

not on judgements submitted by market participants, but on a large volume of actual transactions and heavier use of alternative benchmark rates should be promoted. Duffie and Stein (2015) argue that the first proposal could be achieved in part by widening the time window over which rates are calculated and by broadening the set of instruments or types of trades that are used. Saakvitne (2016) also examined how widening the Fix calculation window affects the optimal execution of fix orders and the associated price distortion and shows that such a measure would be highly effective. In contrast to Saakvite's prediction regarding the efficiency of widening the Fix calculation window, Osler and Turnbull (2016) argue that this measure will have no effect and that we will continue to see similar trading patterns around the Fix, as also documented by industy reports (e.g. Pragma (2015))[8]. However, any potential impact of widening the calculation window on market liquidity has not been yet considered.

3 Data

This section describes the currency data used in the empirical analysis and the construction of our variables. We also provide some basic summary statistics. We focus our discussion on the British pound / American dollar (GBP/USD) currency pair, as those results are representative of all currency pairs examined in our study. Results for AUD/USD and NZD/USD can be found in the appendinx. Our data set is comprised of two different components, one data set for the spot rate and one for the futures rate. Both data sets span the period between January 01, 2010 and December 31, 2013. We denote spot and futures rates in levels as S and F, respectively.

[8]In this research report is stated that the widening of the calculation window in conjunction with the industry's reported shift towards automated time-slicing handling of Fix orders has created strong momentum in rate changes throughout the 5-minutes Fix window, followed by a marked reversion. This pattern is more pronounced at month and quarter ends than on ordinary days. In a later report one year later they argue that the pattern has essentially disappeared to the point it provides no value, but the overall pattern of trading around the Fix has remained consistent.

3.1 Spot Rates

Our spot data include all the GBP/USD, AUD/USD and NZD/USD transactions that occurred from January 1, 2010 to December 31, 2013, on the electronic inter-dealer trading system called Reuters Dealing, one of the two dominant brokered trading platforms used in the inter-dealer spot foreign exchange market[9]. Thus the data contain no information on customer-dealer spot trades. The raw data come at the millisecond frequency, at GMT time and include a time stamp for every trade, the transaction price, the best bid and ask quote as well as the trade direction (i.e. a variable indicating whether the trade was a market buy or sell). Thus, for the spot foreign exchange market data, we do not need to make use of trade classification algorithms to assign trade direction. Information on traded quantities of individual transactions as well as the identity of individual market participants is not available. The lack of traded quantities is not expected to have a material effect on the empirical results. For evidence that the number of trades rather than the aggregate size of trades matters for prices and volatility and that trade size contains no information beyond that in the number of transactions see Jones et al. (1994), Fleming (2003) and Green (2004).

We choose a one minute sampling frequency and we aggregate the irregularly spaced raw data accordingly excluding the first and the last 30 seconds of each day of trading activity so as to exactly match the Fix calculation window (i.e., a one minute window from +/- 30 seconds either side of the specified

[9]Today, two electronic platforms process the vast majority of global inter-dealer spot trading in the major currency pairs, one offered by Reuters, and one offered by EBS. These platforms, which are both electronic limit order books, have become essential utilities for the foreign exchange market. The BIS reported that in 2000, between 85 and 95% of all interbank trading took place using electronic brokers, increasing from about 50% in 1998 and 20-30% in 1995 (Bank for International Settlements, 2001, 71st annual report, section 5, 'Foreign exchange markets'.). Importantly, trading in each major currency pair has over time become very highly concentrated on only one of the two systems. The decision by an FX trader whether to use EBS or Thomson Reuters is driven largely by currency pair. In practice, EBS is the primary trading venue for EUR/USD, USD/JPY, EUR/JPY, USD/CHF, EUR/CHF and USD/CNH, and Thomson Reuters is the primary trading venue for commonwealth (GBP/USD, AUD/USD, NZD/USD, USD/CAD) and emerging market currency pairs.

fix time, i.e. London 4 p.m. The Fix minute is calculated from 15:59:30 until 16:00:30)[10]. Thus, we construct 1,439 equally spaced 1-minute intervals of trading activity per trading day. For each minute of trading activity, we record the last price (transaction, bid and ask) and we calculate the mean price, the bid-ask spread, the midpoint, absolute return and the number of trades (number of buys and number of sells) from which order flow and absolute order flow is calculated.

Certain sparse trading periods are also removed from the sample. These include weekends and some public holidays where trading activity is found to be very thin. Weekends are defined as from Friday 21:00 GMT to Sunday 21:00 GMT and all trading activity during these hours is removed. Public holidays include Christmas, New Year, Easter (Good Friday and Easter Monday). We also drop certain days of light activity, such as December 24 and December 26, January 31 and January 2. All other trading days with no activity were also removed from the sample.

3.2 Futures Rates

The futures dataset contains trade as well as quote level information, where a new entry is included in the data every time there is either a trade or a change in the front end of the limit order book, i.e. if there is a change in the best bid or ask price, or if the quantities available at these prices are altered. So, our futures data cover both trading and quoting activity on GBP/USD, AUD/USD and NZD/USD futures rates listed on the Chicago Mercantile Exchange (CME). All trades and quotes were collected from the Thomson Reuters Tick History (TRTH) database. Again, the data cover the period from January 1, 2010 to December 31, 2013. The futures contracts used are those with the nearest maturity. Each contract has a monetary value of 100,000 US dollars. The raw data come at the millisecond frequency, at GMT time and include a time stamp for every quote or trade, the transaction price and volume of contracts traded and the new bid or new ask price and number of contracts offered at each new quote. For consistency reasons in relation to

[10]For a detailed description of Fix calculation methodology, please refer to Appendix A.

the spot data, we do not take into consideration traded quantities of futures transactions. No information is provided on the trade type (i.e. there is no variable indicating whether the trades was a market buy or sell). The data contains no information on the identity of individual market participants.

In order to sign futures trades we use the Lee and Ready (1991) algorithm. The Lee and Ready (1991) algorithm classifies a trade as buyer- (seller-) initiated if it above (below) the prevailing quote midpoint. If the trade is exactly at the midpoint of the quote, the trade is classified as buyer- (seller-) initiated if the last price change prior to the trade is positive (negative). Of course, there is inevitably some assignment error, so the resulting order imbalances are imperfect estimates. We are able to sign 99.64% of all trades in our final futures rates sample. All unclassified trades, are excluded. We also drop from our sample trades with no trading quantity. Futures data are aggregated in exactly the same manner as spot data were aggregated.

During the one-minute Fix calculation window a significantly larger number of trades is taking place as compared to all other trading minutes. Due to speed in trading there is the risk that trades are not recorded in a sequential manner. The higher trading activity and the speed in trading, the higher the probability that some error will be committed in reporting transaction data. In order to test for the accuracy of our trade direction / classification algorithm, we apply our algorithm for the futures data to spot data during the Fix minute and check whether the algorithm has correctly classified the trades. No significant discrepancies were identified.

3.3 Variables

The main variables used are measured as follows:

Exchange Rate Returns: The exchange rate returns are defined as 100 times the logarithmic change in the last transaction price between minute m and minute $m-1$ on day t. Overnight returns are removed from the sample, as they are not comparable to our one-minute sampling frequency. Overnight returns affect return distributions and removing overnight returns is enough to remove fatter tails in return distributions. Spot returns are denoted by ΔS_t and futures returns are denoted by ΔF_t.

Order Flow: Due to the non-availability of traded quantities for spot rates, the order flow measure is calculated as simply the difference between the number of buyer-initiated inter-dealer trades and seller-initiated inter-dealer trades in an interval (e.g. one-minute in our case). If the aggressive dealer buys (sells) dollars, then order flow from that trade is +1(-1). For example, if a dealer initiates a trade against another dealer's GBP/USD quote and the trade is a dollar purchase (sale), then order flow is +1 (-1). These unit order flow values are cumulated over each minute of trading activity. Thus our data allow us to distinguish between periods when no trades are executed and periods when trades are executed but order flow aggregates to zero. Order flow is a measure of net buying pressure (a negative sign denotes net dollar sales) and spot inter-dealer order flow is denoted by X_t^S and futures inter-dealer order flow is denoted by X_t^F. Note that interbank order flows are primarily assumed to reflect the risk management activities of the banks in the network as they respond to their end-user customer order flows. Absolute order flow is just the absolute value of our order flow measure.

Basis: The basis is defined as the difference between the spot rate and the futures contract rate. It is denoted by $Basis_t$ and calculated as $Basis_t = log(S_t) - log(F_t)$. More broadly speaking, the basis is the market risk related to differences in the market performance of two similar positions. The more the instrument to be hedged and the underlying used are imperfect substitutes, the larger the basis risk is.

Volatility: We use intra-minute absolute return as a proxy for volatility. More specifically, we estimate minutely volatility as the absolute intra-minutely log return on each minute m for any given day. Given the presence of market frictions, standard realized volatility is inappropriate (Aït-Sahalia et al. (2005)). In order also to minimize the impact of outlier returns, we use absolute returns as a proxy for volatility.

3.4 Basis & Cross-Market Regressions

Although foreign exchange markets operate on a 24-hour basis, trading activity is concentrated around normal European and U.S. banking hours for most currency pairs. Given also that the focus of our study is trading activity in London, we concentrate our analysis on London trading hours and thus we restrict our sample to London trading hours, i.e. from 08:00 to 17:00 London time. Since both our raw data, i.e. both spot and futures data, come at GMT time we have to account for differences for British Summer Time (BST). So during BST, we move all GMT observations 1-hour ahead.

For the cross-market regressions and the calculation of the basis, where the prices in the two markets are determined jointly, only the periods where no breakdowns in any of the two exchange rate data feeds are considered (1,034 common trading days, 7 days were omitted).

We also split the dataset into two subsets, the first running from January 01, 2010 to March 31, 2013 and the second covering the period of June 01, 2013 until December 31, 2013. We conducted our analysis for the full sample as well as separately on both sets of data. This was done because in June 2013 the Fix attracted a lot of media attention[11], which may have led to a potential change in the behaviour of dealers. The dataset contains approximately three years and a half years of data before June 2013 and seven months afterwards. Since our results for the full sample are not materially different to our results from the two subsets and no additional important empirical findings emerged, these results are not reported.

3.5 Summary Statistics

We show summary statistics for the one-minute and daily returns, trades and order flow data of GBP/USD in Table 1 below. Summary statistics for AUD/USD and NZD/USD can be found in the Appendix D.

[11] Bloomberg (2013). For the time line of the Fix scandal, please refer to Appendix A.

Table 1: Summary Statistics for Spot and Futures GBP/USD.

	Spot Data			**Futures Data**		
	Trades	**Flows**	**Returns**	**Trades**	**Flows**	**Returns**
Panel A: Minute (obs: 558,360)						
Mean	12.005	-0.010	1.05×10^{-5}	85.196	-0.141	7.6×10^{-6}
Median	8.000	0.000	0.000	54.000	0.000	0.000
Maximum	718.000	171.000	0.774	3,689.000	975.000	0.753
Minimum	0.000	-142.000	-1.093	0.000	-1,432.000	-1.074
Std.Dev.	16.382	5.940	0.021	107.144	29.311	0.023
Q(5)	3,515.867	2,983.541	734.804	4,904.481	7,745.701	7,680.053
ADF	-327.834	-706.639	-771.063	-301.299	-678.063	-837.964
AR(1)	0.504	0.056	-0.031	0.543	0.097	-0.114
Panel B: Daily (obs: 1,034)						
Mean	6,482	-5.149	1.05×10^{-5}	46,005	-76.105	7.7×10^{-6}
Median	6,341	0.000	3.04×10^{-5}	45,912	-78.500	3.5×10^{-5}
Maximum	18,341	768.000	2.7×10^{-3}	141,379	3,802.000	2.7×2.7^{-3}
Minimum	661	-758.000	-3.0×10^{-3}	176	-3,326.000	-3.0×10^{-3}
Std.Dev.	2,313	222.244	8.1×10^{-3}	16,844	1,075.749	8.1×10^{-4}
Q(5)	948.585	28.280	15.976	482.517	135.700	15.955
ADF	-5.497	-28.490	-31.527	-5.843	-26.672	-31.680
AR(1)	0.506	0.119	0.018	0.458	0.180	0.014

This table presents summary statistics for trades, order flow and returns for both the spot and futures market for the GBP/USD currency pair. Full period statistics are calculated over the period January 2010 to December 2013. Number of observations correspond to each market separately. Q(5) denotes the Ljung-Box Q-test statistic for the first five serial correlations of returns. Under the null hypothesis of no serial correlation, the LBQ statistic is asymptotically distributed as $\chi^2(5)$. ADF denotes an Augmented Dickey-Fuller test for non-stationarity in each series.

In terms of the number of trades per day, we observe many more in the futures market that spot market. This difference seems contradictory given the relatively small size of the currency futures market compared to the spot market. Note, however that trading on Reuters platform is only a fraction of total interdealer spot trading as well as that the mean trade size is different. Each futures contract has a monetary value of 100,000 US dollars whereas that of the spot contract is 1,000,000 US dollars. Returns and order flow are serially correlated, which is consistent with some informed trading models. For example, Easley and O'Hara (1987) model a situation where sequences of large purchases (sales) arise when insiders with positive (negative) signals are present in the market. The positive serial correlation in order flow is also consistent with strategic order splitting, i.e. a trader willing to buy for informational or non-informational reasons and splitting his order to reduce market impact.

3.6 Data Considerations

One empirical limitation of our methodology is related to the use of Lee-Ready algorithm to sign trades in futures markets and thus measure order flow. As explained earlier, this error could possible lead to regression coefficient bias. Another possible potential issue is related to the nature of high-frequency data. High-frequency data are likely to contain outliers possibly posted by a dealer in error or simply to withdraw, perhaps temporarily, from the market (so-called stub quotes). Classic OLS estimates may be adversely affected by these atypical observations. One solution to this issue would be to remove outliers from the sample. To the extent that we have no reason to believe that those transactions did not actually occur, deletion of outliers based on some arbitrary condition or based on algorithms (e.g. as that proposed by Brownlees and Gallo (2006)), has the risk of removing legitimate transaction data. Finally, due to the sheer quantity of data there is the possibility that within a time-stamp more that one trades or quotes may be recorded at the same or different price. Given that the modeling of high-frequency data requires one observation per time stamp, we checked for this possibility but no such cases were identified, possibly because traders operate on a millisecond time scale.

4 Empirical Approach & Results

The existing literature related to the Fix focuses exclusively on describing price dynamics around the Fix and does not take into consideration order flow. Although the FX market is extensively studied, it is surprising that it's most important institutional characteristic has not yet received the required attention. As Melvin and Prins (2015) and Osler and Turnbull (2016) point out, "price dynamics around fixes are not well accounted for in existing microstructure models". Our paper contributes towards this end by extending the analysis in the literature as it looks at inter-dealer order flow behavior around the Fix and thus contributes towards a better understanding of FX market dynamics around fixes for both the spot and futures markets.

In this section we describe our empirical approach and we present our results. Our empirical approach is based on three distinct steps. The first one is intraday graphical analysis, the second one regression analysis and the last one is based on comparing the observed price-flow patterns around the Fix with those observed at other intraday points. The steps in each part of the analysis are described below.

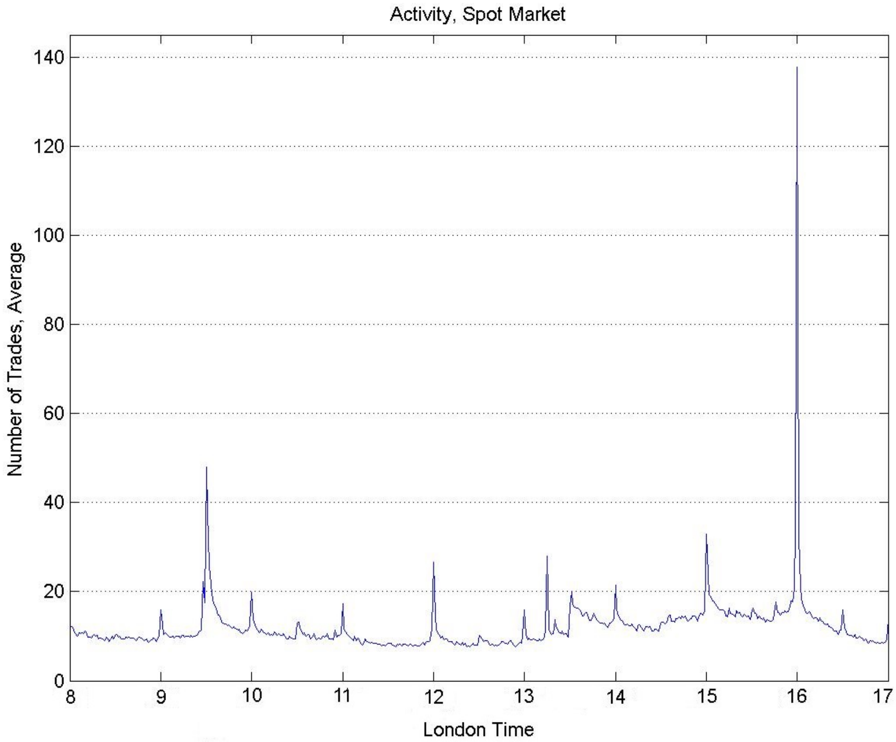
4.1 Graphical Analysis

The objective of this section is to increase our understanding of the average behaviour of spot and futures exchange rates and of trading behaviour around the Fix and to put this in the context of the observed behaviour over the rest of the trading day.

4.1.1 Activity

Currency benchmarks play an important role for a variety of transactions in financial markets. From a theoretical perspective, the introduction of a benchmark in a market reduces the information asymmetry regarding the value of the traded assets and attracts trades as investors are looking to materialize the information and liquidity related benefits. Therefore, we could expect a concentration of trading activity during fixing periods. Figures 1 and 2 below depict intraday activity levels for the spot and futures markets respectively, as measured by the average number of trades executed per minute over the full sample period during London trading hours. Note that trading activity is considered as an indirect measure of liquidity. According to Amihud and Mendelson (1986), in equilibrium liquid assets should be held by investors with short investment horizons and, therefore, exhibit a higher trading activity. From Figure 1 below, it becomes apparent that we can immediately identify a significant spike in trading activity at exactly 4 pm London time and smaller spikes at the end of each hour. The number of trades at the Fix is approximately seven times the average number of trades during all over minutes of trading activity within the day.

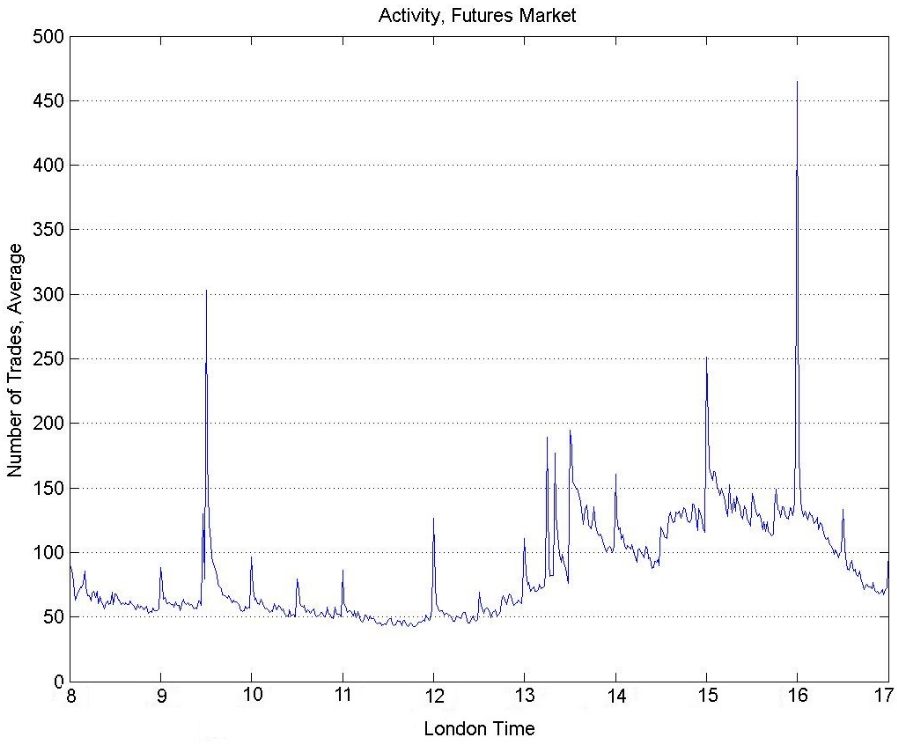
Figure 1: Spot Market Intraday Activity (1-minute average trades)



This pattern is in line with the results of the literature (see for example Melvin and Prins (2015)). The spikes at the end of each trading hour could possibly partly be attributed to trading concentration at fixing periods and partly due to effects from algorithmic trading. The point with the second highest number of trades during the day is at 9:30 am London time where major UK macroeconomic indicators are published. The third highest spike is at 3 pm London time and could be attributed to three factors: the option expiration time at 10 am Eastern Time (ET), the announcement of some U.S. macroeconomic indicators published at 10 am ET as well as to the fact that 3 pm is a fixing period. The fourth highest spike is observed at the ECB fixing time at 1:15 pm London time. In general over the day, trading activity rises when both London and New York are actively trading (the New York trading session begins at 8 am ET, i.e. 1 pm London time). The 1:30 pm London time spike in trading activity is caused by US news announcements as most important US macroeconomic releases come out at this time (8:30

am ET)[12].

Figure 2: Futures Market Intraday Activity (1-minute average trades)



Similar trading patterns are observed in the futures markets, as evident in Figure 2 above. Moreover, spikes associated with the Fix tend to be largest at month ends and quarter ends, likely reflecting portfolio rebalancing needs at those times, as documented by Melvin and Prins (2015) and Evans (2016).

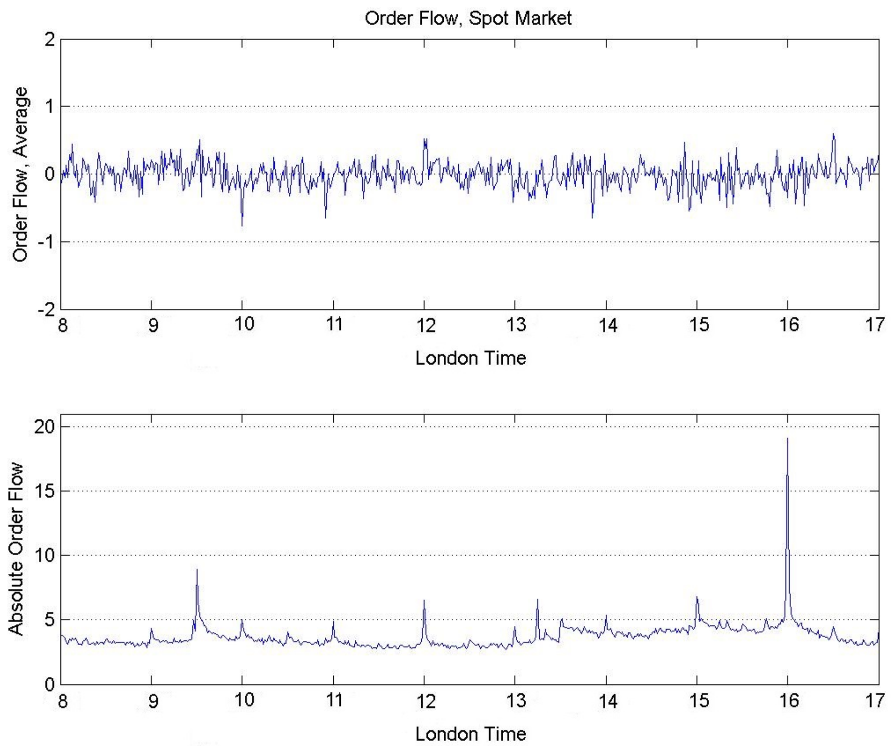
4.1.2 Order Flow

Given the decentralised structure of the foreign exchange market and the heterogeneity of market participants, the foreign exchange market is characterized by informational asymmetries and so dealers and market-makers gather

[12]Note that some US macroeconomic announcements are also published at 10 am ET, i.e. 3 am London time.

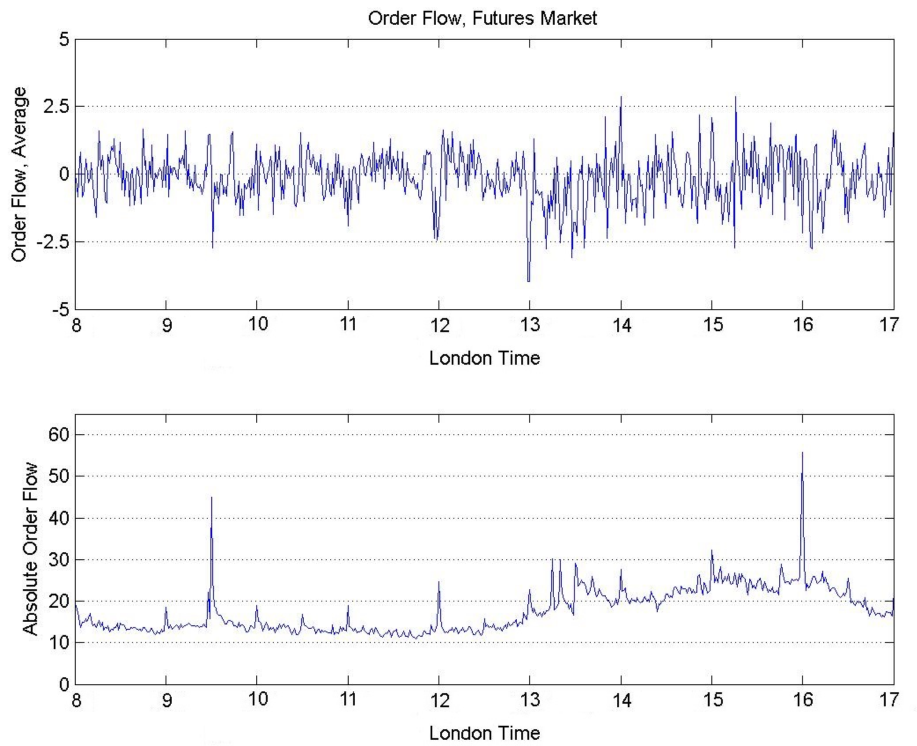
disperse and private information from the orders placed by their customers (Lyons (1997)). Thus, although Thompson Reuters database is mainly an interdealer trading platform, underlying retail (customer) order flow is a key driver of interdealer flow through "hot potato" trading after a customer trade. That is to say, when an FX dealer receives a customer trade he/she is on average expected to lay it off with other dealers through the interdealer market within a few minutes (Lyons (1997)). In our analysis, inter-bank order flow is measured as the difference between the number of buyer-initiated and seller-initiated trades over the one-minute interval and absolute order flow is just the absolute value of the order flow measure. On average, the size and direction of this order flow measure for both markets does not have an obvious predictable pattern and seems on average to converge to zero.

Figure 3: Spot Market Intraday Order Flow



Futures order flow is more volatile as compared to spot order flow. This could potentially be explained by the use of the Lee-Ready algorithm to sign futures trades and some bias is introduced. However, when considering absolute order flow, there seems to be a significantly larger order flow, positive or negative, during the Fix than at any other period of the day, including the time of the release of UK macroeconomic indicators and the North America options expiration period.

Figure 4: Futures Market Intraday Order Flow

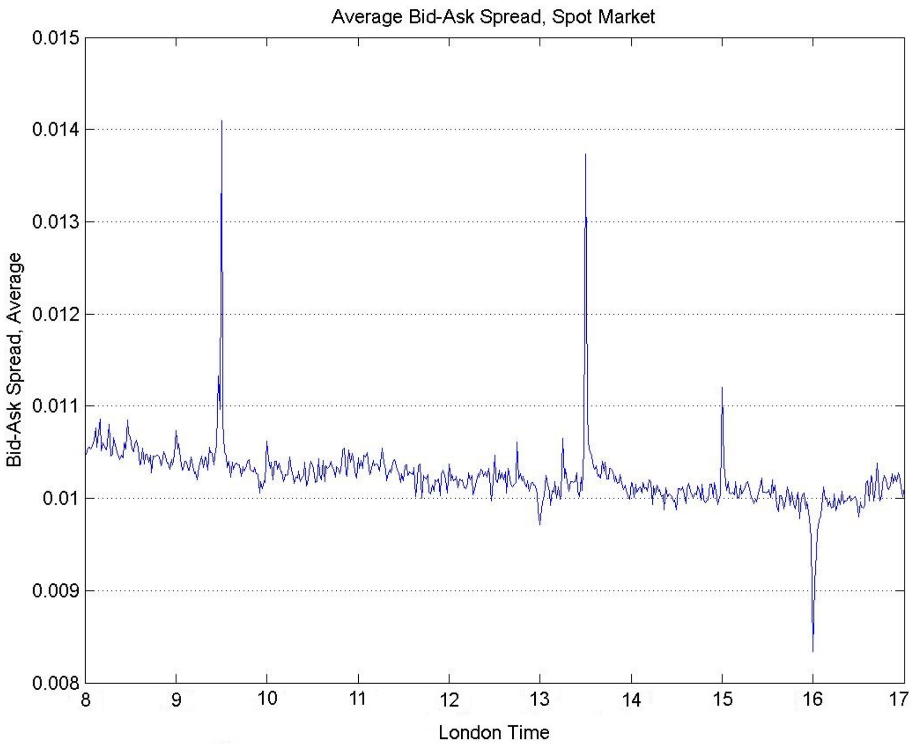


From our graphical analysis, it seems that spot and futures absolute order flow may be correlated ($\rho = 0.38$). This potentially raises the question of whether the spot and the futures order flow contain the same information or not, as all price discovery in the foreign exchange market may take place in the spot market and the futures market just responds to the spot market.

4.1.3 Liquidity

Usually high levels of activity in the currency markets are perceived to go hand-in-hand with ample liquidity. Spreads tend to increase with volume at constant volatility (Glassman (1987)). Liquidity in a currency pair is often referred to as a measure of whether an order can be executed quickly with limited price impact and low transaction costs. It is difficult, however, to find a precise measure of liquidity. In the microstructure literature, as well as in our analysis, the spread between bid and ask prices as a percentage of the midprice is a widely used measure of transaction costs and of market liquidity. In liquid financial markets bid-ask spreads should be lower than in rather illiquid markets, i.e. a lower spread indicates better liquidity. Note also that modelling the bid-ask spread is not an easy task as a large number of institutional details have to be taken under consideration. Figures 5 and 6 depict average intraday spreads for the spot and futures markets respectively per minute of trading activity over the full sample period during London trading hours.

Figure 5: Spot Market Intraday Spread (measured in bps)



For the spot market, the bid-ask spread remains relatively stable on average throughout the day with the notable exception of four specific points in time: 9:30 pm, 1:30 am, 3 pm and 4 pm London time. At 9:30 pm, 1:30 am and 3 pm London time, the average spread per minute tends to spike upwards, whereas at 4 pm London time tends to spike downwards. Interestingly, no other downward spike of the average spread is observed during the trading apart from the one observed at the 4 pm Fix. The common feature of the first three points is the release of new information: at 9:30 UK macroeconomic indicators are published, at 1:30 am there is the opening of the NY trading session where new expectations from market participants manifest and at 3 pm there is the option expiration period. Note also that the publication of some U.S. macroecnomic indicators is taking place at 1:30 am and 3 pm London time. At these points, significant market activity is concentrated and the new information is incorporated into prices. At this point, based on the information cost model of the bid-ask spread developed by Glosten and Milgrom (1985), we have two forces in action. On one hand, we have liquidity motivated traders[13], who are willing to pay to the market maker the spread in exchange for speedy trade execution and on the other hand we have informed investors who can speculate at the expense of the market maker due to a superior information set. In this framework, if market makers cannot easily distinguish between liquidity traders and informed traders and perceive the large trading activity to be positively correlated with the probability of getting into a trade with a better informed counterpart, the larger number of trades increases their expected costs of making the market, are thus induced to widen spreads for both categories of market participants to protect themselves[14]. Thus, at these points, as new information is released into the market and incorporated into prices, probably market makers attempt to protect themselves and as a result they increase the spread. However, despite the huge concentration of trades at the Fix, spreads tend to reduce significantly. This specific behaviour of the spread at the Fix could potentially be explained by the uninformative nature of fill-at-fix orders and the competition among market makers. In short, as

[13]Liquidity traders can be thought of as market participants who need to buy or sell foreign exchange in response to international trade in goods and services and who do not speculate or hedge their exposure in any way.

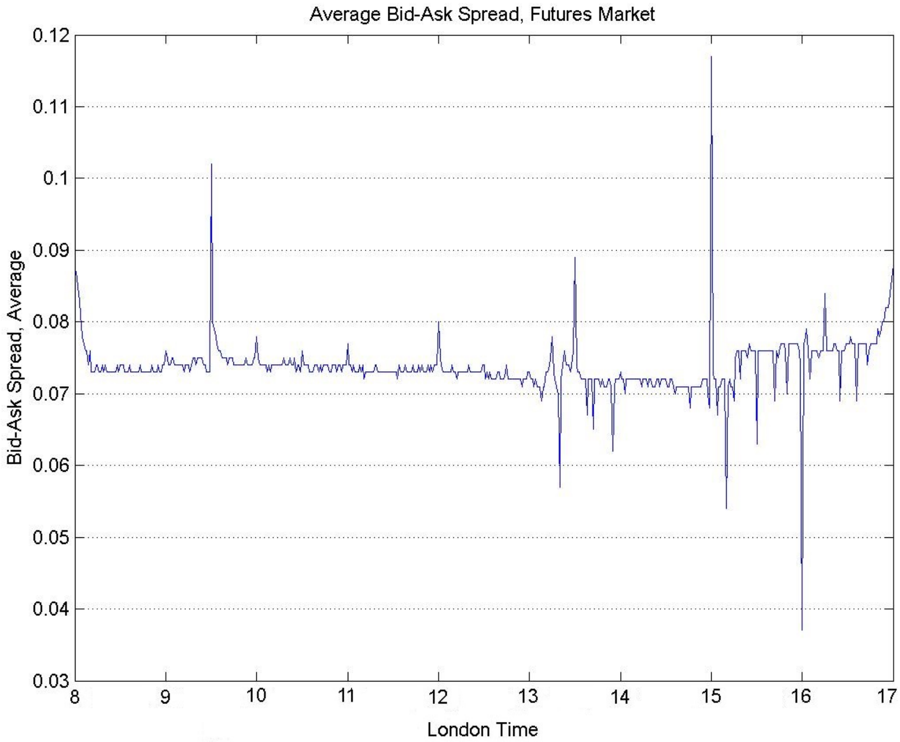
[14]Widening the spread will protect the market maker as it may deter some of the informed traders to transact with the market maker or allows market makers to increase their earnings from liquidity motivated traders.

explained in the introductory section of this study, fund managers tend to trade at the Fix in order to minimize tracking-errors and corporate market participants tend to trade at the Fix as they can reliably verify the broker's claim of good trade execution as well as because it reduces search costs and increases matching efficiency. These fill-at-fix orders will be executed at 4 pm at a price that is unknown at the time of their submission. Thus their information content should be limited and any information conveyed by these customer trades is aggregated through inter-dealer order flow. In our regression analysis section, we examine how informative order flow is at the Fix. At the same time, due to the high concentration of trades there is also competition among market makers to attract trades and these predictable patterns in rate behaviour may also allow market makers to trade more profitably despite higher volatility. So, due to lower search costs, increased matching efficiency, increased participation by less-informed market participants and the competition among market makers, profit margins will tend to reduce. This disadvantage for market makers could potentially be offset through increased number of trades.

In futures markets, we observe a relatively different pattern for the average bid-ask spread as to the one observed in the spot market. On average, the spread in the futures markets is lower as compared to the spread in the spot market. Additionally, spreads are slightly higher during the opening and closing periods of the trading session. Usually, currency futures traders tend to square up or close any open positions at the end of each trading day to limit their overnight exposure or for margin requirement reasons. Spreads tend to spike at the same points in time as in the spot market, but the major upward spike in the futures markets is during the 3 pm Fix (most probably associated with the 10 am ET option expiration cut-off point[15] and the U.S. macro news release at 3 pm London time (10 ET)). The average spread tends to reduce at the Fix, but this reduction in the spread is not unique as it is

[15]Although the foreign exchange market operates on a 24/7 basis, market participants require a specified opening and closing to each trading day in order to record trades and define settlement periods. Currency options are typically set to expire either at the Tokyo expiry (3 pm Tokyo time) or the New York (10 am ET). The New York option expiry is considered to be the most important one, as it captures both European and North American option market interest.

Figure 6: Futures Market Intraday Spread (measured in bps)



in the spot market. Finally, there is higher variability of the spread in the futures markets as compared to the variability of the average spread in the spot market.

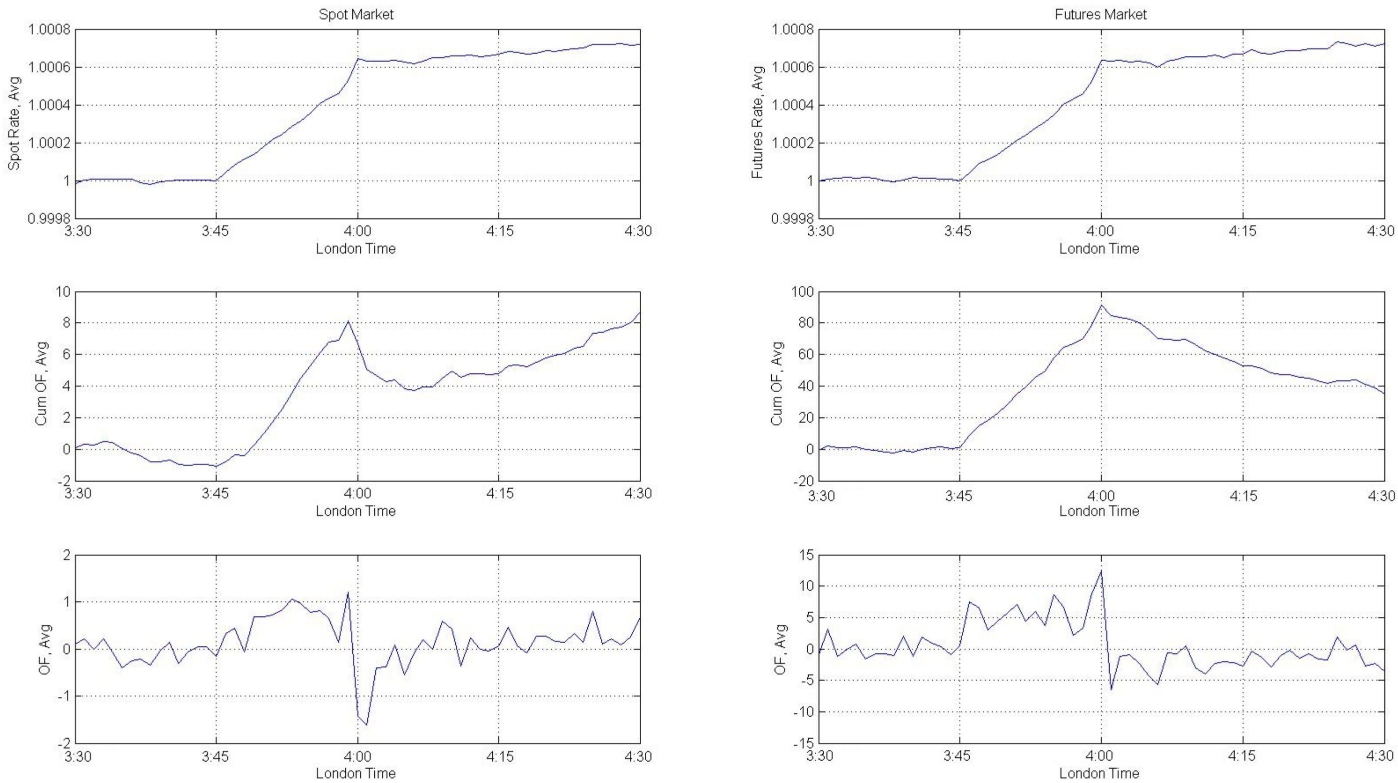
4.1.4 Price-Flow Dynamics

In order to better understand the behavior of spot prices around the Fix, we first plot the average price path for the spot rate around the Fix conditioned on the pre-Fix price change. We plot the average paths for the USD/GBP spot rate during 30 minutes before and after the 4:00 pm Fix[16]. The black

[16]The USD/GBP spot and futures rates plotted correspond to the price of the last trade of every minute of trading activity. We restricted our analysis to 30 minutes before and after the Fix because based on market practices, fill-at-fix orders must be submitted to dealer banks before the 3:45 pm.

line plot the average level of spot rates measured in basis points relative to their level at 3:45 pm (i.e., the series are indexed to 100 at 3:45 pm) for all trading days included in our sample. We do not distinguish between intra-month and end-of-month trading days. Thus, the vertical axis shows basis points relative to the price at 3:45 pm while the horizontal axis shows minutes before and after the Fix. The upper branch of the graph exhibits the average spot and futures rate levels respectively on those days when rates rose in the 15 minutes before the Fix. Similar graphs for spot rates can also be found in Evans (2016) and Osler and Turnbull (2016).

Figure 7: Price-Flow Dynamics around the Fix.
(Full Sample Period, Positive Spot Price Movement before the Fix.



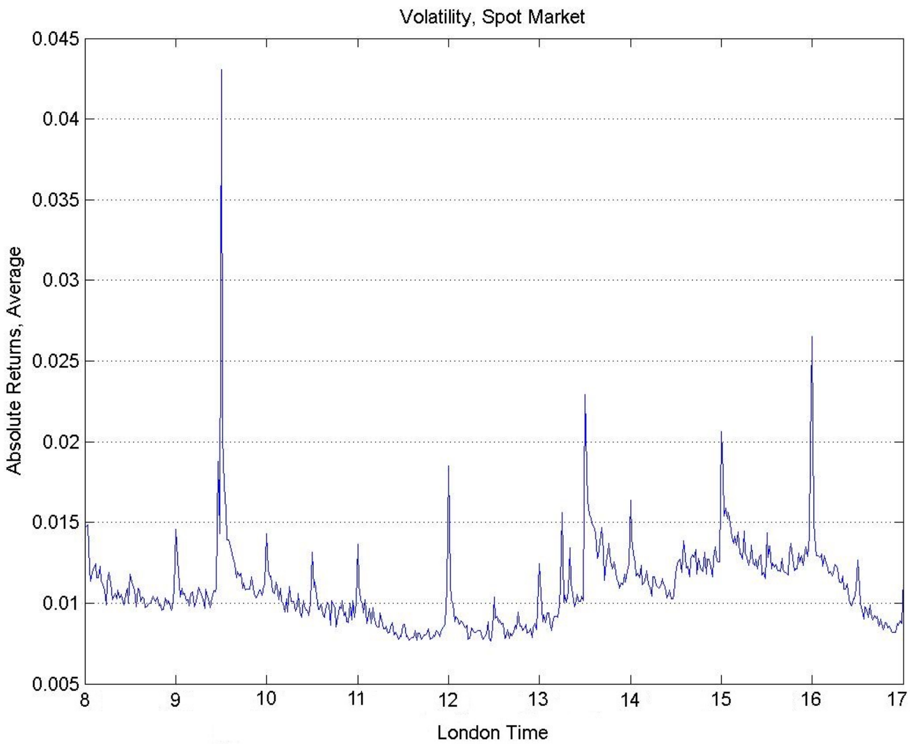
We extend the analysis of Evans (2016) and Osler and Turnbull (2016) by also considering the behavior of inter-dealer order flows around the Fix and by simultaneously examining price and flows in the futures market. For those days for which spot rates rose in the 15 minutes before the Fix, we plot in a similar manner, as described above, spot flows, futures rates and futures flows for the exact same days. We also plot for those days for which spot rates fell in the 15 minutes before the Fix (refer to Appendix C).

From the upper left graph of Figure 7 we see that there is a difference between the level of the Fix and the prior level of spot prices. Figure 7 shows that relative to the 3:45 pm rate level, the difference is roughly +6.5 basis points in average (we make no distinction between end-of-the month and intra-month days). Similar results are also reported by Evans (2016) and Osler and Turnbull (2016). This path identify very small reversals during the first minute after the Fix (on the order of half to one basis point). This pattern implies that all relevant information is fully incorporated into prices by the end of the Fix minute and thus there is no systematic tendency for rates to rise or fall after that minute. Since all customer orders must be submitted to dealer banks by 3:45 pm, this implies that inter-dealer order flow drives the price changes in the 15 minutes before the Fix. Average order flow turns positive in the 15 minutes interval before the Fix indicating buying pressure. This buying pressure may result from inventory adjustments and risk management operations of dealer banks in response to the fill-at-fix orders submitted by retail customers. Recall that the bank by agreeing to transact with the client, currency risk is transferred to the bank and spot desks guarantee their retail customers to deliver the amount of the currency pair agreed, no matter what the Fix price is. Average order flow reaches its highest point 1 to 3 minutes before the Fix, go to zero during the Fix window and then, on average, is equal to zero. This most probably implies that traders often do not begin to execute their fix-related trades until they are very close to the start of the one-minute calculation window and all inventory adjustments and risk management operations conclude just before the Fix window, likely reflecting the fact that dealers are trying to minimise their inventory price relative to the fixing price they guarantee their customers. According to the manipulation scandal, dealers during this period colluded and shared information regarding their order imbalances. This information sharing enables them to infer price direction in the 15 minutes period before the Fix. Assume a trader receives an order at 3:45 pm to buy 1 billion British pounds in exchange for US dollars at the 4 pm Fix. A trade of such a size most probably will drive the price upwards. The trader would have a strong incentive to buy from other market participants British pounds at a lower rate before the Fix and try to push the rate upwards so that at 4 pm he/she could sell the currency back to his/her client at a higher price. His/her profit will be equal to the difference between the reference rate and the average price he/she paid for buying British pounds before the Fix. Thus, this behaviour could explain the observed pattern in average order flow. Average cumulative order flow follows a similar path to that of the spot price. Symmetrical patterns are also observed for the days for which spot rates fell in the 15 minutes before the Fix with the rate reversal pattern in the one minute after the Fix to be more pronounced (refer to Appendix C). For exactly the same days for which the spot price rose relative to its 3:45 pm level, we plot the price-flow relation also for the futures market. The futures price exhibits a similar pattern to those of the spot price. Futures price tends to increase relative to the 3:45 pm minute and this difference is roughly +6.5 basis points in average. Futures average order flow turns positive during the 15 minutes prior the Fix, however, seems to spike at exactly the Fix minute and turn negative through the 30 minutes interval after the Fix. Despite futures order flow turning negative in the 30 minutes interval after the Fix, futures rate changes seem to remain relatively stable during the same interval. This pattern in the futures market is at odds with the behavior of the spot market and it is open to interpretation.

4.1.5 Volatility

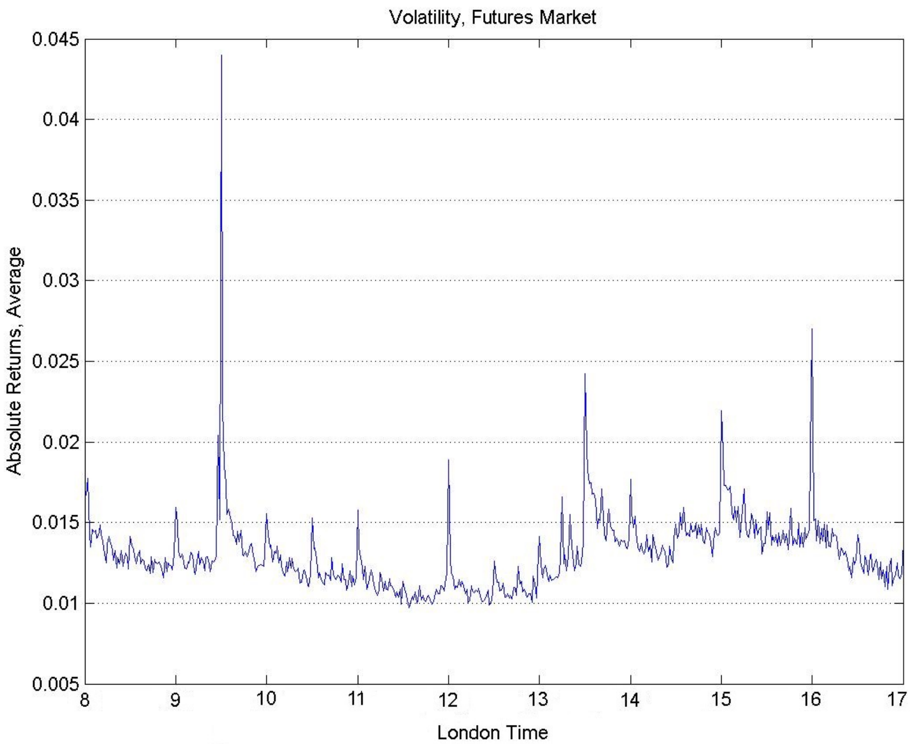
Foreign exchange market volatility has extensively been studied in the market microstructure literture. Studies from a number of different market settings and different frequencies document a time-varying positive relationship between volatility and volume (see Karpoff (1987)). The literature however does not provide a clear explanation of this relationship as it is not evident whether trading on private or public information is the underlying driving force of this empirical regularity. In our analysis, for the reasons explained in the data section, we use as a measure of volatility absolute price changes over the one-minute interval. Figures 8 and 9 depict the average absolute return per minute of trading activity during London trading hours. Our analysis shows that, on average over the days of our sample, the large spike in trading volume at the time of the Fix is not associated with a correspondingly large spike in volatility at that time. In fact, the highest average volatility experienced during the day in a one-minute interval is associated with the 09:30 am London local time where the release of UK macroeconomic indicators is taking place. The time of the Fix is associated with the second highest spike in average price volatility during the day. Average volatility during the Fix rises significantly relative to the minutes before and after the Fix, but the increase is not especially large, particularly when taking into account the high number of trades and the order flow at that time.

Figure 8: Spot Market Intraday Volatility



Notice, however, that average volatiliy increases after the opening of the NY trading session and as we get closer and closer to the Fix. The spike in average price volatility at the Fix is probably due in great part to the high market activity present at that time. Volatility seems to gradually increase in the minute before the Fix window and reaches its maximum value during the Fix window. Since banks do not know what the fixing price will be, they attempt to execute trades as close as possible to the price that will prevail at the Fix. Thus, this pattern could partially be explained by an optimal execution strategy aiming to come close to the Fix while possibly avoiding any potential high price impact that might come from trading large quantities in the 60 seconds window. Interestingly, while volatility increases in the build-up period to the Fix, spreads tighten rather than widen out and this behaviour could suggest that dealers either know where the market is going or that are so eager to close their positions that do not actually care about the cost.

Figure 9: Futures Market Intraday Volatility



This behaviour contrasts other periods of high volatility were spread widen. Such periods of high volatily are observed during the opening of the NY trading session, the 10 am ET option expiration cut-off point[17] as well as U.S. and UK macro news releases (1:30 pm (8:30 ET) and 3:00 pm (10:00 ET) for U.S. and 9:30 am London time for the U.K.). All these points in time are points were new public information is released or revealed in the marketplace. The observed pattern of the average intraday volatility of our analysis is in line with the results of the literature (see for example Michelberger and Witte (2016)). In the futures market, average price volatility behaves in a very similar way to the behaviour of average price volatility in the spot market. However, the average price volatility per minute in futures markets is slightly larger as compared to that of the spot market. Harvey and Huang (1991) investigate intraday volatility behaviour in the currency futures market and report evidence that the disclosure of private information through trading may partly explain the behaviour of volatility and that the increased volatility is more likely driven by macroeconomic news announcements.

4.2 Regression Analysis

In this part of our analysis, we attempt to quantify the returns-flows relationship as well as to capture effects and patterns which cannot be easily identified through graphical analysis.

4.2.1 Single Market Effects

In order to examine the relationship between rate changes and contemporaneous order flow, we start our analysis with the framework proposed by Evans and Lyons (2002). However, we drop the interest rate differential used by Evans and Lyons (2002) as we do not expect interest rate changes intraday. As interest rates do not change intraday, the interest rate differential is set equal to zero. Moreover, inventory-cost models generally assume that market makers optimise their holding inventory. Holding inventory may be

[17] When an option expires, the related option contract ceases to exist. Any hedging position in the spot market needs to be unwound, thus triggering price changes in the minutes leading up to and just after the option expiry time.

risky, because the holder is exposed to market movements in the value of the inventory. The desired (or optimal) level of inventory is zero or close to zero and thus dealers do not hold overnight positions (Bjønnes and Rime (2005)). Thus in our analysis, the generic order flow model is represented by the following equation for the spot market:

$$\Delta S_t = \alpha_1 + \beta_1 X_t^S + \epsilon_t \tag{1}$$

and

$$\Delta F_t = \alpha_2 + \beta_2 X_t^F + \upsilon_t \tag{2}$$

for the futures market, where ΔS_t and ΔF_t are the minutely log change in spot and futures rates respectively, X_t^S and X_t^F are the total net inter-dealer order flow for the spot and futures market respectively, and ϵ_t, υ_t are white-noise error terms[18]. We expect β_1 and β_2, the coefficients of contemporaneous order flow, to be positive and significant. If this proves to be the case, we say that the purchase of USD by dealer banks results in a depreciation of the GBP (increase in the exchange rate versus the US Dollar). This refers to the null hypothesis of the order flow concept which states that information from order flow causes exchange rate changes i.e. the higher the order flow is, the higher the rate change should be since positive order flow indicates buying pressure leading to rate increases. This impact can be explained via the information discovery process of the dealer, who updates his/her quotes after receiving orders from clients and other dealers. We estimate equations (1) and (2) using classic OLS, and we also apply the Newey-West procedure which results in standard errors that are consistent in the presence of both serial correlation and heteroskedasticity (max 5 lags). The results for that set of regressions are reported in Table 2.

Coefficient estimates for both β_1 and β_2 are positive and statistically significant, as expected, for the full sample for both markets. This result suggests that contemporaneous inter-dealer order flow of signed trades has explanatory power over price changes, i.e. flows contain information for both the spot and futures market.

[18] Even though the generic model of Evans and Lyons (2002) does not call for a constant term in the regression, we include one to check robustness.

Table 2: Generic Order Flow Model

	Spot Rates			**Futures Rates**		
	GBP	**AUD**	**NZD**	**GBP**	**AUD**	**NZD**
$\boldsymbol{X_t}$	0.1583***	0.1660***	0.3012***	0.0410***	0.0526***	0.1716***
	(134.91)	(202.80)	(125.78)	(110.03)	(132.22)	(105.38)
$\boldsymbol{R^2}$	0.21	0.27	0.10	0.28	0.17	0.09

Regression of minutely change in log exchange rates (both spot and futures) on total order flow over the full sample period as well as over the two sub-periods (equations (1) and (2)). All equations are estimated using OLS with Newey-West standard errors (max 5 lags). We multiply the order flow coefficients with 100, t-statistics are given in parentheses below coefficient estimates. To check robustness, we include a constant in the regression, even though the model does not call for one. The constant is insignificant. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Nevertheless, it is unlikely that this model will be successful at capturing the dynamics around the Fix. Therefore, in order to examine how informative is order flow for returns at the Fix, we extend the above model to include an interaction dummy variable at the Fix. The set of equations for the spot and futures market now becomes:

$$\Delta S_t = \alpha_1 + \beta_1 X_t^S + \gamma_1 X_t^S \times D_t + \epsilon_t \tag{3}$$

and

$$\Delta F_t = \alpha_2 + \beta_2 X_t^F + \gamma_2 X_t^F \times D_t + \upsilon_t \tag{4}$$

where D_t is an interaction dummy variable, assuming the value 1 at the Fix and 0 elsewhere.

We expect β_1 and β_2, the coefficients of order flow, to be positive and significant and the sum of coefficients $\beta_1 + \gamma_1$ and $\beta_2 + \gamma_2$ to be a measure of the price impact of inter-dealer order flow at the Fix for the spot and futures market respectively. However, we can only speculate about the sign of γ_1 and γ_2 coefficients. Conditional on the high trading volume concentrated at the Fix, one might suggest that the price impact of order flow should be larger since greater trading activity may be associated with the presence of more private information revealed through trading and which needs to be incorporated into the price. In this case, the coefficients γ_1 and γ_2 should be positive. On the other hand, the huge inter-dealer trading that is seen around the Fix largely results from fill-at-fix customer orders. Since these trades are relatively uninformative by definition, the price impact of any order flow should be small when volume is high and thus the coefficients γ_1 and γ_2 should be negative. Again, we estimate equations (3) and (4) using OLS and Newey-West standard errors. The results are reported in Table 3 below.

Table 3: Order Flow Model with an Interaction Dummy Variable at the Fix

	Spot Rates			**Futures Rates**		
	GBP	**AUD**	**NZD**	**GBP**	**AUD**	**NZD**
$\boldsymbol{X_t}$	0.1637***	0.1691***	0.3123***	0.0411***	0.0529***	0.1722***
	(145.30)	(214.36)	(137.89)	(108.84)	(131.47)	(107.21)
$\boldsymbol{X_t * D_{Fix}}$	−0.1559***	−0.1330***	−0.3342***	−0.0104***	−0.0186***	−0.0391**
	(-32.67)	(-23.99)	(-17.56)	(-7.14)	(-12.03)	(-2.11)
$\boldsymbol{R^2}$	0.22	0.28	0.10	0.28	0.17	0.09

Regression of minutely change in log exchange rates (both spot and futures) on total order flow and on a interaction dummy variable at the Fix over the full sample period (equations (3) and (4)). All equations are estimated using OLS with Newey-West standard errors (max 5 lags). We multiply the order flow coefficients with 100, t-statistics are given in parentheses below coefficient estimates. To check robustness, we include a constant in the regression, even though the model does not call for one. The constant is insignificant. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

As previously, coefficient estimates for order flow are positive and statistically significant for both markets. However, spot inter-dealer order flow seems to be completely uninformative at the Fix while on the contrary, futures order flow retains information content at Fix, although slightly smaller. Thus, spot order flow at the Fix might not be as informative as it might be during other time periods within the trading day. One possible explanation for this result is that fill-at-fix orders (which are not placed from customers during the build-up period to the Fix), might not be so informative for the currency's valuation, as they are to be filled at an unknown price and mainly stem from the need to minimize tracking error. This feature seems to be incorporated into inter-dealer order flows. Another potentially contributing factor could be dealers' execution strategy in trading small amounts so as to limit price impact and volatility. Such a strategy is also in line with the manipulation story as it would also allow dealers to move Fix rates to the favourable direction. As the benchmark rate calculation is based on the median of trades during the Fix window, placing a number of smaller trades could be more effective in driving the rate than one big deal, minimizing also price impact at the same time. On the other hand, futures order flow retains its information content at the Fix. This could suggest that futures traders are aware of the uninformative nature of trading at the Fix and spot trading at the Fix does not lead them to revise their valuations.

This result also implies that any informed trades at the Fix are swamped by uninformed trades. It is that large the size of uninformed order flow at the Fix that the price impact of any trade is minimal and so any private information contained in trades of informed traders is swamped by uninformed order flow. Thus, it is optimal for informed traders wishing to hide, to choose to trade at the Fix.

Motivated by the Fix manipulation story, we also examine for flows-based price reversals around the Fix. Our set of equations becomes:

$$\Delta S_t = \alpha_1 + \beta_1 X_t^S + \gamma_1 X_{t-1}^S + \delta_1 X_t^S \times D_t + \zeta_1 X_{t-1}^S \times D_{t-1} + \epsilon_t \quad (5)$$

and

$$\Delta F_t = \alpha_1 + \beta_1 X_t^F + \gamma_1 X_{t-1}^F + \delta_1 X_t^F \times D_t + \zeta_1 X_{t-1}^F \times D_{t-1} + \upsilon_t \quad (6)$$

where X_{t-1} is one-minute lagged order flow and D_t is an interaction dummy variable, assuming the value 1 at the Fix and 0 elsewhere. The results are reported in Table 4 below.

The lagged order flow effect exhibits a significantly negative effect on the current return after controlling for the contemporaneous order flow. This negative relation accounts for the fact that price changes caused by the history-dependent portion of the current order flow has partially been incorporated into prices in previous trading rounds. This effect is in line with the positive autocorrelation in our order flow measure. The coefficient ζ is negative and statistically significant and in conjunction with the sign of γ, this suggests that in one minute after the Fix, prices tend to move back to their original pre-Fix level to some extent.

Table 4: Returns Reversal at the Fix

	Spot Rates			**Futures Rates**		
	GBP	**AUD**	**NZD**	**GBP**	**AUD**	**NZD**
$\boldsymbol{X_t}$	0.1648^{***}	0.1707^{***}	0.3135^{***}	0.0416^{***}	0.0532^{***}	0.1722^{***}
	(145.54)	(217.14)	(137.93)	(113.82)	(135.22)	(107.39)
$\boldsymbol{X_{t-1}}$	-0.0149^{***}	-0.0191^{***}	-0.0189^{***}	-0.0050^{***}	-0.0049^{***}	-0.0062^{***}
	(-24.35)	(-35.19)	(-10.76)	(-31.18)	(-22.75)	(-6.09)
$\boldsymbol{X_t * D_{Fix}}$	-0.1568^{***}	-0.1349^{***}	-0.3350^{***}	-0.0108^{***}	-0.0186^{***}	-0.0386^{**}
	(-32.61)	(-24.21)	(-17.56)	(-7.45)	(-11.98)	(-2.10)
$\boldsymbol{X_{t-1} * D_{Fix-1}}$	-0.0369^{***}	-0.0390^{***}	-0.0068^{***}	-0.0030^{*}	-0.0155^{**}	0.1181^{***}
	(-4.36)	(-5.25)	(-2.45)	(-1.71)	(-2.10)	(4.10)
$\boldsymbol{R^2}$	0.22	0.28	0.10	0.28	0.17	0.09

Regression of minutely change in log exchange rates (both spot and futures) on total contemporaneous and lagged order flow and on a interaction dummy variable at the Fix and one-minute before the Fix, over the full sample period (equations (5) and (6)). All equations are estimated using OLS with Newey-West standard errors (max 5 lags). We multiply the order flow coefficients with 100, t-statistics are given in parentheses below coefficient estimates. To check robustness, we include a constant in the regression, even though the model does not call for one. The constant is insignificant. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

This result is in line with the reported by Evans (2016) significant and negative correlation between pre- and post-Fix price changes and evident in our graphical relationship between order-flow and prices around the Fix (Fig.7). However, temporal price reversal is statistically present but economically probably uninteresting as the size of the reversal, especially after controlling for transaction costs, may not be exploitable. Moreover, this result has been interpreted in the literature as indicative of price manipulation. An alternative explanation based on our zero price impact at the Fix result, may just be that the type of order flow at the Fix is different at that observed at other intraday points. At the Fix, we have a massive concentration of uninformed order flow coming from traders seeking transparency and liquidity and thus, in a sense, it is natural to observe a temporal reversion after the Fix as order flow is uninformative and probably no new information is incorporated into prices.

4.2.2 Price Impact around the Fix

Based on our results from estimating equations (3) and (4), we argued that spot order flow at the Fix might not be as informative as it might be during other time periods within the trading day. Given that fill-at-fix orders must be submitted by customers to the banks, up to 15 minutes before the fix, it is important to examine the price-order flow relationship to the build-up period to the Fix and examine how different this relation is as compared to the after the Fix period. In a sense, our approach could give us a fairly accurate description of price impacts around the Fix as well as whether these impacts, if any, persist or not after the Fix. If the effects of unexpected flows are persistent then that means that information is conveyed by order flow. On the other hand, if the effects are not persistent this could be attributed to a variety of liquidity effects (e.g. inventory management). To examine whether effects of order flow around the Fix are in a sense purely temporary or trades have a more persistent effect on prices, we run the following set of regressions:

$$\Delta S_t = \alpha_1 + \beta_1 X_t^S + \gamma_1 X_t^S \times D_{1-15min}^{Before} + \delta_1 X_t^S \times D_{1-15min}^{After} + \epsilon_t \qquad (7)$$

and

$$\Delta F_t = \alpha_2 + \beta_2 X_t^F + \gamma_2 X_t^F \times D_{1-15min}^{Before} + \delta_2 X_t^F \times D_{1-15min}^{After} + \upsilon_t \qquad (8)$$

where $D_{1-15min}^{Before}$ and $D_{1-15min}^{After}$ are dummies variables assuming the value 1 for the 15 minutes before the Fix and the 15 minutes after the Fix respectively and, zero elsewhere. We estimate our set of equations for the periods before and after the 4 pm Fix, for the full sample period using OLS and Newey-West standard errors. The results are reported in Table 5.

Based on our results, price impact for the spot market tends to converge to zero as closer we get to the Fix, becoming completely uninformative at the Fix, and gradually recovering after the Fix. However, the situation is different for the futures market. As we get closer to Fix, price impact reduces but it does not become uninformative at the Fix. That is, the price impact line around the Fix for the futures markets would like more flat as compared to that of the spot market.

For a higher level of detail, we further narrow down the 15-minutes time interval to 5-minutes time interval and we run the following set of regressions

Table 5: Price Impact Regression around the Fix

	Spot Rates			Futures Rates		
	GBP	**AUD**	**NZD**	**GBP**	**AUD**	**NZD**
$\boldsymbol{X_t}$	0.1656***	0.1709***	0.3134***	0.0419***	0.0540***	0.1735***
	(136.22)	(206.08)	(131.61)	(100.10)	(128.58)	(101.89)
$\boldsymbol{X_t * D_{Fix}}$	−0.1578***	−0.1347***	−0.3353***	−0.0112***	−0.0198***	−0.0403**
	(-32.89)	(-24.29)	(-17.64)	(-7.62)	(-12.68)	(-2.17)
$\boldsymbol{X_t * D^{BeforeFix}_{1min-15min}}$	−0.0225***	−0.0240***	−0.02624***	−0.0074***	−0.0135***	−0.0084**
	(-7.02)	(-7.52)	(-2.70)	(-7.64)	(-6.94)	(-2.56)
$\boldsymbol{X_t * D^{AfterFix}_{1min-15min}}$	−0.0215***	−0.0168***	0.0038**	−0.0085***	−0.0094***	−0.0192**
	(-6.37)	(-4.61)	(2.34)	(-7.73)	(-7.96)	(-2.21)
$\boldsymbol{R^2}$	0.22	0.28	0.10	0.28	0.17	0.09

Price impact regressions for the 15 minutes before and after the Fix (equations (7) and (8)). All equations are estimated using OLS with Newey-West standard errors (max 5 lags). We multiply the order flow coefficients with 100, t-statistics are given in parentheses below coefficient estimates. To check robustness, we include a constant in the regression, even though the model does not call for one. The constant is insignificant. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

for spot and futures returns:

$$\Delta S_t = \alpha_1 + \beta_1 X_t^S + \gamma_1 X_t^S \times D^{Before}_{1-5min} + \gamma_2 X_t^S \times D^{Before}_{6-10min} + \gamma_3 X_t^S \times D^{Before}_{11-15min} + \delta_1 X_t^S \times D^{After}_{1-5min} + \delta_2 X_t^S \times D^{After}_{6-10min} + \delta_3 X_t^S \times D^{After}_{11-15min} + \epsilon_t \tag{9}$$

and

$$\Delta F_t = \alpha_1 + \beta_1 X_t^F + \gamma_1 X_t^F \times D^{Before}_{1-5min} + \gamma_2 X_t^F \times D^{Before}_{6-10min} + \gamma_3 X_t^F \times D^{Before}_{11-15min} + \delta_1 X_t^F \times D^{After}_{1-5min} + \delta_2 X_t^F \times D^{After}_{6-10min} + \delta_3 X_t^F \times D^{After}_{11-15min} + \epsilon_t \tag{10}$$

The results are reported in Table 6 and the coefficients for the dummy variables are plotted in Figure 10 with a 95% confidence interval.

From our results from the 5-minute intervals price impact around the Fix, the pattern that emerges is similar to that observed for the 15-minutes interval for the spot market. However, for the futures markets price impact tends to increase after 3:45 pm, slightly decline at the Fix, bounce back immediately and thereafter steadily decline, as evident from Figure 10. This result could potentially be linked to the risk management operations of banks related to their risk exposure at the Fix.

Table 6: Price Impact Regression around the Fix

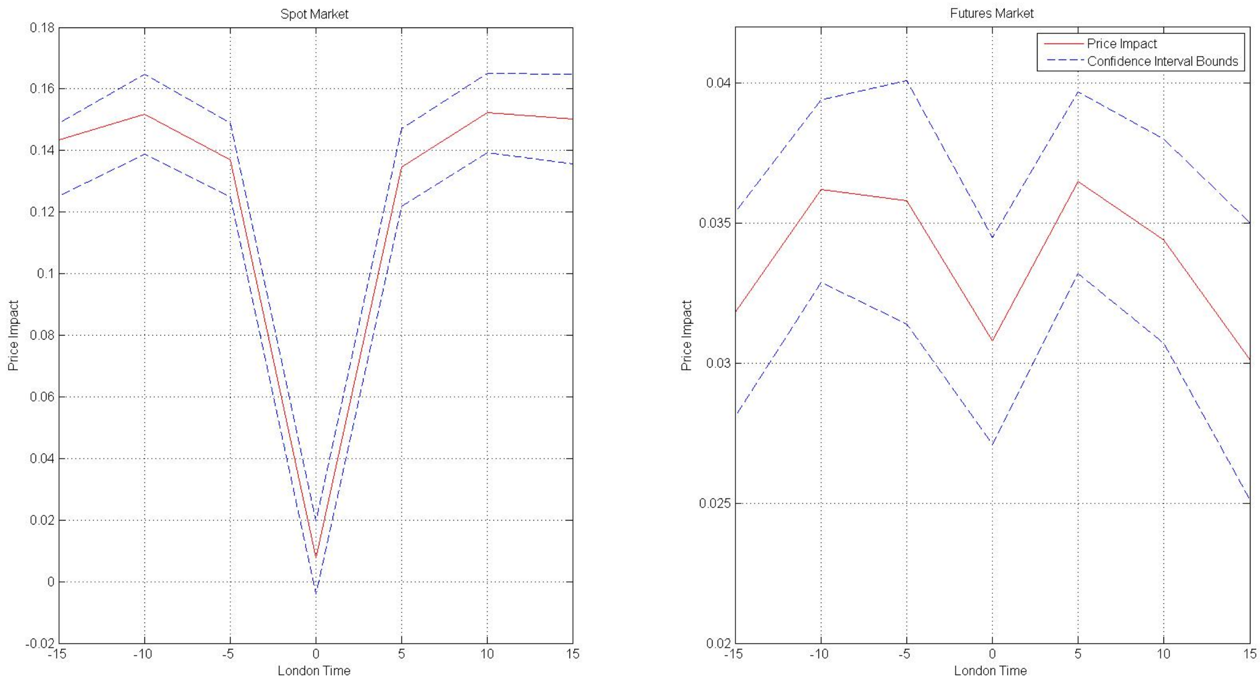
	Spot Rates			Futures Rates		
	GBP	**AUD**	**NZD**	**GBP**	**AUD**	**NZD**
$\boldsymbol{X_t}$	0.1656***	0.1709***	0.3134***	0.0419***	0.0540***	0.1735***
	(136.22)	(206.08)	(131.61)	(100.10)	(128.58)	(101.89)
$\boldsymbol{X_t * D_{Fix}}$	−0.1578***	−0.1347***	−0.3353***	−0.0112***	−0.0198***	−0.0403**
	(-32.89)	(-24.29)	(17.64)	(-7.62)	(-12.68)	(-2.17)
$\boldsymbol{X_t * D^{BeforeFix}_{1min-5min}}$	−0.0287***	−0.0318***	−0.0451***	−0.0062***	−0.0120***	-0.0078
	(-5.96)	(-6.41)	(-3.04)	(-3.42)	(-4.72)	(-0.92)
$\boldsymbol{X_t * D^{BeforeFix}_{6min-10min}}$	−0.0137**	−0.0153***	−0.0329**	−0.0058***	−0.0156***	-0.0074
	(-2.53)	(-2.98)	(-2.01)	(-4.63)	(-3.80)	(-0.90)
$\boldsymbol{X_t * D^{BeforeFix}_{11min-15min}}$	−0.0222***	−0.0208***	0.0097**	−0.0102***	−0.0129***	-0.0103
	(-4.06)	(-3.74)	(2.52)	(-7.12)	(-6.12)	(-1.01)
$\boldsymbol{X_t * D^{AfterFix}_{1min-5min}}$	−0.0311***	−0.0242***	0.0100**	−0.0055***	−0.0112***	-0.0033
	(-5.99)	(-6.02)	(2.58)	(-4.43)	(-5.79)	(-0.33)
$\boldsymbol{X_t * D^{AfterFix}_{6min-10min}}$	−0.0134**	−0.0065**	0.0282**	−0.0076***	−0.0073***	-0.0193
	(-2.53)	(-2.08)	(2.42)	(-5.19)	(-4.08)	(-1.07)
$\boldsymbol{X_t * D^{AfterFix}_{11min-15min}}$	−0.0155**	−0.0175**	−0.0292**	−0.0119***	−0.0095***	−0.0375*
	(-2.50)	(-1.98)	(-2.57)	(-5.65)	(-4.97)	(-2.48)
$\boldsymbol{R^2}$	0.22	0.28	0.10	0.28	0.17	0.09

Price impact regressions around the Fix (equations (9) and (10)). All equations are estimated using OLS with Newey-West standard errors (max 5 lags). We multiply the order flow coefficients with 100, t-statistics are given in parentheses below coefficient estimates. To check robustness, we include a constant in the regression, even though the model does not call for one. The constant is insignificant. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

However, these results gives rise to the question of how distinct or different is price impact around the Fix as compared to price impact throughout the remaining trading day. In order to address this question, we divide our sample into 30 minutes intervals and we regress, for each of those 30 minute intervals, the average contemporaneous order flow on average returns for both markets. Then, the estimated coefficients are plotted and thus we can have an indication of how price impact behaves, on average, for the entire trading day. The estimated parameter coefficients are plotted in Figure 11 below with a 95% confidence interval.

Based on the plotted price impact coefficients, it seems that price impact in the spot market significantly reduces during the 30 minute interval containing the 4 pm Fix. This is important as, on average, it is the only interval during the day where price impact reduces and provides further support for the unique features of the Fix. In the futures market, price impact seems to be relatively stable during the day.

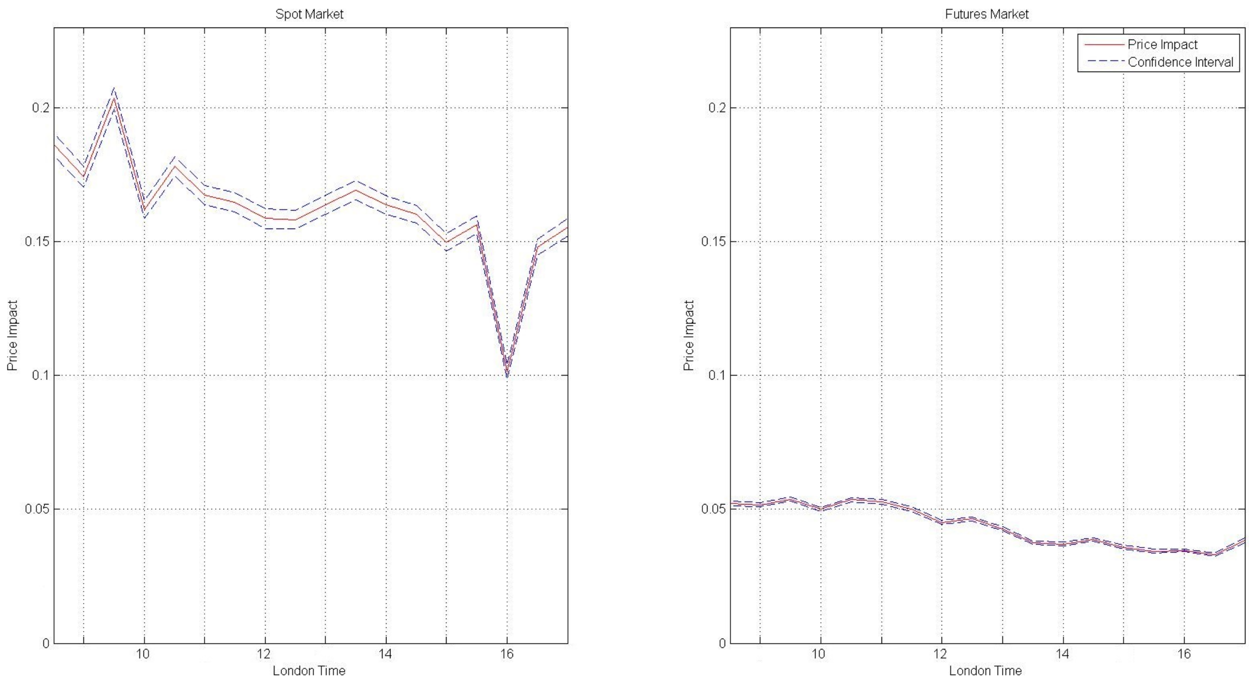
Figure 10: Price Impact around the Fix



4.2.3 Cross-Markets Effects

The vast majority of FX order flow research papers concentrates on one market at a time. However, since exchange rates are relative prices in the sense that they are prices for the same asset at different points in time and hence will be affected in very similar ways by given pieces of information. Given also that currency futures rates are contractually linked to the spot rate and given the manipulation story of the Fix, it is of interest to investigate how order flow in one market may be used to explain the returns in the other market. The reason for considering cross-market effects between the spot and the futures market, stems from the assumption that an informed trader in one of those markets may use his/her private information to devise profitable trading strategies to use in the other market. Private information could result from proprietary information about order flow or from superior analysis of the effects of public news announcements. Thus, observed order

Figure 11: Intraday Price Impact



flow by other market participants in one market may lead them to revise their expectations and so order flow in one market might drive rate changes in the other market. In this section of our analysis, we investigate the importance of the cross-market order flow in exchange rate determination, focusing on the information content of futures order flow and the role of the futures market in spot foreign exchange price discovery.

We follow Evans and Lyons (2002) order flow regression methodology as the basis for our analysis, and we incorporate cross-market effects by extending equations (1) and (2) to include order flow from both markets as follows:

$$\Delta S_t = \alpha_1 + \beta_1 X_t^S + \gamma_1 X_t^F + \epsilon_t \tag{11}$$

and

$$\Delta F_t = \alpha_2 + \beta_2 X_t^F + \gamma_2 X_t^S + \upsilon_t \tag{12}$$

Note that it is possible that price discovery in spot market occurs exclusively in the spot market and that futures prices quickly adjust to spot price changes through Covered Interest Parity (CIP) without adding significant information in the price determination process (Rosenberg and Traub (2009)). If this is the case, then there is no reason for futures order flow to be correlated with spot exchange rate returns, and we would not find a statistically significant relationship when we regress spot returns on futures order flow. Or, futures order flow could simply represent the same information as spot order flow. In that case, we would initially see a significant relationship between futures order flow and spot returns, but once we control for spot order flow, this relationship would disappear. In this case, coefficients γ_1 and γ_2 would be equal to zero. If we find a positive, statistically significant effect of futures order flow on spot exchange rate returns, this confirms that there is market-relevant information in futures order flow and more importantly, different information from that it is conveyed by spot inter-dealer order flow. As previously, we estimate equations (11) and (12) using OLS and Newey-West standard errors. The results are reported in Table 7 below.

Table 7: Cross-Market Order Flow Model

	Spot Rates			**Futures Rates**		
	GBP	**AUD**	**NZD**	**GBP**	**AUD**	**NZD**
$\boldsymbol{X_t^S}$	0.0994***	0.1097***	0.2548***	0.0905***	0.0963***	0.1944***
	(86.04)	(125.82)	(110.97)	(77.30)	(98.69)	(78.44)
$\boldsymbol{X_t^F}$	0.0317***	0.0356***	0.1154***	0.0341***	0.0395***	0.1538***
	(98.11)	(101.23)	(90.57)	(96.13)	(100.29)	(96.10)
$\boldsymbol{R^2}$	0.39	0.39	0.15	0.33	0.21	0.12

Regression of minutely change in log exchange rates (both spot and futures) on total spot and futures order flow over the full sample period (equations (11) and (12)). All equations are estimated using OLS with Newey-West standard errors (max 5 lags). We multiply the order flow coefficients with 100, t-statistics are given in parentheses below coefficient estimates. To check robustness, we include a constant in the regression, even though the model does not call for one. The constant is insignificant. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Coefficient estimates γ_1 and γ_2, are positive and statistically significant. This result suggests that futures order flow contains information that is relevant for spot determination and that it is different information from that conveyed by spot order flow. The reverse also seems to be true, i.e. spot order flow contains market-relevant information for futures rate determination. Adding order flow from the futures markets increases the fit significantly, R^2 is larger for both equations, as compared to equations (1) and (2).

Again, it is unlikely that this model will be successful at capturing the dynamics around the Fix. Therefore, in order to examine how informative is order flow for returns at the Fix across markets, we extend the above model to include an interaction dummy variable at the Fix. The set of equations for the spot and futures market now becomes:

$$\Delta S_t = \alpha_1 + \beta_1 X_t^S + \gamma_1 X_t^F + \delta_1 X_t^S \times D_t + \zeta_1 X_t^F \times D_t + \epsilon_t \tag{13}$$

and

$$\Delta F_t = \alpha_2 + \beta_2 X_t^S + \gamma_2 X_t^F + \delta_2 X_t^S \times D_t + \zeta_2 X_t^F \times D_t + \upsilon_t \tag{14}$$

where D_t is an interaction dummy variable, assuming the value 1 at the Fix and 0 elsewhere. We estimate this set of equations with OLS and Newey-West standard errors and the results are reported on Table 8.

In relation to the spot market, both spot and futures order flow is completely uninformative at the Fix, but futures order flow contains its information content. However, in relation to the futures market, spot order flow is uninformative at the Fix but futures order flow retains information content at the Fix, although somewhat smaller. Based on this result, we could argue that price discovery temporarily migrates from the spot to the futures market at the Fix. This result can be view more of as a spot phenomenon, just a time of day effect driven by the institutional set-up of the Fix.

Currency futures are most closely compared to outright FX forward transactions and are priced in accordance with so-called Cost-of-Carry hypothesis. The no-arbitrage condition for futures price states that every time that the relationship between spot and futures prices, given by equation

$$F_t = S_t \times e^{rT} \tag{15}$$

Table 8: Cross-Market Order Flow Model with an Interaction Dummy Variable at the Fix

	Spot Rates			Futures Rates		
	GBP	**AUD**	**NZD**	**GBP**	**AUD**	**NZD**
$\boldsymbol{X_t^S}$	0.1036***	0.1123***	0.2648***	0.0942***	0.0987***	0.2021***
	(89.91)	(131.12)	(120.03)	(80.01)	(101.73)	(82.97)
$\boldsymbol{D_{Fix}^S}$	−0.1052***	−0.1020***	−0.2832***	−0.0942***	−0.0929***	−0.2279***
	(-28.66)	(-20.46)	(-15.52)	(-25.35)	(-18.18)	(-12.21)
$\boldsymbol{X_t^F}$	0.0314***	0.0354***	0.1143***	0.0339***	0.0394***	0.1533***
	(96.62)	(100.29)	(91.00)	(94.62)	(99.22)	(96.97)
$\boldsymbol{D_{Fix}^F}$	-0.0008	-0.0003	0.0011	−0.0031**	−0.0058**	-0.0205
	(-0.56)	(-1.38)	(0.63)	(-2.16)	(-3.55)	(-1.10)
$\boldsymbol{R^2}$	0.39	0.39	0.15	0.33	0.21	0.12

Regression of minutely change in log exchange rates (both spot and futures) on total spot and futures order flow and an interaction dummy variable at the Fix over the full sample period (equations (13) and (14)). All equations are estimated using OLS with Newey-West standard errors (max 5 lags). We multiply the order flow coefficients with 100, t-statistics are given in parentheses below coefficient estimates. To check robustness, we include a constant in the regression, even though the model does not call for one. The constant is insignificant. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

does not hold, arbitrageurs should immediately exploit that to make a riskless profit and therefore to drag prices back towards the equilibrium values where r is a continuously compounded risk-free rate and T is the time period applicable to delivery of the futures contract[19]. In this sense, spot and futures prices are tied to a long-run equilibrium given by the Cost-of-Carry hypothesis. However, that theory does not take into consideration transaction costs[20] and other market frictions. For that reason, the relationship between spot and future prices can deviate from the theoretical equilibrium value. However, arbitrageurs monitor and promptly act upon situations where futures and spot prices are misaligned. The market mismatch between a position in the spot market and the corresponding futures contract is known as the *Basis* and it is defined as the difference between the spot rate and the futures

[19]Due to the nature of the FX market, dividends and storage costs are not applicable and thus we drop them from the Cost-of-Carry equation.

[20]Such costs may be largely captured by the market buying (ask) and selling (bid) quotes of interest rates and exchange rates. The spread between ask and bid quotes for an asset covers inventory, information and order processing costs associated with the trading of the asset.

contract rate. The Basis may be either positive or negative contingent upon the relationship between short-term interest rate differential. The closer we get towards the expiration date of the futures contract, the Basis should converge to zero. We plot the Basis for our full sample period (Appendix C).

Motivated by the Fix manipulation story, we further investigate whether there are any significant and atypical spikes in the Basis which may be suggestive of manipulation. Market forces arising from no-arbitrage conditions suggest that there should be an equilibrium relationship between the spot and futures prices. This implies that the two prices tend to converge in the long-run while any short-run adjustments are allowed. Given that spot price spikes at the Fix, any atypical spike of the Basis (potential driven by those spot price spikes at the Fix) could be suggestive of manipulation. Thus, we extend our cross-market order flow model (equations 13 and 14) by including the Basis as well as an interaction dummy variable of the Basis at the Fix. We also lagged spot and futures returns to control for the autocorrelation in returns. Our model is described by the following equations:

$$\begin{aligned}\Delta S_t &= \alpha_1 + \beta_1 X_t^S + \gamma_1 X_t^F + \delta_1 X_t^S \times D_t + \zeta_1 X_t^F \times D_t \\ &\quad + \eta_1 Basis_{t-1} + \kappa_1 Basis_{t-1} \times D_t + \lambda_1 \Delta S_{t-1} + \mu_1 \Delta F_{t-1} + \epsilon_t\end{aligned} \tag{16}$$

$$\begin{aligned}\Delta F_t &= \alpha_2 + \beta_2 X_t^S + \gamma_2 X_t^F + \delta_2 X_t^S \times D_t + \zeta_2 X_t^F \times D_t \\ &\quad + \eta_2 Basis_{t-1} + \kappa_2 Basis_{t-1} \times D_t + \lambda_2 \Delta S_{t-1} + \mu_2 \Delta F_{t-1} + \epsilon_t\end{aligned} \tag{17}$$

where $Basis_{t-1} = log(S_{t-1}) - log(F_{t-1})$ and ΔS_{t-1}, ΔF_{t-1} are the lagged spot and futures returns and can be seen as our co-integrating factor. The results are reported in Table 9.

Coefficients η and κ measure the magnitude of price adjustment given the price differential between spot and futures prices and help us assess which price series exerts a greater influence on the determination of prices. Consistent with the literature, we find that coefficients η_1 and η_2 are different from 1 for both markets and statistically significant. The GBP should on average appreciate next period to restore equilibrium when it is at a forward premium i.e., when $F_t > S_t$. The negative coefficient estimates of η_1 imply that the GBP actually tends to depreciate when it is at a forward premium.

Table 9: Cross-Market Order Flow Model with Basis

	Spot Rates			Futures Rates		
	GBP	**AUD**	**NZD**	**GBP**	**AUD**	**NZD**
X_t^S	0.1033^{***}	0.1134^{***}	0.2643^{***}	0.0947^{***}	0.1009^{***}	0.2038^{***}
	(90.17)	(132.49)	(120.26)	(81.00)	(104.30)	(84.84)
D_{Fix}^S	-0.1055^{***}	-0.1043^{***}	-0.2832^{***}	-0.0961^{***}	-0.0955^{***}	-0.2272^{***}
	(-28.93)	(-20.68)	(-15.48)	(-25.82)	(-18.73)	(-12.20)
X_t^F	0.0317^{***}	0.0359^{***}	0.1147^{***}	0.0341^{***}	0.0395^{***}	0.1519^{***}
	(97.79)	(100.60)	(91.32)	(96.10)	(99.71)	(94.77)
D_{Fix}^F	-0.0009	-0.0002	0.0107	-0.0033^{**}	-0.0061^{***}	-0.0197
	(-0.66)	(-1.43)	(0.60)	(-2.30)	(-3.63)	(-1.07)
$Basis_{t-1}$	-0.1996^{***}	-0.1136^{***}	-0.0979^{***}	0.2380^{***}	0.2843^{***}	0.2452^{***}
	(-29.78)	(-29.56)	(-15.15)	(19.68)	(18.76)	(19.99)
D_{Fix}^{Basis}	0.0299^{*}	0.0004	0.0014	-0.0166	-0.0005	-0.0014
	(1.83)	(0.19)	(0.34)	(-1.08)	(-0.03)	(-0.35)
ΔS_{t-1}	0.1751^{***}	0.1137^{***}	0.0954^{***}	-0.1961^{***}	-0.2819^{***}	-0.2389^{***}
	(26.35)	(29.57)	(14.86)	(-17.31)	(-18.63)	(-19.62)
ΔF_{t-1}	-0.0047^{***}	-0.0076^{***}	0.0011^{***}	-0.0078^{***}	-0.0010^{***}	-0.0004
	(-17.60)	(-28.88)	(3.22)	(-26.12)	(-18.22)	(-0.59)
R^2	0.40	0.40	0.17	0.37	0.30	0.16

Estimation of the cross-market order flow model with basis and interaction dummy variables at the Fix over the full sample period (equations (16) and (17)). All equations are estimated using OLS with Newey-West standard errors (max 5 lags). We multiply the order flow coefficients with 100, t-statistics are given in parentheses below coefficient estimates. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

The coefficient η_1, representing the magnitude of price adjustment in the spot market, is smaller in absolute value than the magnitude of price adjustment in futures prices, η_2. This suggests that reactions in the spot market to price differentials are generally smaller than reactions in the futures markets. Based on these results we could also argue that spot market lead the futures markets, since lagged changes in spot prices lead to positive change in the subsequent futures price. Coefficients λ_1 and λ_2 are positive and statistically significant, indicating on average a positive autocorrelation in spot returns.

4.3 Intraday Comparisons

Based on our graphical analysis, we have identified some points of activity during the day that seem to have a special role in the workings of the foreign exchange market. These points are the 9:30 am and 3 pm London time.

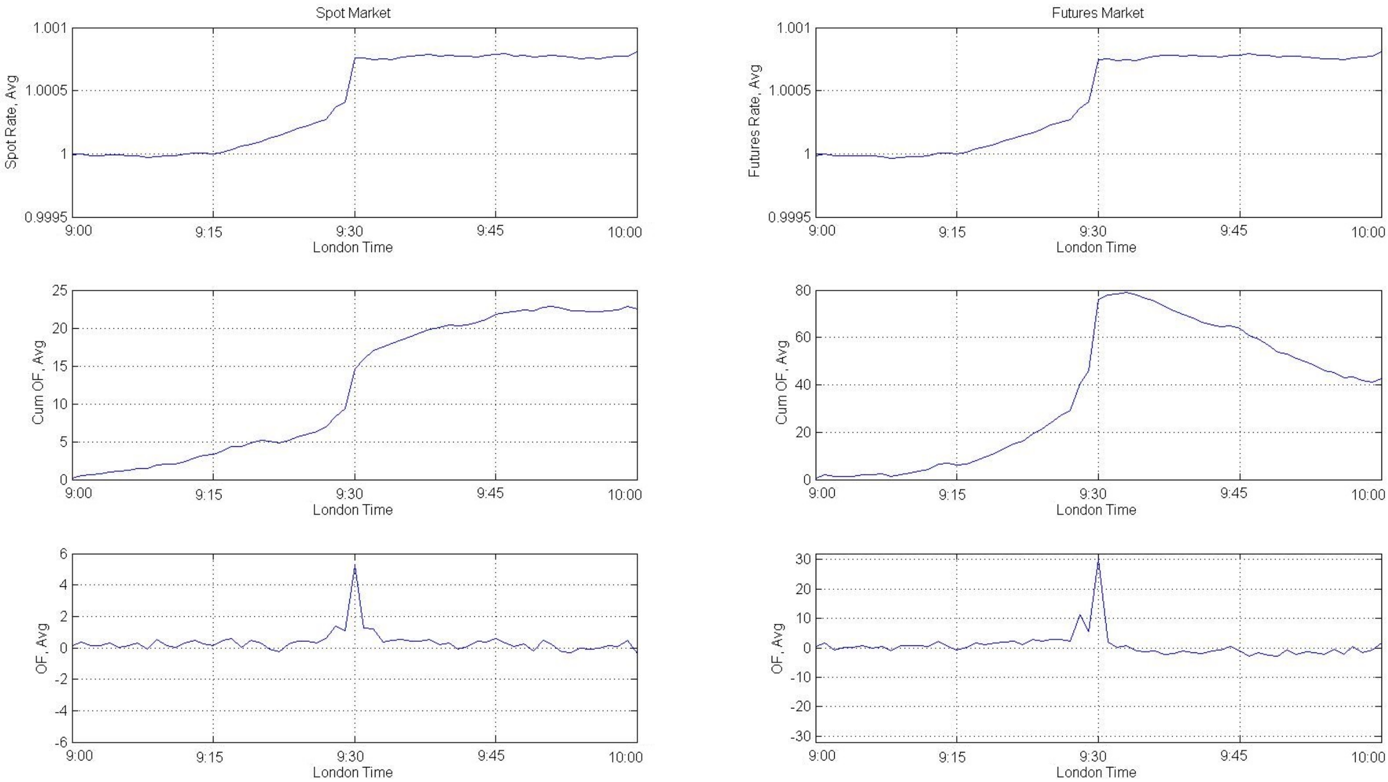
Additionally, another important institutional characteristic of the foreign exchange market but not so extensively studied is the ECB Fix. In this section of our empirical analysis, we are examining the returns-flows relationship around these points and we compare our findings with our results concerning the London 4 pm Fix, using both graphical analysis and regressions. Graphical analysis is restricted in the cases for which the spot rate increased relative to the 3:45 level. The remaining cases and graphs are symmetrical and can be found in Appendix C.

4.3.1 9:30 am London Time

We start by considering the flows-returns relationship around 9:30 am London time. This is a point in time were UK macroeconomic indicators are released. In other words, is a point in time where new public information arrives to the market and is incorporated into prices. Market participants develop expectations about the future state of macroeconomic variables. When macroeconomic announcements contain surprises (i.e. or unexpected changes, defined as actual reported number - forecasts) the price will change and adjust to a new level (Almeida et al. (1998); Chaboud et al. (2004)). However, price behaviour during fixing periods responds to temporary inventory and risk management needs. Therefore, it is useful to examine and contrast the returns-flows relation during the Fix and the time of macroeconomic announcements.

As evident by our initial graphical analysis, UK macroeconomic data releases at 9:30 am are clearly accompanied by large spikes in trading activity, volatility and spreads. The average spot price tends to gradually increase (approximately 7 basis points) in the build up period before the release of the news and then sharply adjust to the new level and remain unchanged. The spot rates increase prior to 9:30 am is similar in size to the spot rates increase prior to the 4 pm Fix, however the price path prior 9:30 am is more convex as compared to the price path before the Fix. Regression results (Table 10) provide evidence for the absence of return reversal in one minute interval after the news release above the reversal due to information incorporated in previous trading rounds. However, price reversal is present in the

Figure 12: Price-Flow Dynamics around 09:30 am London Time.
(Full Sample Period, Positive Spot Price Movement.)



minute following the Fix window.

There is no reason for the rate to significantly vary sharply, after the news release, as all new information is reflected in the price. Spot rates rise before the macro news release is possibly driven by the expected and predictable rise in trading volume generated by macroeconomic announcements. Average order flow is marginally positive in the periods before and after the news release time and spikes during the point of the news release. This pattern suggests that macro news trigger trading that reveals dispersed information that is aggregated and transmitted to prices via order flow. Regression results suggest a positive and statistically significant relation between inter-dealer order flow and returns at that point, for both markets, whereas order flow is

Table 10: Returns-Order Flow Regressions around 9:30 am London Time

	Spot Rates			Futures Rates		
	GBP	**AUD**	**NZD**	**GBP**	**AUD**	**NZD**
$\boldsymbol{X_t}$	0.1565***	0.1660***	0.3010***	0.0406***	0.0526***	0.1715***
	(143.87)	(202.60)	(125.60)	(116.77)	(132.07)	(105.28)
$\boldsymbol{X_t * D_{9:30am}}$	0.1161***	0.0217	0.1003**	0.0191*	0.0227***	0.0921***
	(3.45)	(1.13)	(2.10)	(1.66)	(4.65)	(3.90)
$\boldsymbol{R^2}$	0.21	0.28	0.10	0.28	0.17	0.09
$\boldsymbol{X_t}$	0.1573***	0.1673***	0.3018***	0.0411***	0.0529***	0.1716***
	(144.30)	(204.95)	(125.55)	(123.38)	(135.43)	(105.47)
$\boldsymbol{X_{t-1}}$	−0.0146***	−0.0189***	−0.0187***	−0.0050***	−0.0049***	−0.0063***
	(-23.80)	(-34.49)	(-10.60)	(-31.30)	(-22.80)	(-6.12)
$\boldsymbol{X_t * D_{9:30am}}$	0.1153***	0.0212	0.1007**	0.0188*	0.0226*	0.0914***
	(3.43)	(1.12)	(2.12)	(1.70)	(1.96)	(3.91)
$\boldsymbol{X_{t-1} * D_{9:30am-1min}}$	0.0182	0.0060	−0.0813*	0.0168***	0.0078	0.0444**
	(1.04)	(0.48)	(-1.87)	(3.88)	(1.14)	(2.13)
$\boldsymbol{R^2}$	0.21	0.28	0.10	0.28	0.17	0.09
$\boldsymbol{X_t^S}$	0.0987***	0.1096***	0.2546***	0.0897***	0.0962***	0.1942***
	(91.53)	(125.68)	(110.78)	(81.73)	(98.56)	(78.28)
$\boldsymbol{X_t^S * D_{9:30am}}$	0.0407	0.0140	0.1073**	0.0446	0.0169	0.0954**
	(1.17)	(0.75)	(2.30)	(1.31)	(0.93)	(2.36)
$\boldsymbol{X_t^F}$	0.0314***	0.0356***	0.1154***	0.0338***	0.0395***	0.1537***
	(106.19)	(101.12)	(90.49)	(103.31)	(100.18)	(96.01)
$\boldsymbol{X_t^F * D_{9:30am}}$	0.0150	0.0134***	0.0358	0.0123	0.0159***	0.0754***
	(1.23)	(2.95)	(1.56)	(1.01)	(3.41)	(3.42)
$\boldsymbol{R^2}$	0.39	0.39	0.15	0.33	0.21	0.11

All equations are estimated using OLS with Newey-West standard errors (max 5 lags). We multiply the order flow coefficients with 100, t-statistics are given in parentheses below coefficient estimates. To check robustness, we include a constant in the regression, even though the model does not call for one. The constant is insignificant. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

uninformative for spot returns at the Fix. The spike in order flow at the time of the release could also be a result of the adjustment of dealers inventories to the new asset valuation. The behaviour of average order flow in the 15 minutes before the news release is significantly different to the one observed in the 15 minutes before the Fix. Average order flow does not increase in the 15 minutes build up period to the news realse, as it is the case with the 4 pm Fix. Futures returns and flows behave in a similar manner and futures flows matter for both markets. Given that this point of time does not coincides with an hourly fix calculation window and new public information is released into the market, the observed patterns in rates and order flow could be considered as informationally driven. Given the important differences in the the observed behaviour of rates and order flow at 9:30 am and at 4 pm, we could argue that the patterns observed at the Fix are most probably not driven by information-based trading.

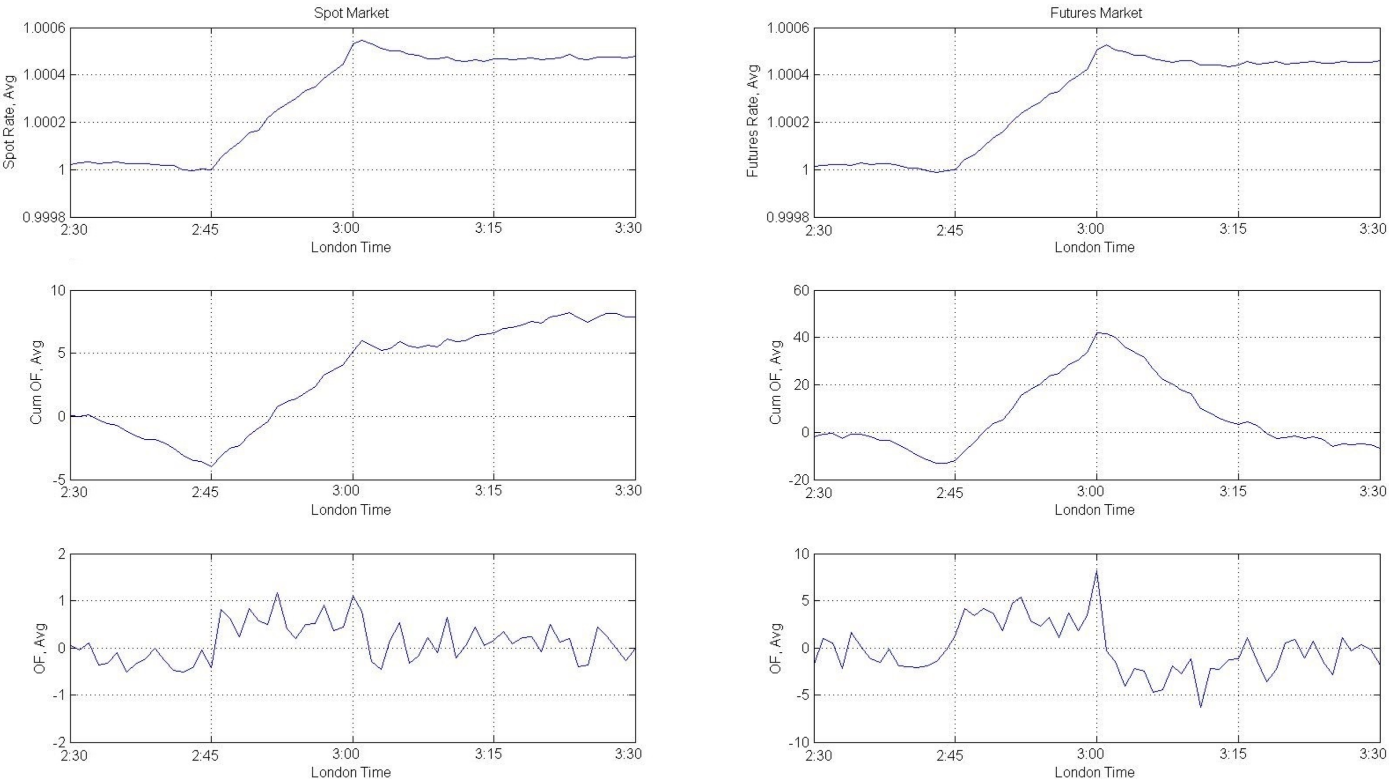
4.3.2 3 pm London Fix

Another important intraday point is the 3 pm London fix. At this point we have: the one-minute calculation window of the fix, the option expiration cut-off (10 am New York time (ET)) as well as the announcement of some U.S. macroeconomic indicators (10 am ET). The option expiration cut-off is a time were almost all major FX options expire. A significant portion of those over-the-counter FX options in the inter-bank market are European type options with delivery of the underlying asset. Exercise and settlement of the options is performed by London based trading centers, as the London FX trading session coincides with early morning US trading hours as well as Asian late trading hours. In a sense, at this point market participants expectations regarding future FX rate movements may manifest. Moreover, the publication of some major U.S. macroeconomic indicators may also reveal new information to the market and may lead market participants to revise their expectations.

Thus as the cut-off point approaches, both activity and volatility tend to increase. The average spot price tends to gradually increase (approximately 5.5 basis points) in the build up period before the 3 pm fix, but at a lesser extend as compared to the observed price increase at the London 4 pm Fix (approximately -1 basis points). Regression results (Table 11) provide evidence for the absence of return reversal in the one minute after the 3 pm fix above the reversal due to information incorporated in previous trading rounds.

Recall that price reversal is present in the minute following the Fix window. The average order flow behaviour at 3 pm fix is slightly different to that observed at the Fix. Average order flow turns positive in the 15 minutes before the 3 pm fix indicating buying pressure, just like as the Fix. However, average order flow does not reach zero during the 3 pm window but instead spikes upwards, before turning on average equal to zero after the 3 pm fix.

Figure 13: Price-Flow Dynamics around 3 pm London Time.
(Full Sample Period, Positive Spot Price Movement.)



This most probably suggests that traders begin executing fix-related trades as soon as they reach the start of the one-minute window. Again, regression results suggest a positive and statistically significant relation between order flow and returns at the 3 pm fix, in contrast to the Fix, where order flow is uninformative for returns. Average cumulative order flow follows a similar path to that of the spot price. Futures returns and flows do not follow an exact same pattern as that related with the spot price but it is consistent with the behaviour of the futures returns-flows relationship as that observed at 4 pm Fix. The returns-order flow relation at the 3 pm Fix is positive and statistically significant but order flow seems only to loose a small part of its informational content, there is no signs of returns reversal and flows contain information for both markets. Based on these findings, we could argue that

Table 11: Returns-Order Flow Regressions around the London 3 pm Fix

	Spot Rates			**Futures Rates**		
	GBP	**AUD**	**NZD**	**GBP**	**AUD**	**NZD**
X_t	0.1586***	0.1659***	0.3012***	0.0410***	0.0526***	0.1715***
	(136.00)	(202.71)	(125.91)	(109.56)	(131.84)	(105.10)
$X_t * D_{3pm}$	−0.0482**	0.0268*	-0.0075	−0.0029*	0.00084*	0.0256
	(-2.38)	(1.88)	(-0.18)	(-1.90)	(1.73)	(1.17)
R^2	0.21	0.27	0.10	0.28	0.17	0.09
X_t	0.15945***	0.1673***	0.3021***	0.0415***	0.0530***	0.01716***
	(136.38)	(204.92)	(125.79)	(114.89)	(138.89)	(105.18)
X_{t-1}	−0.01468***	−0.0189***	−0.0187***	−0.0050***	−0.0049***	−0.0063***
	(-23.94)	(-34.50)	(-10.59)	(-31.15)	(-23.09)	(-6.11)
$X_t * D_{3pm}$	−0.04972**	0.0265*	-0.0082	-0.0032	0.0082	0.0256
	(-2.37)	(1.86)	(-0.19)	(-1.15)	(1.58)	(1.17)
$X_{t-1} * D_{3pm-1min}$	-0.02042	−0.0266***	−0.0766**	-0.0009	−0.0265***	-0.0097
	(-1.19)	(-2.58)	(-2.40)	(-0.45)	(-3.33)	(-0.50)
R^2	0.21	0.28	0.10	0.28	0.17	0.09
X_t^S	0.0996***	0.1096***	0.2548***	0.0907***	0.0961***	0.1943***
	(86.20)	(125.67)	(110.94)	(77.29)	(98.28)	(78.67)
$X_t^S * D_{3pm}$	−0.0298**	0.0228*	0.0174	-0.0226	0.0319**	0.0236
	(-2.02)	(1.80)	(0.46)	(-1.58)	(2.51)	(0.45)
X_t^F	0.0317***	0.0355***	0.1151***	0.0341***	0.0394***	0.1535***
	(97.66)	(100.75)	(90.25)	(95.67)	(99.90)	(95.80)
$X_t^F * D_{3pm}$	0.0023	0.0136***	0.0533***	0.0001	0.0088*	0.0372*
	(0.94)	(3.56)	(2.87)	(0.05)	(1.87)	(1.99)
R^2	0.39	0.39	0.15	0.33	0.21	0.11

All equations are estimated using OLS with Newey-West standard errors (max 5 lags). We multiply the order flow coefficients with 100, t-statistics are given in parentheses below coefficient estimates. To check robustness, we include a constant in the regression, even though the model does not call for one. The constant is insignificant. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

the 3 pm Fix is characterized by relatively different trading patterns from those observed at the 4 pm Fix.

4.3.3 ECB Fix

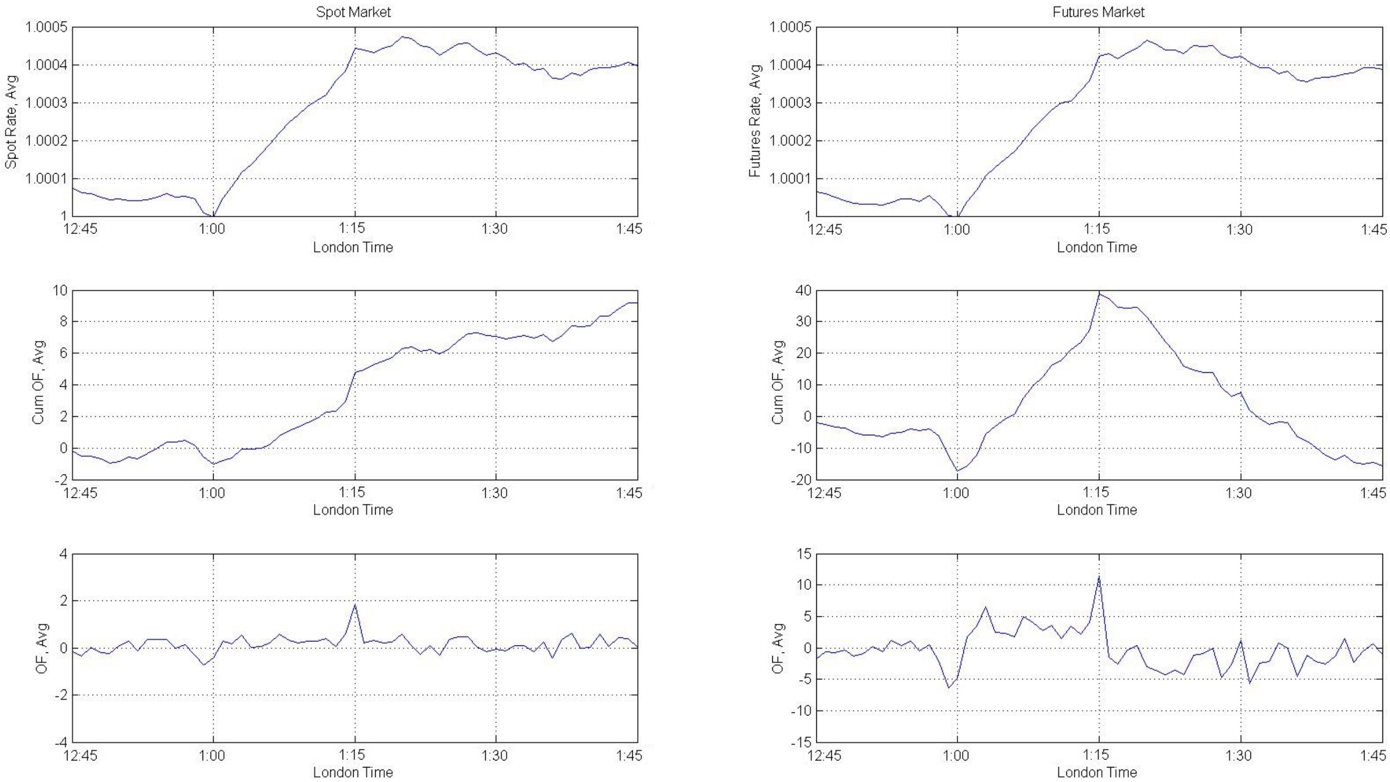
Another important institutional characteristic of the foreign exchange market is the so-called ECB fix. The ECB has been setting, administering and publishing euro foreign exchange benchmark rates for approximately 32 different currencies on a daily basis since January 1999. The Euro foreign exchange rates set by the ECB at 2:15pm CET (1:15 London local time)[21] are also used by a wide range of participants, especially European non-financial companies both for transaction and information purposes (as e.g. in contractual obligations, internal transactions as well as for financial reporting and inter-company valuation purposes). The benchmark rate is calculated using transactional data between buyers and sellers given that those data are available and reflect sufficient liquidity. In a market where there is lower liquidity, the benchmark rates may be calculated using an average of quoted bid and ask prices for the various currencies against the Euro or prior transactions. This suggest that the calculation of the ECB benchmark rate does not necessarily reflect actual transactions.

This point in time, is more appropriate as a comparison point than the 3 pm London fix as it is not directly associated with any event that reveals new information to the market. Again, the spot price tends to rise as compared to the 1:00 am level and as approaches the fixing period (approximately 4 basis points), but not as pronounced as in the case of the London fixes (both 3 pm and 4 pm) or at 9:30 am.

Regression results (Table 12) provide evidence for the absence of return reversal in the minute after the ECB Fix above the reversal due to information incorporated in previous trading rounds. Average order flow seems to uniformly behave in the periods before and after the ECB fixing window and seems to spike at the fix. There is no increase in average order flow in the 15 minutes before of the fix window, as it is the case for the 3 am and 4 am fixes. Average order flow behaviour looks similar to the 9:30 pm order flow behaviour, apart from the magnitude of the spike during the fixing window. Regression results reveal, as expected, a positive and statistically significant relation between order flow and returns. However, average order flow at the

[21] Based on the recommendations of the Financial Stability Board on FX benchmarks, as well as the principles for benchmark-setting practices dictated by the European Securities and Markets Authority (ESMA) and the European Banking Authority (EBA), the ECB changed the publication time of the fix from 2:30 CET to 4:00 CET as of July 01, 2016. The ECB fixing rates will continue to be determined using the current methodology, which is based on a point-in-time snapshot at 2:15 CET. These changes underlie ECB's policy to emphasize the "for information only" character of the benchmark rates and discourage their use for transaction purposes.

Figure 14: Price-Flow Dynamics around ECB Fix.
(Full Sample Period, Positive Spot Price Movement.)



ECB fix seems to lose part of its information content but it does not become completely uninformative, as it is with order flow during the Fix window. Futures returns - order flow relation is similar to the one observed at the 3 pm fix. Spot and futures flows contain information for returns in both markets. Thus, the returns-order flow relation at the ECB fix is different from the observed relation at the London 4 pm Fix.

Table 12: Returns-Order Flow Regressions around the 1:15 pm ECB Fix

	Spot Rates			Futures Rates		
	GBP	**AUD**	**NZD**	**GBP**	**AUD**	**NZD**
X_t	0.1585***	0.1661***	0.3014***	0.0410***	0.0526***	0.1716***
	(134.64)	(202.59)	(125.69)	(109.91)	(131.94)	(105.09)
$X_t * D_{ECB}$	−0.0511***	−0.0374***	−0.0860**	−0.0029**	-0.0030	-0.0057
	(-4.69)	(-2.67)	(-1.99)	(-2.36)	(-0.71)	(-0.30)
R^2	0.21	0.27	0.10	0.28	0.17	0.09
X_t	0.1594***	0.1675***	0.3021***	0.0415***	0.0529***	0.1717***
	(135.05)	(204.90)	(125.65)	(115.37)	(135.20)	(105.22)
X_{t-1}	−0.0146***	−0.0189***	−0.0187***	−0.0050***	−0.0049***	−0.0063***
	(-23.86)	(-34.47)	(-10.60)	(-31.14)	(-22.80)	(-6.11)
$X_t * D_{ECB}$	−0.0505***	−0.0367***	−0.0861**	−0.0095**	-0.0027	-0.0052
	(-4.69)	(-2.73)	(-2.00)	(-2.33)	(-0.66)	(-0.28)
$X_{t-1} * D_{ECB-1min}$	0.0124	-0.0089	0.0245	0.0003	−0.0090**	-0.0040
	(0.11)	(-0.75)	(0.51)	(0.12)	(-2.02)	(0.18)
R^2	0.21	0.29	0.10	0.28	0.17	0.09
X_t^S	0.0996***	0.1098***	0.2551***	0.0907***	0.0964***	0.1944***
	(85.86)	(125.82)	(110.90)	(77.12)	(98.65)	(78.35)
$X_t^S * D_{ECB}$	−0.0428***	−0.0434***	−0.1015***	−0.0306***	−0.0346**	-0.0208
	(-5.41)	(-2.95)	(-2.77)	(-3.10)	(-2.42)	(-0.50)
X_t^F	0.0317***	0.03561***	0.1153***	0.0341***	0.0395***	0.1538***
	(98.01)	(101.02)	(90.30)	(96.02)	(100.07)	(95.83)
$X_t^F * D_{ECB}$	-0.0045	0.0044	0.0025	−0.0067*	0.0024	0.0007
	(-1.18)	(0.93)	(1.49)	(-1.74)	(0.53)	(0.40)
R^2	0.39	0.39	0.15	0.33	0.21	0.12

All equations are estimated using OLS with Newey-West standard errors (max 5 lags). We multiply the order flow coefficients with 100, t-statistics are given in parentheses below coefficient estimates. To check robustness, we include a constant in the regression, even though the model does not call for one. The constant is insignificant. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

5 Summary

This study empirically examines the intraday foreign exchange rates and inter-dealer order flow relationship around the WMR 4 pm London Fix for both spot and futures markets for various G10 currencies. We also compare and contrast intraday liquidity and price behaviour with other fixing points, such as the 3 pm London fix and the ECB fix, as well as with other major intraday points in time, such as the 9:30 am London time were macroeconomic indicators are published. Our analysis indicates that benchmark rates play an important role in the workings of currency markets, especially the London 4 pm Fix where the behavior of prices and flows around this time is quite unlike that observed at other points in time. Our main findings are summarized as follows: (1) During the 60 second calculation window of the Fix, there is an extreme concentration of trading activity not present during any other point in time of the day, as measured by the average number of trades per minute of trading activity, generating price and order flow spikes for both the spot and the futures markets (2) The average intraday spread for the spot market exclusively spikes downwards only at the Fix, for the futures markets also spikes downwards but not exclusively (3) The average intraday price volatility, as measured by absolute returns, spikes during fixing periods for both the spot and the futures market (4) Order flow is completely uninformative for returns during the Fix in the spot market with a zero price impact but not for the futures market (5) There is price reversal in one minute after the Fix but not during other fixing points for both markets (6) Based on our results, we can infer that trading around the Fix seems not to be information-driven. The behaviour of liquidity, prices and flows around fixes has not been extensively studied up until recently and not accounted for in existing microstructure FX trading models. Our study contributes towards this end. Further research could be related to the study of returns-order flow relationship after the widening of the calculation window of the Fix and examine whether price and order flow behaviour has qualitatively changed.

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Appendix A: WMR FX Benchmarks

A currency fix is the setting of a daily reference rate. This rate is set at a specific time of day and is intended to express a representative rate of the market at the time at which the rate is calculated. The most important and widely used benchmark rate in spot foreign exchange markets is the London WMR 4pm Fix. It is produced and administered jointly by The World Markets Company and Thomson Reuters[22]. In 2016, Thomson Reuters acquired The World Market's Company WMR FX benchmark calculation business from State Street Corporation. The service was introduced in 1994 to provide a standard set of currency benchmark rates so that portfolio valuations could be compared with each other and their performance measured against benchmarks without having any differences caused by exchange rates. The rates are intended to cover the currencies for those countries that are included in a global or regional stock market index or where there is sufficient liquidity in the currency market to provide accurate fixings. These rates were adopted by index compilers, the Financial Times and other users and became the de facto standard for spot rates on a global basis. WMR provides rates for approximately 155 currencies on an hourly frequency, with half-hourly rates provided for the 22 most traded currencies, and forward rates for 80 currencies.

The calculation differs between forward and spot rates. We focus on spot rates only here. Over a one-minute fix period, actual trades executed and bid and offer order rates from the order matching systems are captured every second from 30 seconds before to 30 seconds after the time of the fix. Note that from 15 February 2015 and onwards, the data sourcing window is widened to a five-minutes fix period. Trading occurs in milliseconds on the trading platforms and therefore not every trade or order is captured, just a sample. From each data source, a single traded rate will be captured – this will be identified as a bid or offer depending on whether the trade is a buy or sell. A spread will be applied to the trade rate to calculate the opposite bid or offer. The spread applied will be determined by the order rate captured at the same time. This may result in some captured data being excluded

[22]WMR FX Benchmarks. Spot & Forward Rates Methodology Guide.

from the fix calculation. Valid trades from all sources captured during the fix period will be "pooled" together. Subject to a minimum number of valid trades being present within this pool of data – the trade rates will be used for the fix. A median trade bid and trade offer are calculated independently, using data from the single pool of trades across data sources. The mid-rate is calculated from the median trade bid and trade offer. A minimum standard spread is applied to the mid-rate to calculate a new bid and offer. These bid, offer and mid rates will be validated prior to publication, against currency specific tolerance thresholds, and this may result in expert judgement being applied. If there are insufficient valid trade rates from the pooled data sources, to be used in the fix then order rates will be used. From each data source, the best bid and best offer rates will be captured simultaneously to the Trade data from each data source. All captured order rates will be subjected to validation checks. This may result in some captured data being excluded from the fix calculation.

Appendix B: Time line of the Forex Scandal

In the summer of 2013, news reports began to circulate stating that Financial Conduct Authority (FCA) began preliminary investigation into potential manipulation of FX benchmarks, amid allegations that traders at banks were colluding in rigging spot benchmark rates. According to the articles, the behavior occurred daily in the spot foreign-exchange market and went on for at least a decade. The investigation quickly went global with at least six regulatory authorities across the globe – the European Commission, Switzerland's financial markets regulator Finma and the country's competition authority Weko, the UK's Financial Services Authority, the Department of Justice in the US and the Hong Kong Monetary Authority - launching formal investigations. In November 2014, the United Kingdom's Financial Conduct Authority (FCA) imposed fines totaling $1.7bn on five of the world's largest banks (Citibank, HSBC, JP Morgan, RBS and UBS) for failing to control business practices in their G10 spot foreign exchange trading businesses. The FCA determined that the five banks had failed to manage risks around client confidentiality, conflict of interest, and trading conduct. The banks used confidential customer order information to collude with other banks to manipulate fixing rates for G10 currency rates and profit illegally at the expense of their customers and the market. The FCA also published transcripts detailing examples of misconduct by traders attempting to manipulate the Fix. On the same day the United States Commodity Futures Trading Commission (CFTC) in coordination with the FCA imposed collective fines of $1.4bn against the same five banks for attempted manipulation of, and for aiding and abetting other bank's attempts to manipulate global FX benchmark rates to benefit the positions of certain traders. The regulators found that currency traders at the five banks coordinated their trading with traders at other banks in order to manipulate the foreign exchange benchmarks rates. Currency traders at the banks used private chatrooms to communicate and plan their attempts to manipulate the foreign exchange benchmark rates. In these chatrooms, traders at the banks disclosed confidential customer order information and trading positions, changed trading positions to accommodate the interests of the collective group, and agreed on trading strategies as part of an effort by the group to manipulate different foreign exchange benchmark rates. These chatrooms were often exclusive and invitation only, and were named for example *The Club*, *The Bandits' Club*, *The Mafia*, *The Dream Team*, *One Team One Dream*, *The Three Musketeers* and *The Cartel.* On 20 May 2015, the five banks pleaded guilty to felony charges by the United States Department of Justice and agreed to pay fines totaling more than $5.7bn. Four of the banks pleaded guilty to manipulation of the foreign banks. UBS also pleaded guilty to committing wire fraud and agreed to a $203m fine. A sixth bank, Bank of America, while not found guilty, agreed to a fine of $204m for unsafe practices in foreign markets. Civil litigation from investors against the perpetrating banks and regulatory investigations into forex trading misconduct are still ongoing.

Appendix C

Figure 15: GBP/USD Price-Flow Dynamics around the Fix
(Full Sample Period, Negative Spot Price Movement before the Fix.)

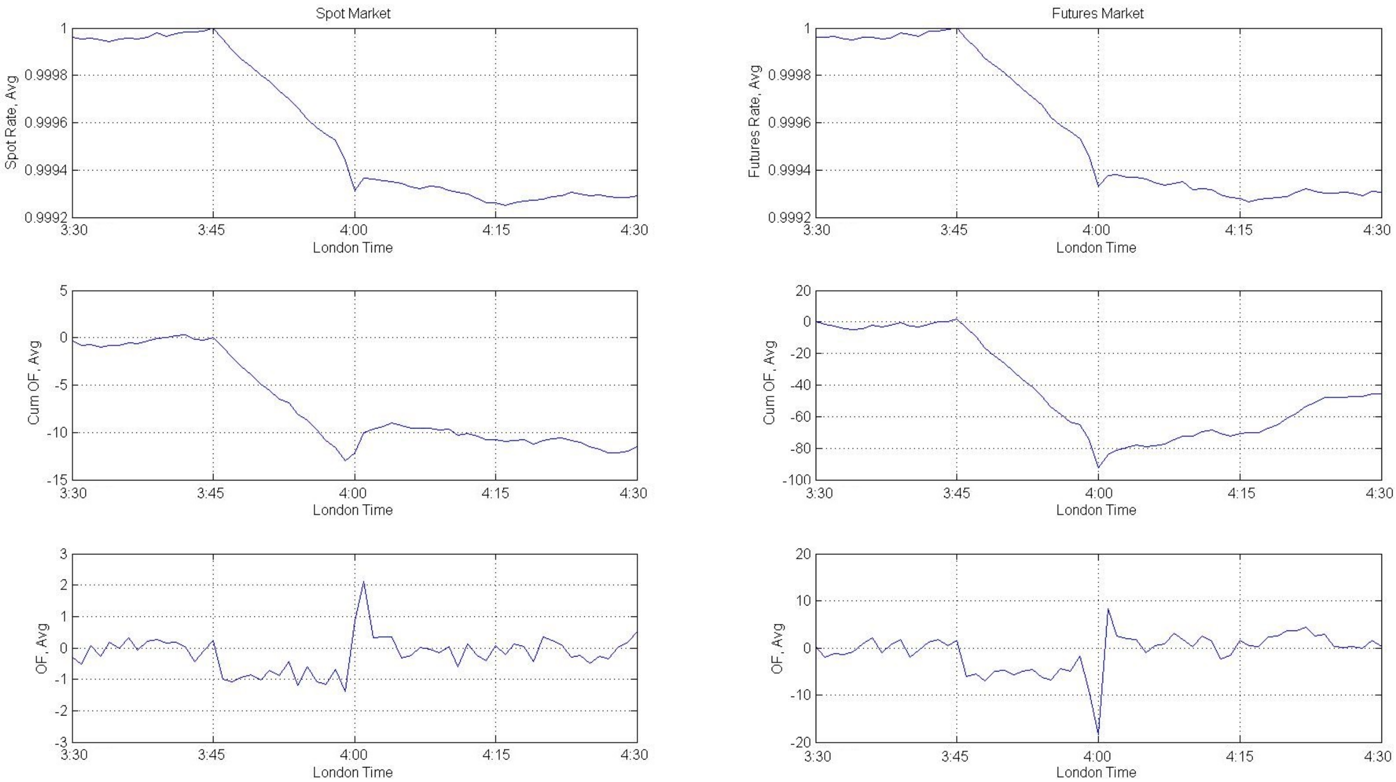

Figure 16: GBP/USD Price-Flow Dynamics around 09:30 am London Time.
(Full Sample Period, Negative Spot Price Movement.)

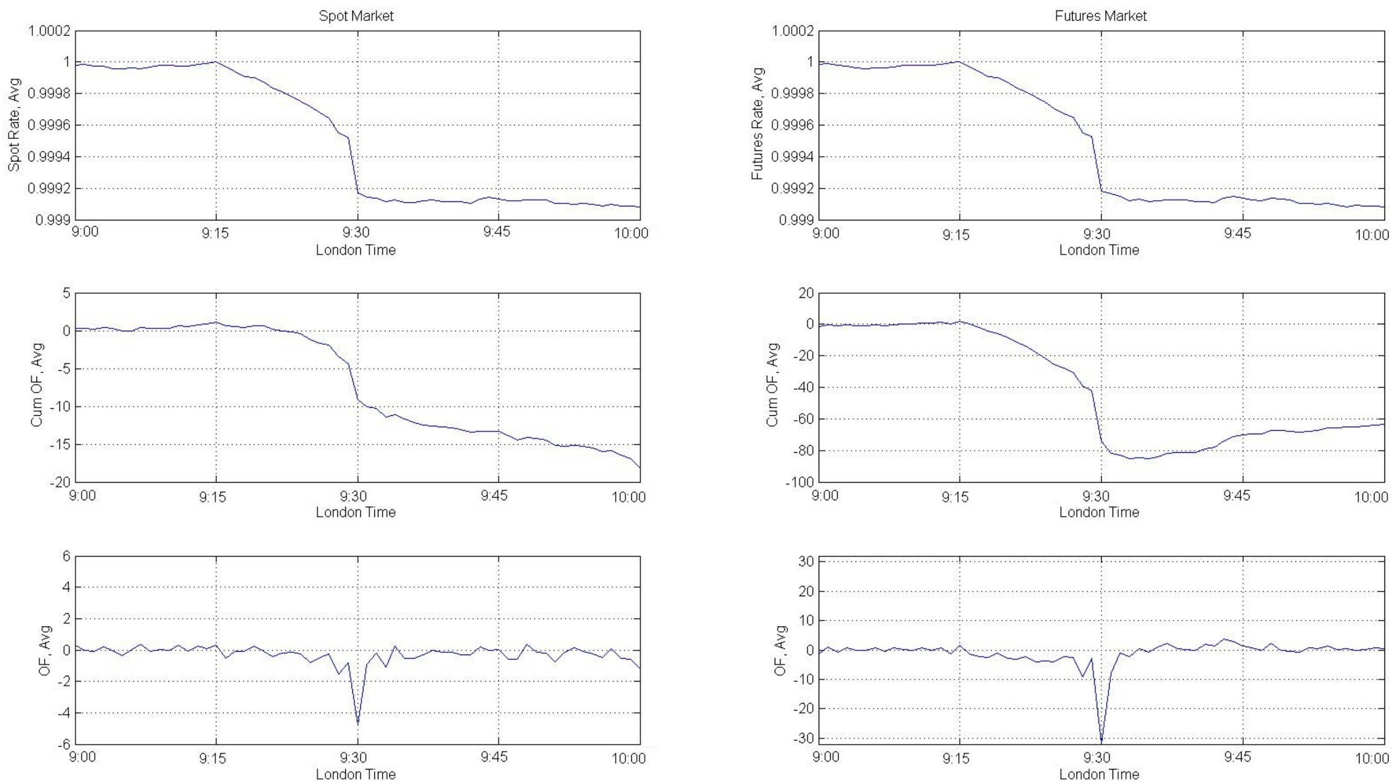

Figure 17: GBP/USD Price-Flow Dynamics around 3 pm London Time.
(Full Sample Period, Negative Spot Price Movement.)

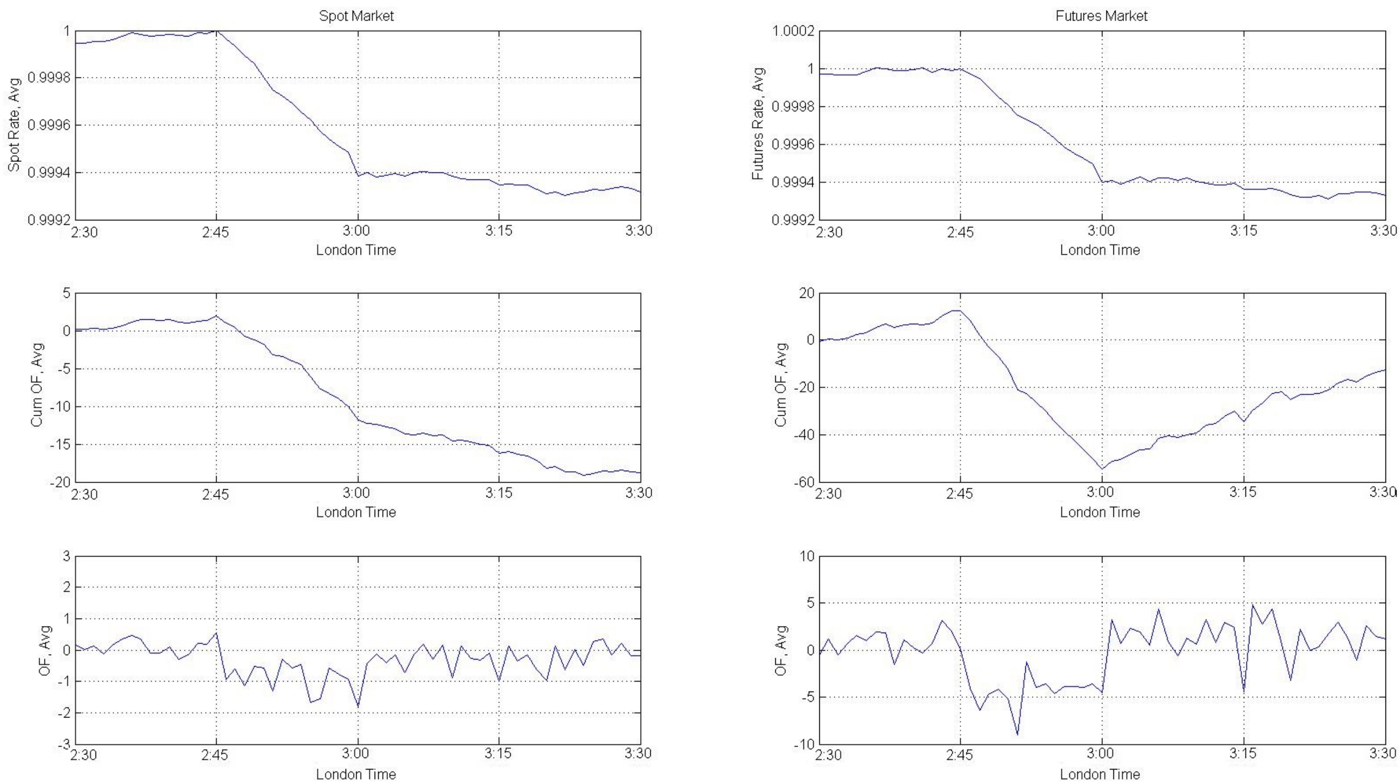

Figure 18: GBP/USD Price-Flow Dynamics around ECB Fix.
(Full Sample Period, Negative Spot Price Movement.)

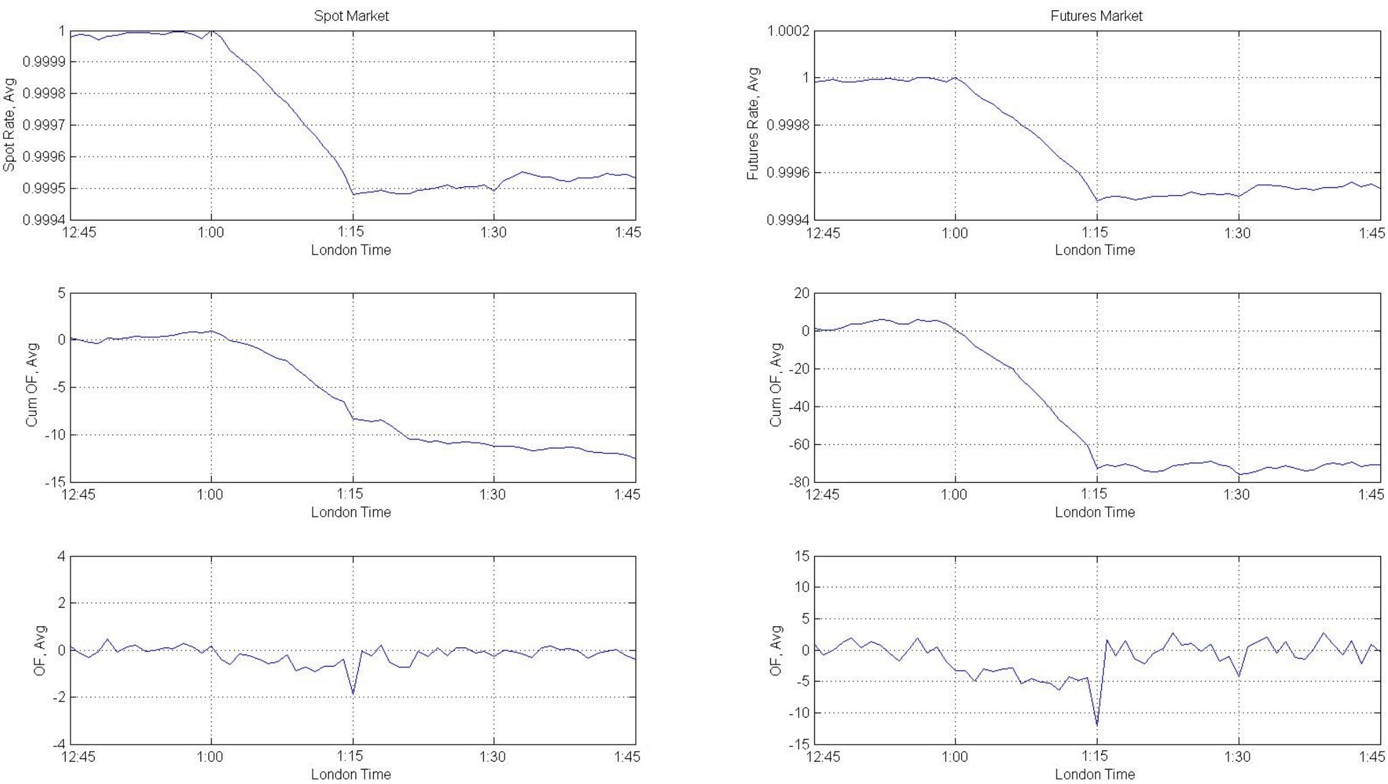

Figure 19: GBP/USD Basis (log)

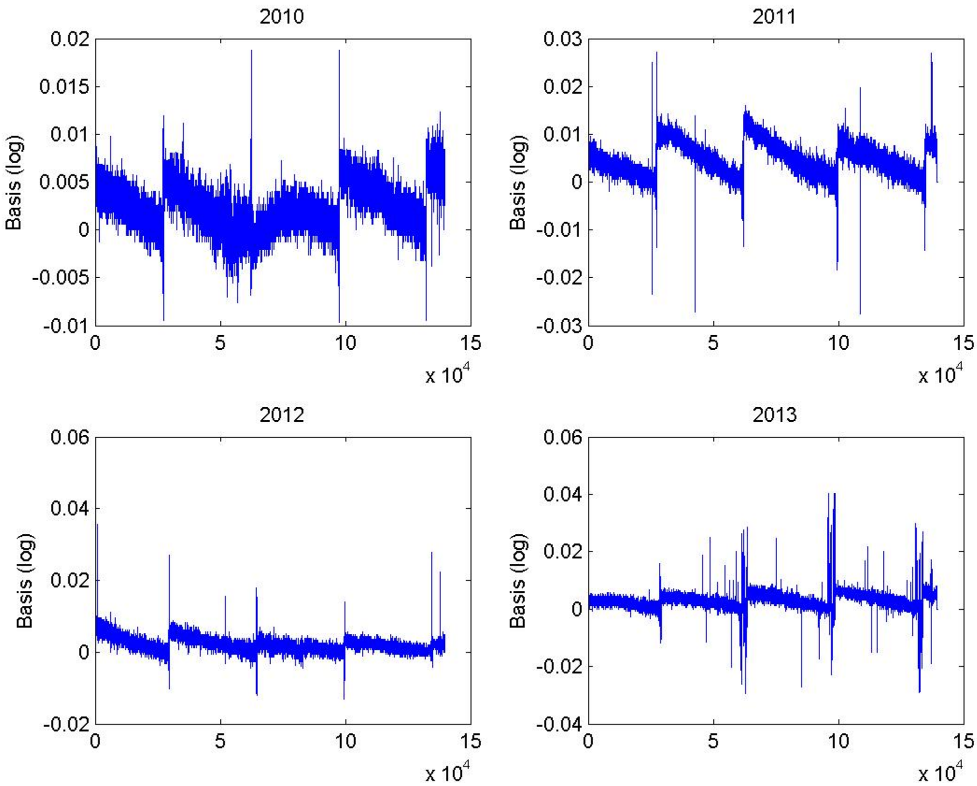

Table 13: Summary Statistics for Spot and Futures AUD/USD.

	Spot Data			Futures Data		
	Trades	**Flows**	**Returns**	**Trades**	**Flows**	**Returns**
Panel A: Minute (obs: 558,360)						
Mean	16.878	-0.086	2.33×10^{-5}	73.628	-0.033	1.83×10^{-5}
Median	11.000	0.000	0.000	45.000	0.000	0.000
Maximum	785.000	162.000	1.071	3,428.000	936.000	1.618
Minimum	0.000	-168.000	-0.777	0.000	-1,017.000	-1.629
Std.Dev.	20.827	7.826	0.025	93.534	26.665	0.034
Q(5)	5,295.298	3,669.310	858.275	6,814.959	3,286.206	2,846.516
ADF	-289.484	-696.927	-772.265	-280.306	-702.502	-939.251
AR(1)	0.568	0.695	-0.033	0.600	0.062	-0.224
Panel B: Daily (obs: 1,034)						
Mean	9,114	-46.554	2.33×10^{-5}	39,759	-17.785	1.83×10^{-5}
Median	8,794	-34.500	1.28×10^{-5}	39,121	-5.000	0.05×10^{-5}
Maximum	28,879	944.000	5.19×10^{-3}	122,591	3,595.000	5.18×10^{-3}
Minimum	541	-1,124.0	-4.83×10^{-3}	53.00	-4,139.000	-4.82×10^{-3}
Std.Dev.	3,704	283.964	9.46×10^{-4}	16,638	815.951	9.55×10^{-4}
Q(5)	1,270.2	13.343	1.183	733.070	67.858	15.955
ADF	-5.614	-28.305	-31.186	-6.057	-26.971	-31.680
AR(1)	0.585	0.102	0.032	0.537	0.172	0.032

This table presents summary statistics for trades, order flow and returns for both the spot and futures market for the AUD/USD currency pair. Full period statistics are calculated over the period January 2010 to December 2013. Number of observations correspond to each market separately. Q(5) denotes the Ljung-Box Q-test statistic for the first five serial correlations of returns. Under the null hypothesis of no serial correlation, the LBQ statistic is asymptotically distributed as $\chi^2(5)$. ADF denotes an Augmented Dickey-Fuller test for non-stationarity in each series.

Table 14: Summary Statistics for Spot and Futures AUD/USD.

	Spot Data			Futures Data		
	Trades	**Flows**	**Returns**	**Trades**	**Flows**	**Returns**
Panel A: Minute (obs: 558,360)						
Mean	3.836	0.002	3.06×10^{-5}	8.360	-0.012	3.82×10^{-5}
Median	2.000	0.000	0.000	3.000	0.000	0.000
Maximum	223.000	77.000	1.131	605.000	208.000	2.228
Minimum	0.000	-57.000	-1.397	0.000	-194.000	-1.762
Std.Dev.	6.139	2.920	0.029	15.102	6.105	0.035
Q(5)	2,413.133	766.769	796.447	2,694.342	276.527	1,124.609
ADF	-387.086	-720.941	-765.787	-405.067	-737.070	-854.652
AR(1)	0.412	0.036	-0.025	0.407	0.014	-0.133
Panel B: Daily (obs: 1,034)						
Mean	2,071	0.991	3.06×10^{-5}	4,514	-6.750	3.82×10^{-5}
Median	1,982	1.500	4.48×10^{-5}	4,293	-3.500	0.000
Maximum	6,782	440.000	4.25×10^{-3}	13,764	1,034.000	4.25×10^{-3}
Minimum	168.000	-338.000	-5.35×10^{-3}	3.00	-1,108.000	-5.46×10^{-3}
Std.Dev.	801.606	86.714	1.07×10^{-3}	2,175	206.069	1.14×10^{-3}
Q(5)	526.638	4.837	2.822	1,104.070	45.651	3.362
ADF	-6.242	-30.936	-32.016	-6.277	-27.602	-30.519
AR(1)	0.446	0.038	0.005	0.608	0.150	0.052

This table presents summary statistics for trades, order flow and returns for both the spot and futures market for the NZD/USD currency pair. Full period statistics are calculated over the period January 2010 to December 2013. Number of observations correspond to each market separately. Q(5) denotes the Ljung-Box Q-test statistic for the first five serial correlations of returns. Under the null hypothesis of no serial correlation, the LBQ statistic is asymptotically distributed as $\chi^2(5)$. ADF denotes an Augmented Dickey-Fuller test for non-stationarity in each series.

Figure 20: AUD/USD Spot & Futures Trading Activity
(Avg Number of Trades & Order Flow)

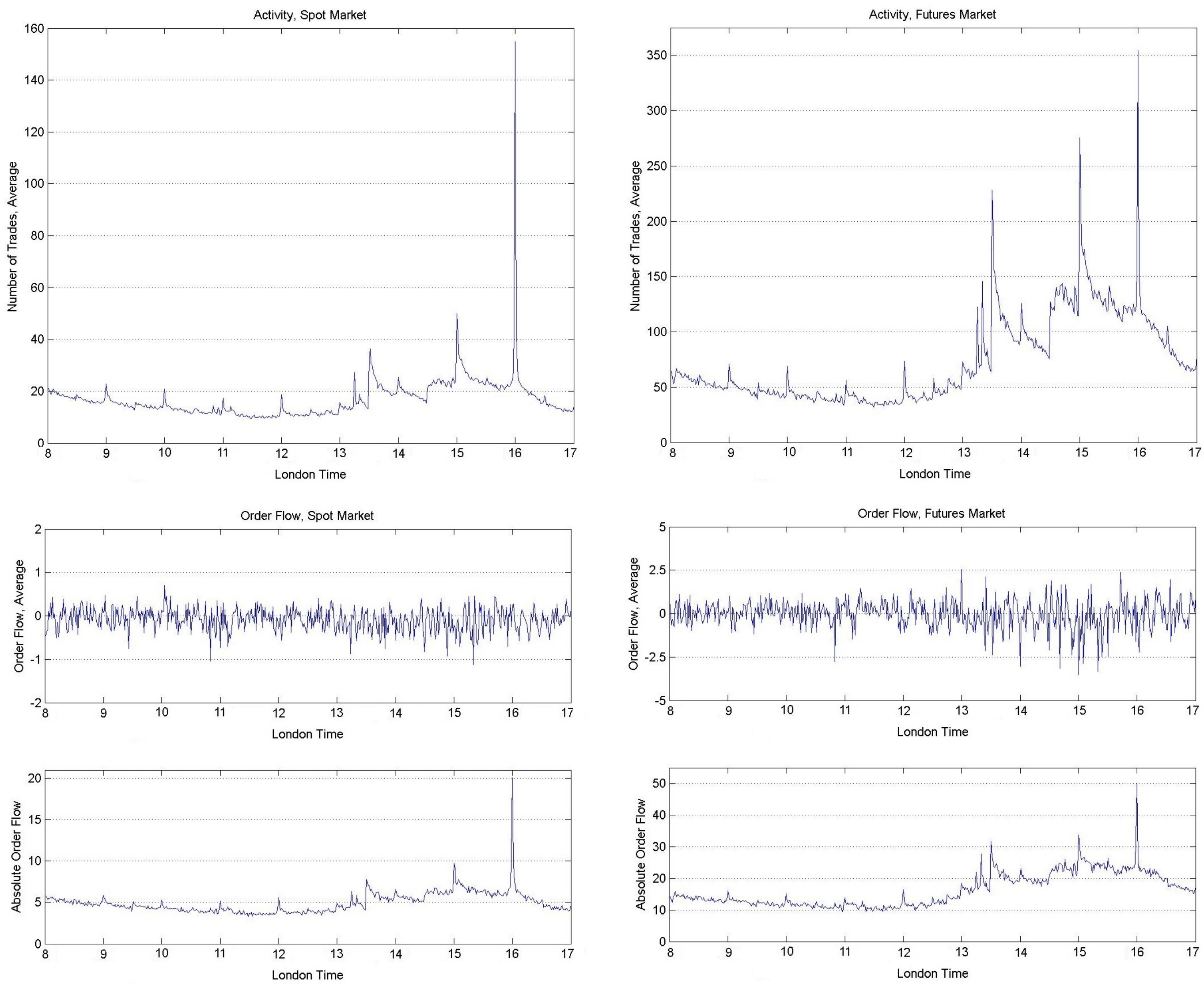

Figure 21: AUD/USD Spot & Futures Bid-Ask Spread

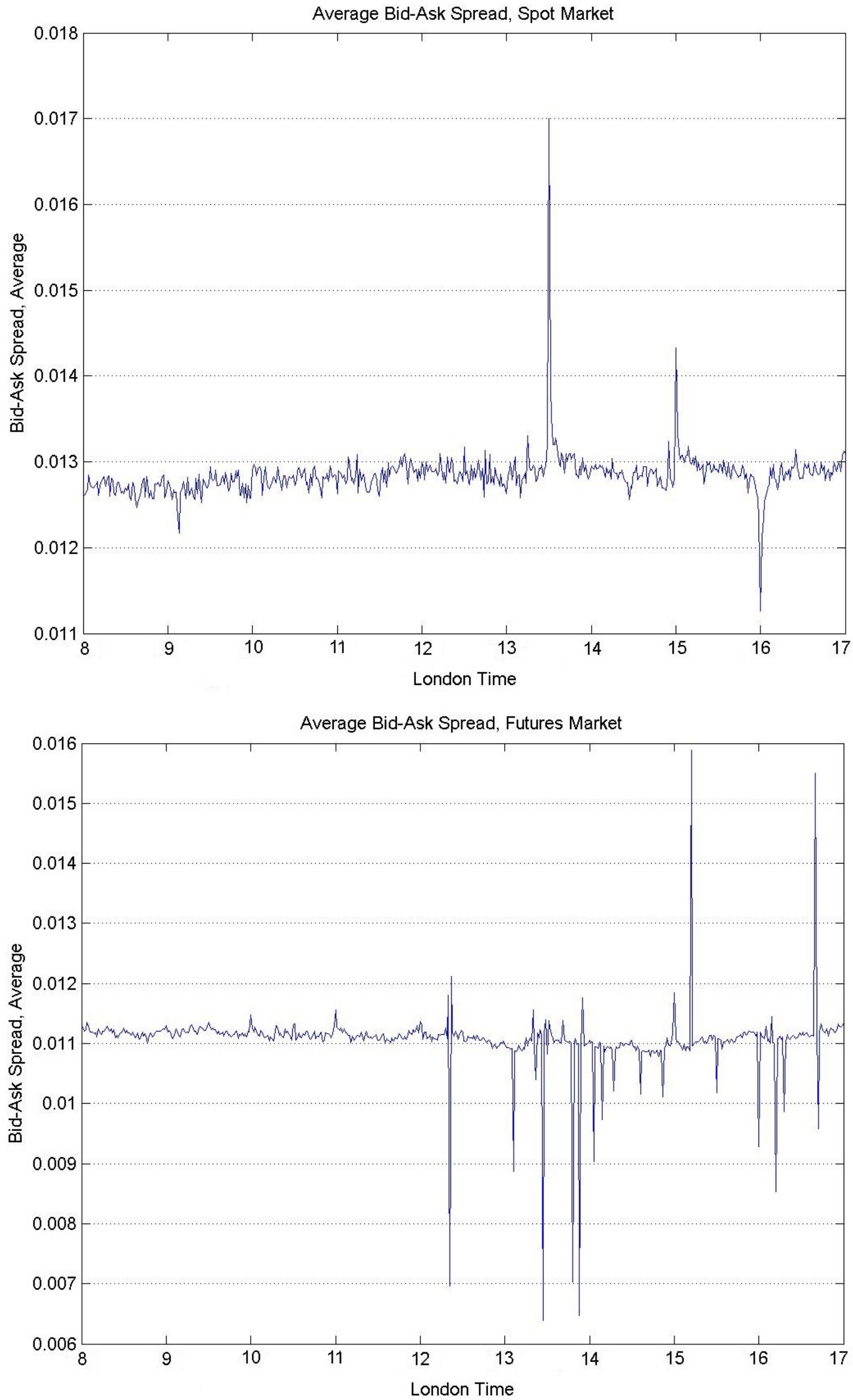

Figure 22: AUD/USD Price-Flow Dynamics around the Fix
(Full Sample Period, Positive Spot Price Movement before the Fix.)

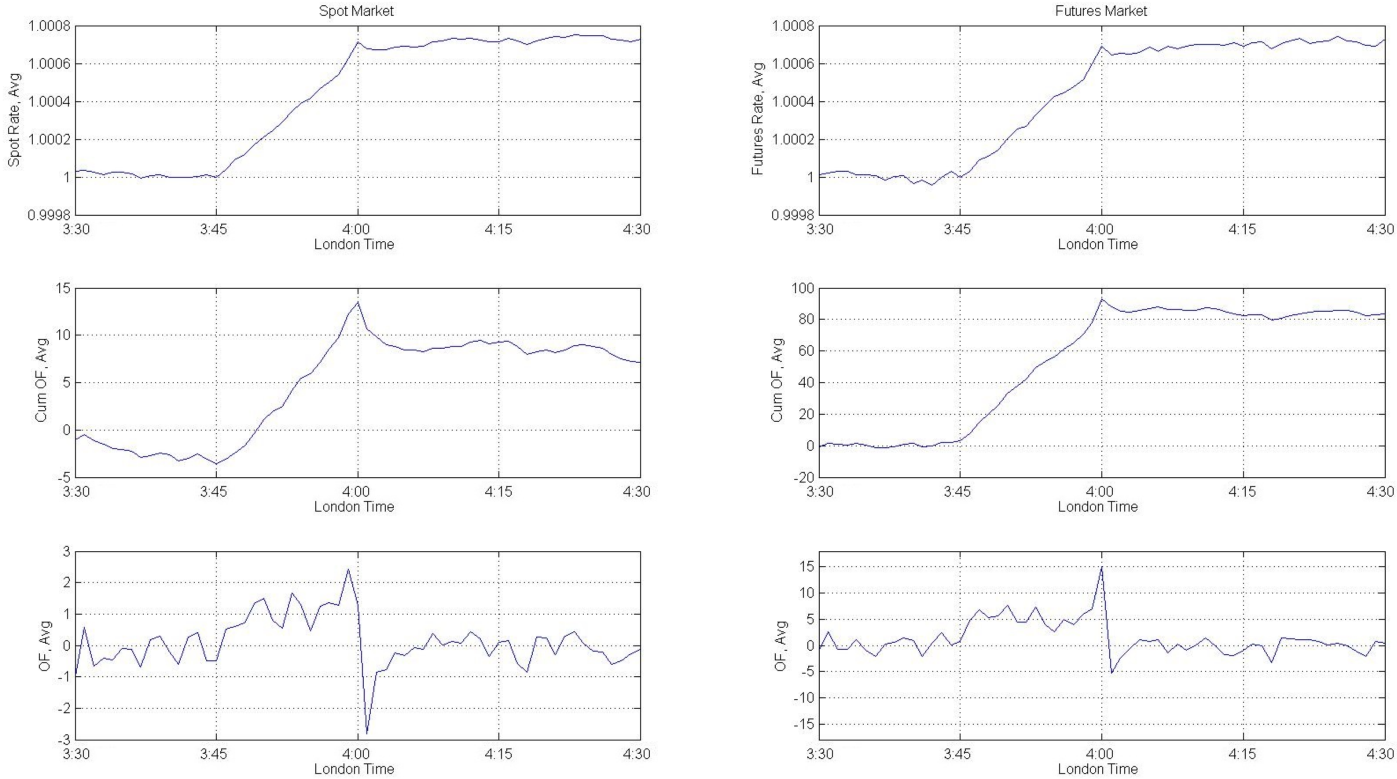

Figure 23: AUD/USD Price-Flow Dynamics around the Fix
(Full Sample Period, Negative Spot Price Movement before the Fix.)

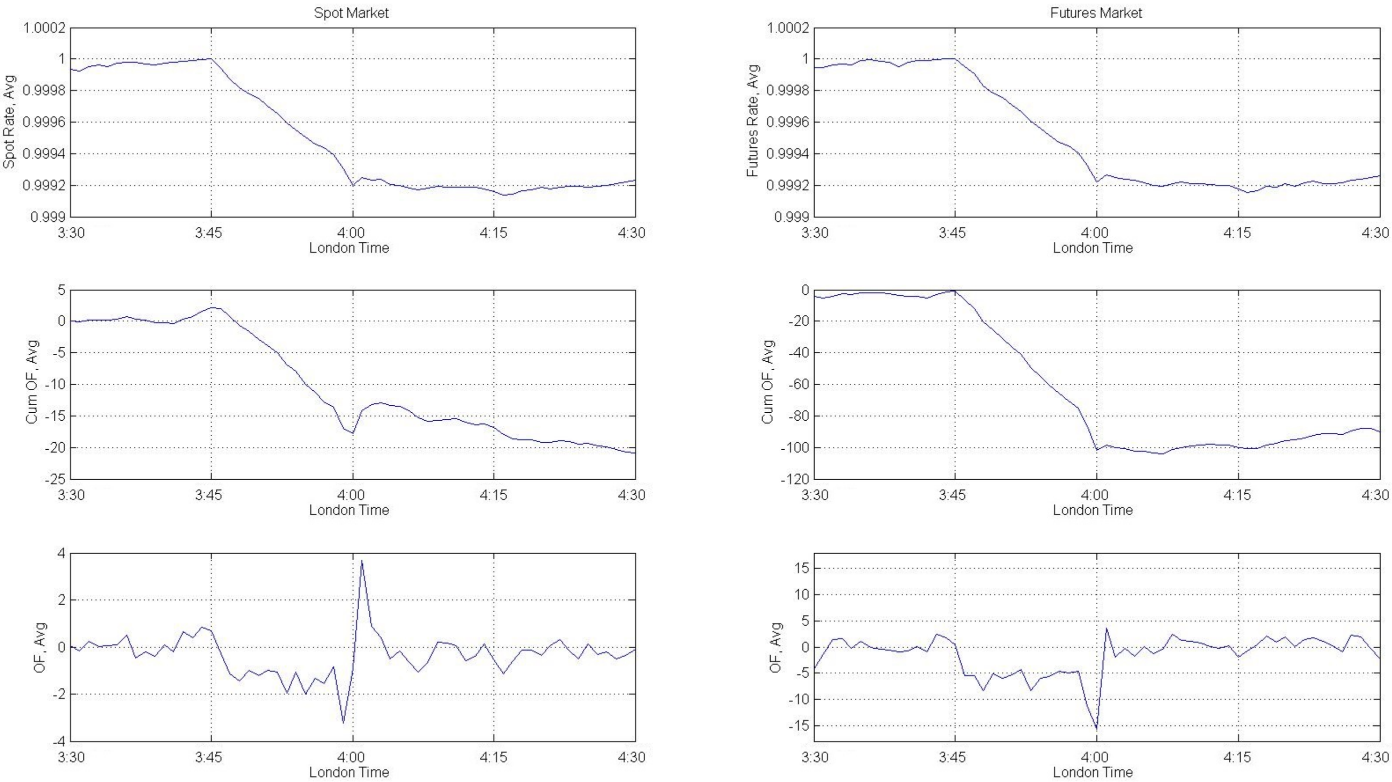

Figure 24: AUD/USD Spot & Futures Volatility

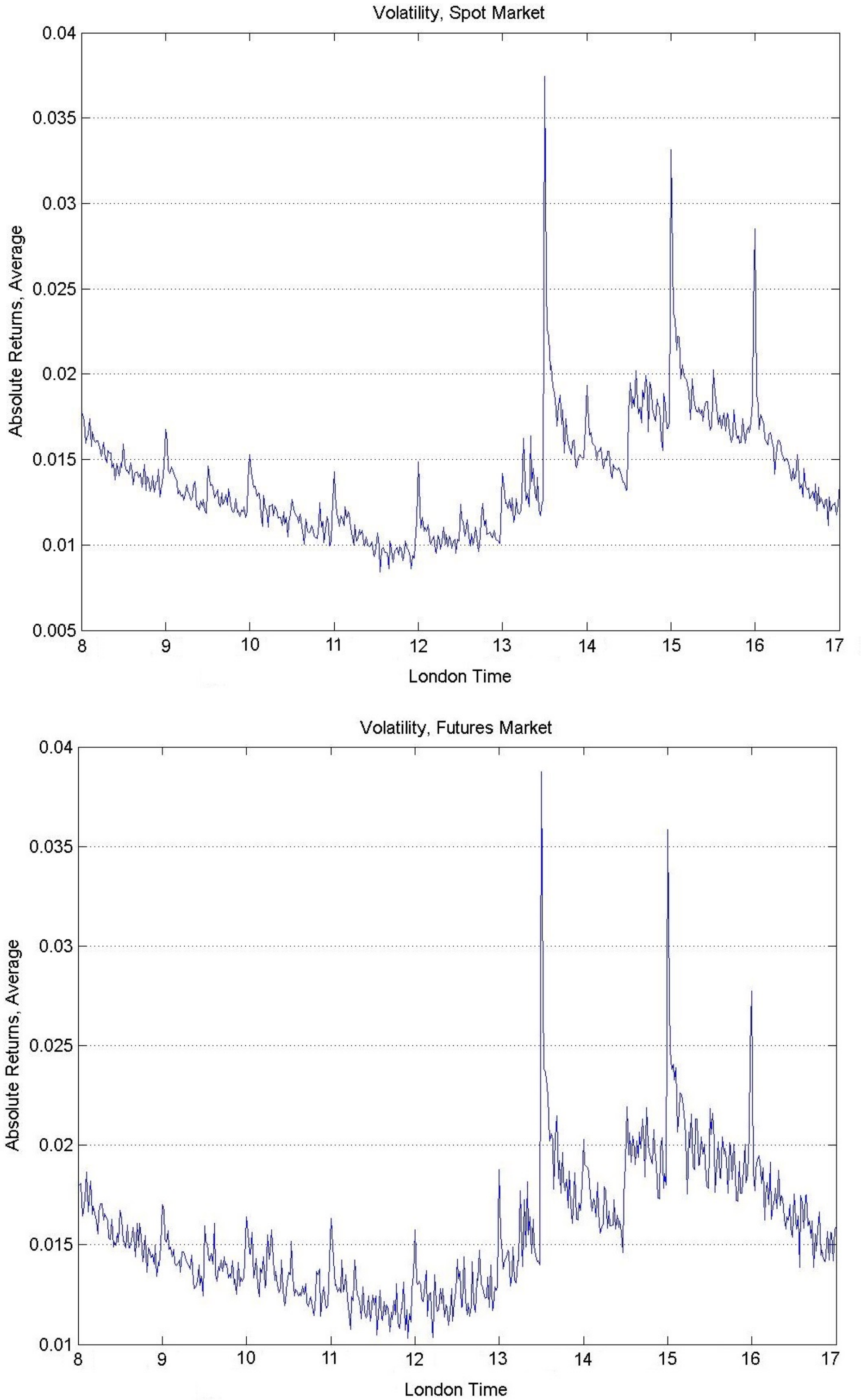

Figure 25: AUD/USD Spot & Futures Price Impact

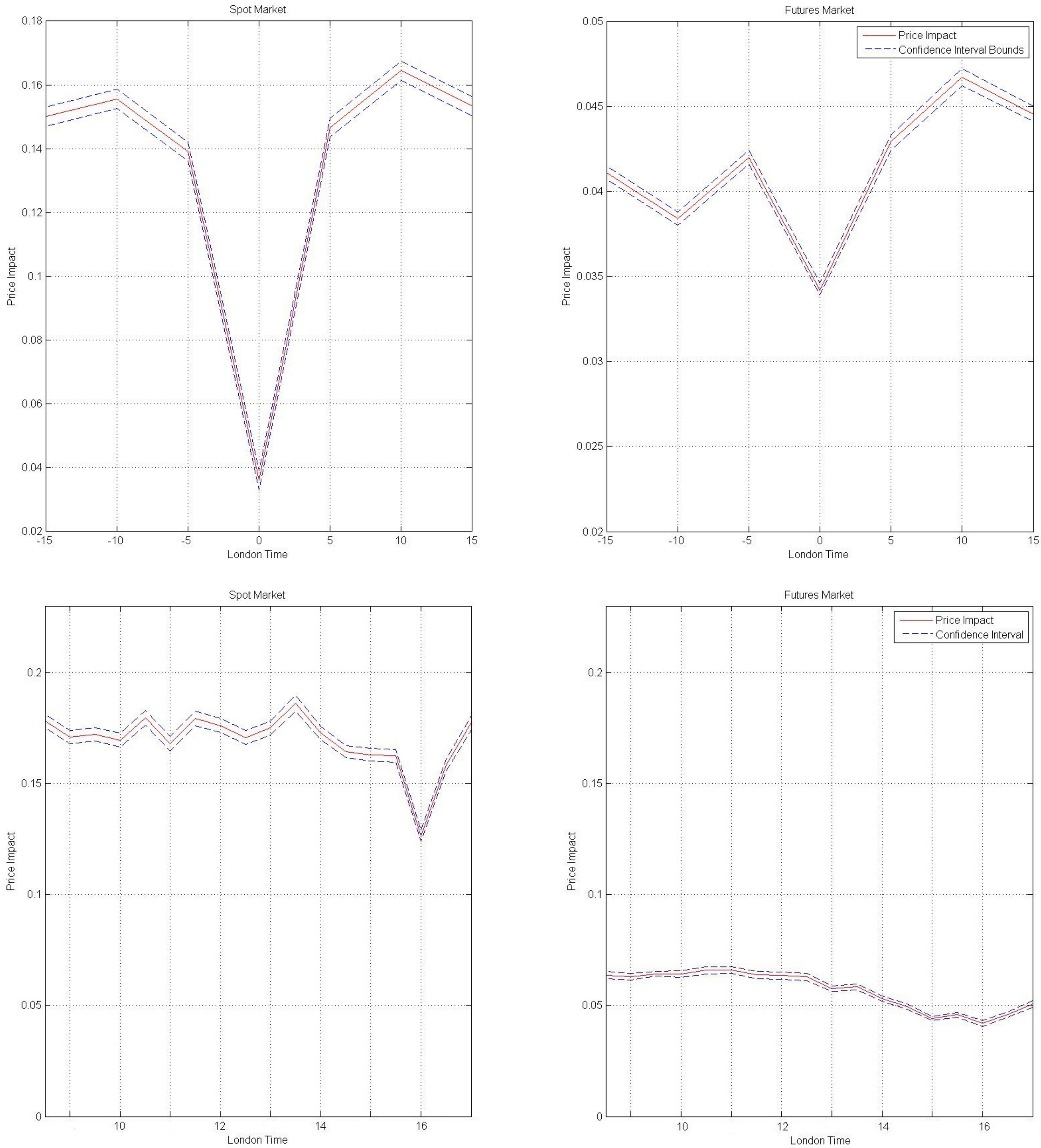

Figure 26: AUD/USD Price-Flow Dynamics around 09:30 am London Time. (Full Sample Period, Positive Spot Price Movement.)

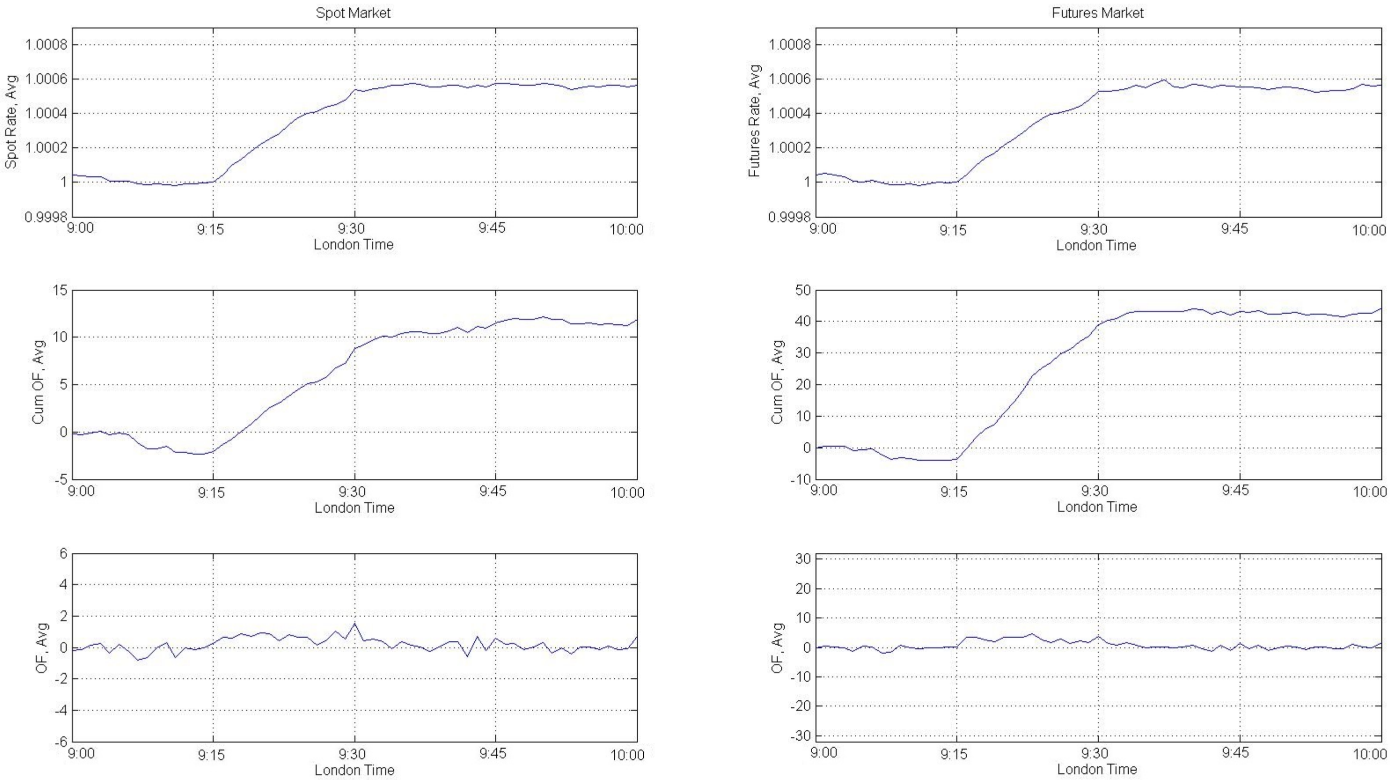

Figure 27: AUD/USD Price-Flow Dynamics around 09:30 am London Time. (Full Sample Period, Negative Spot Price Movement.)

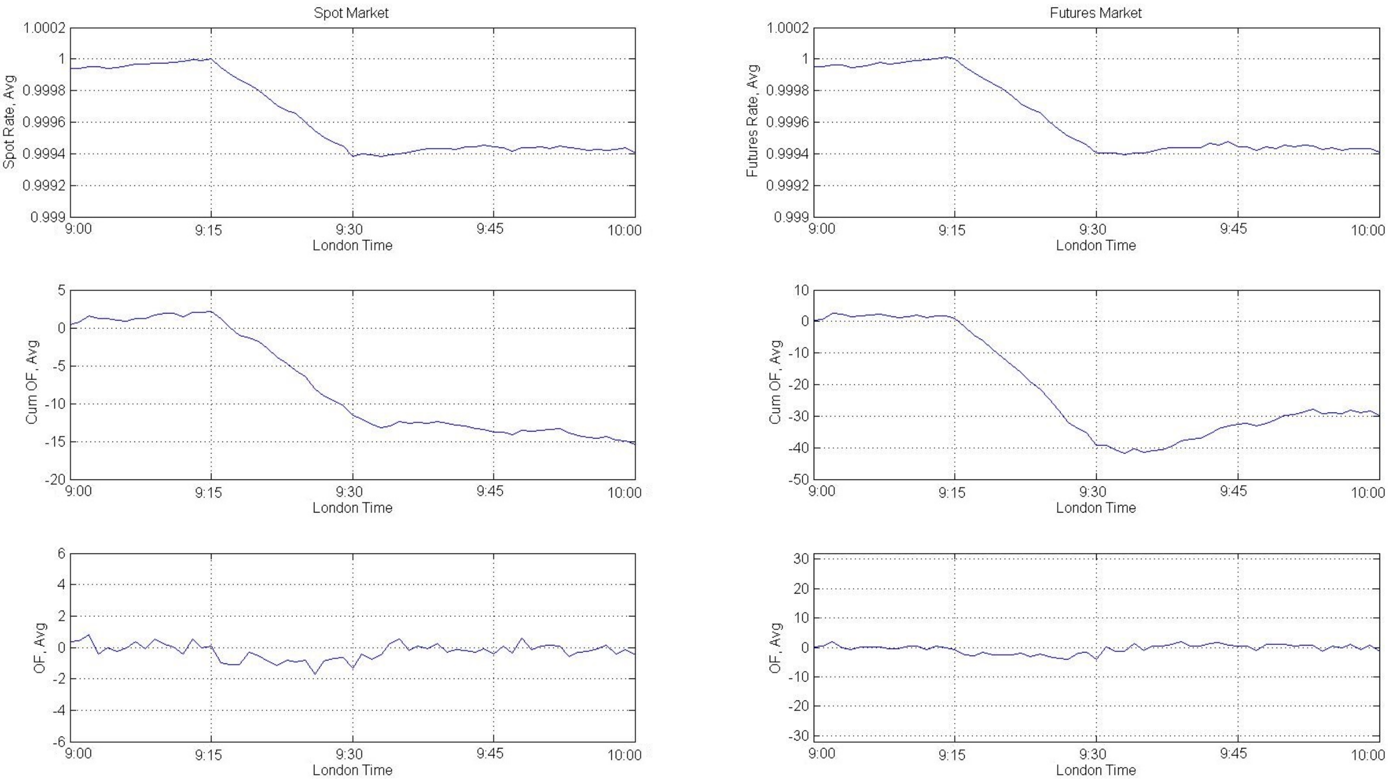

Figure 28: AUD/USD Price-Flow Dynamics around 3 pm London Time.
(Full Sample Period, Positive Spot Price Movement.)

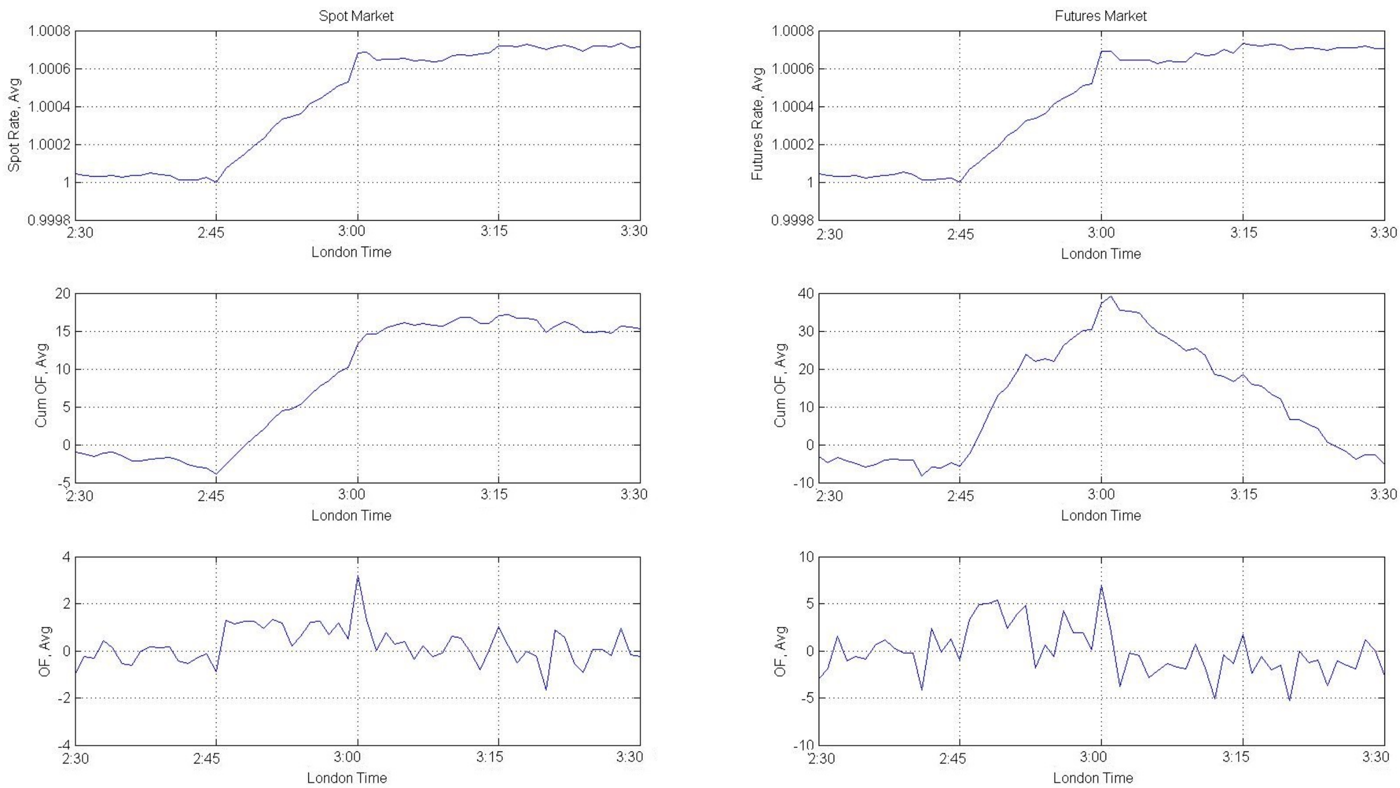

Figure 29: AUD/USD Price-Flow Dynamics around 3 pm London Time.
(Full Sample Period, Negative Spot Price Movement.)

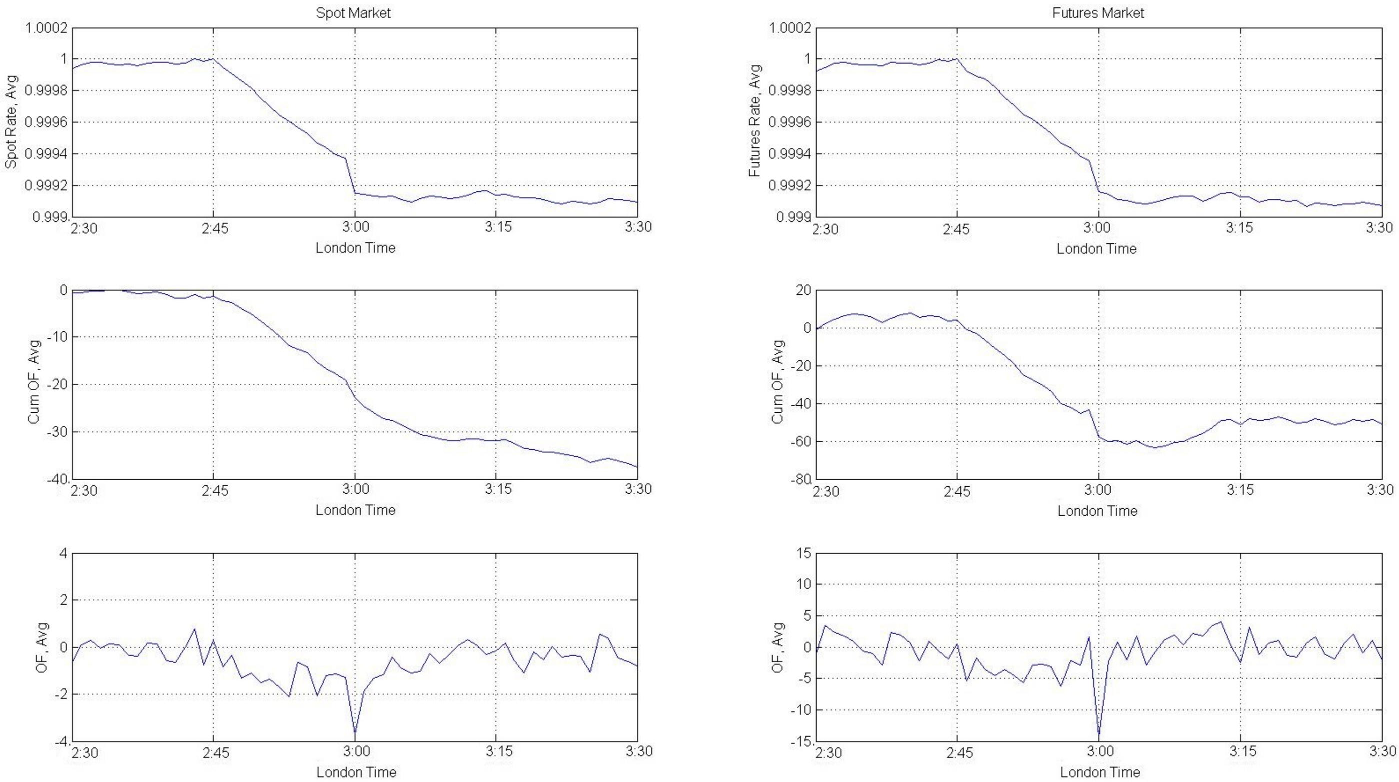

Figure 30: AUD/USD Price-Flow Dynamics around ECB Fix.
(Full Sample Period, Positive Spot Price Movement.)

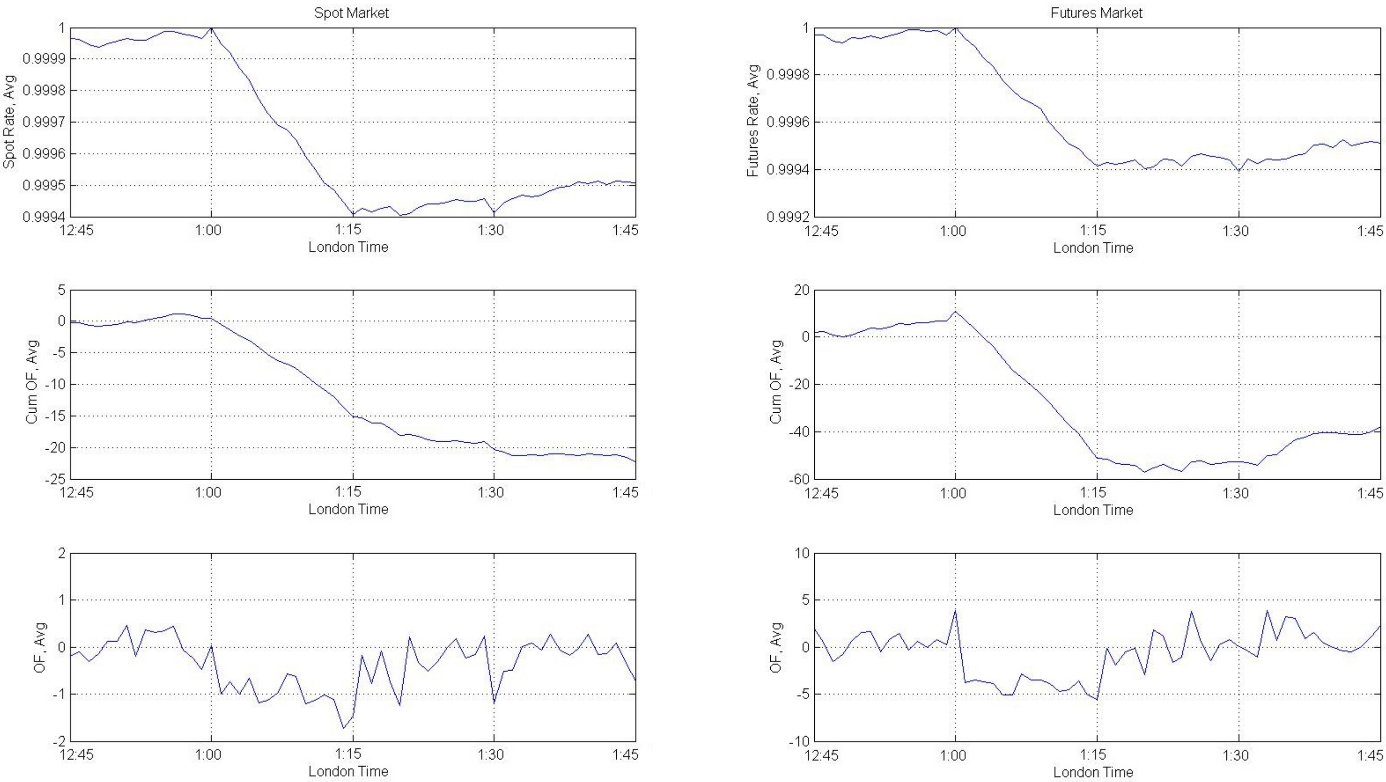

Figure 31: AUD/USD Price-Flow Dynamics around ECB Fix.
(Full Sample Period, Negative Spot Price Movement.)

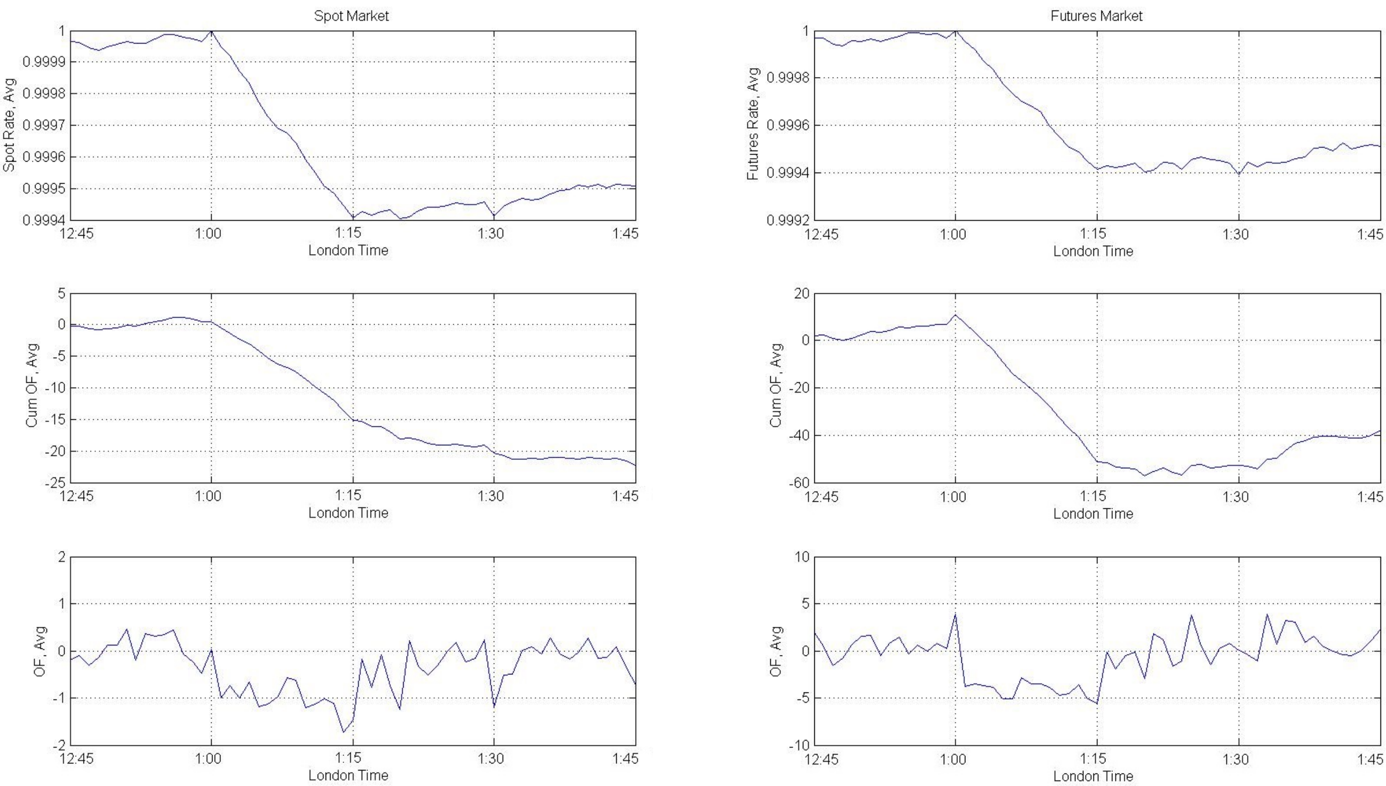

Figure 32: AUD/USD Basis (log)

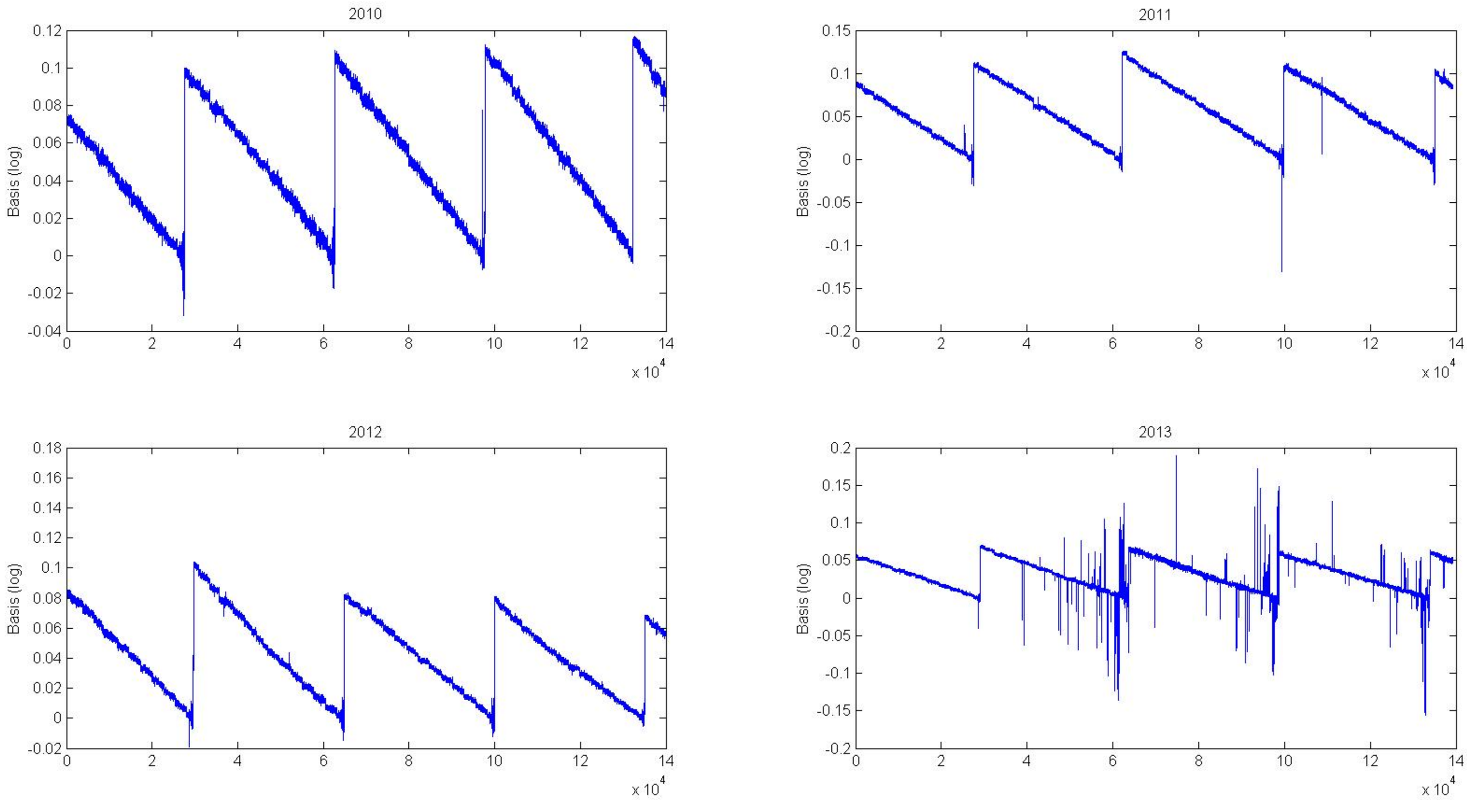

Figure 33: NZD/USD Spot & Futures Trading Activity
(Avg Number of Trades & Order Flow)

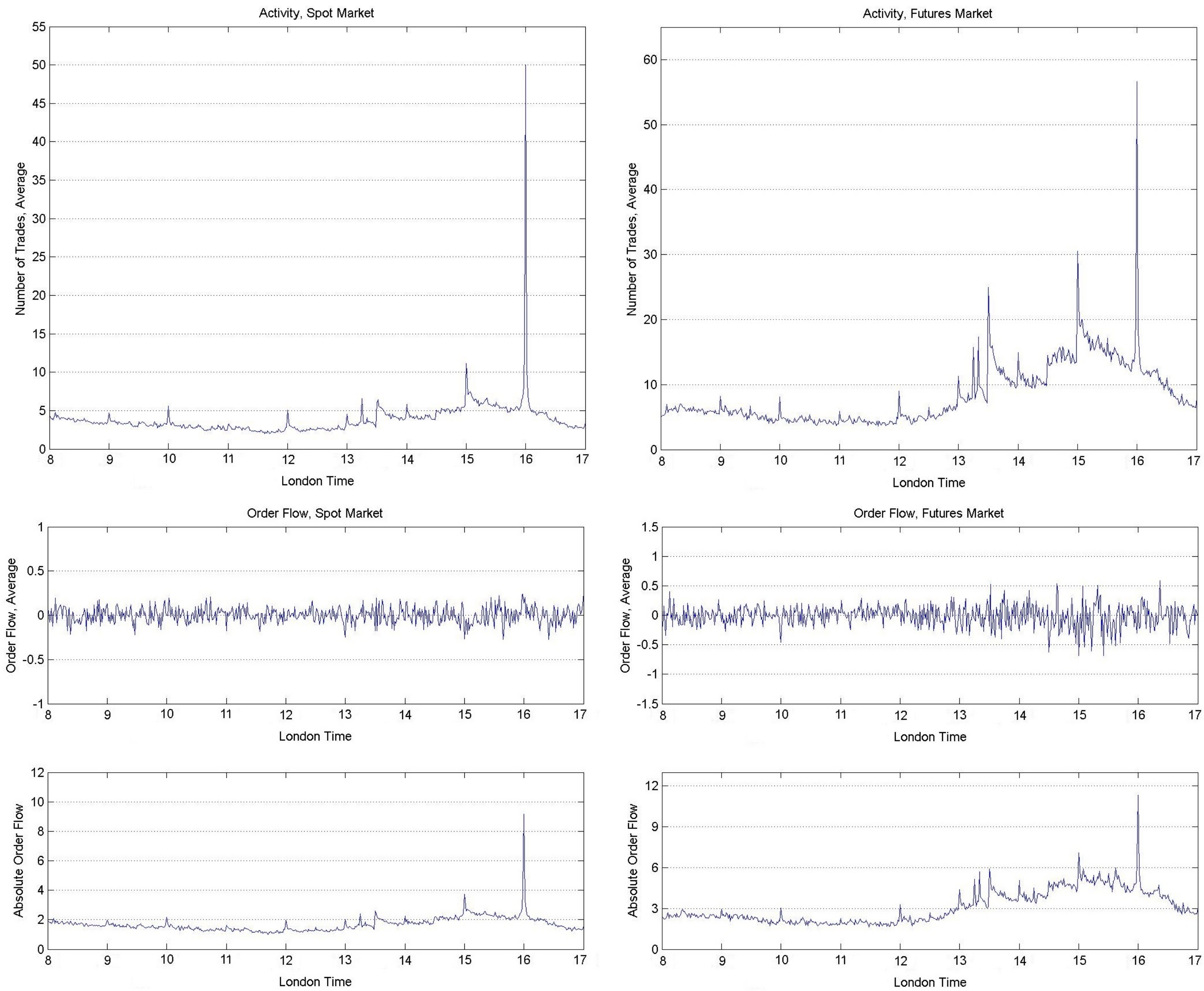

Figure 34: NZD/USD Spot & Futures Bid-Ask Spread

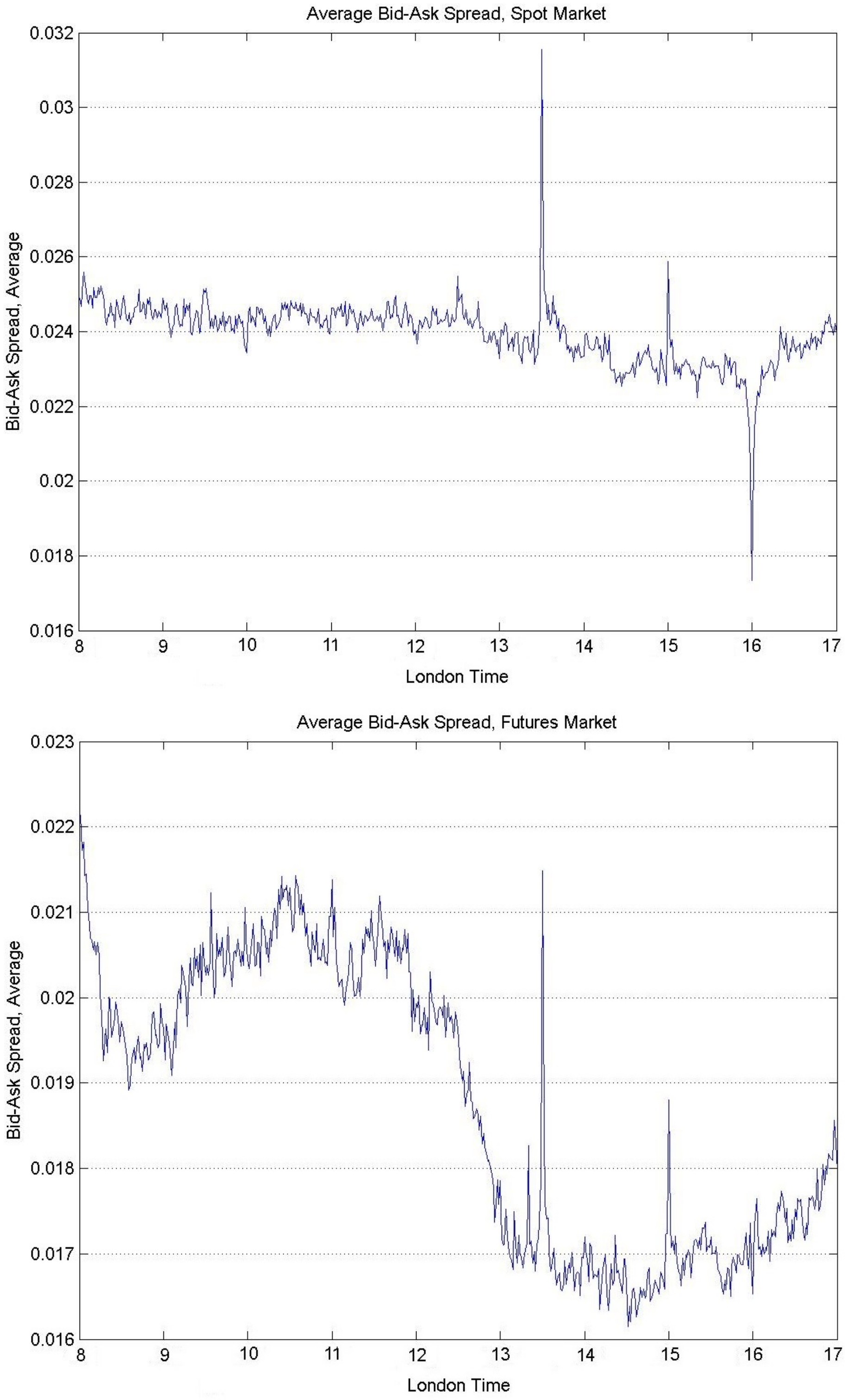

Figure 35: NZD/USD Price-Flow Dynamics around the Fix
(Full Sample Period, Positive Spot Price Movement before the Fix.)

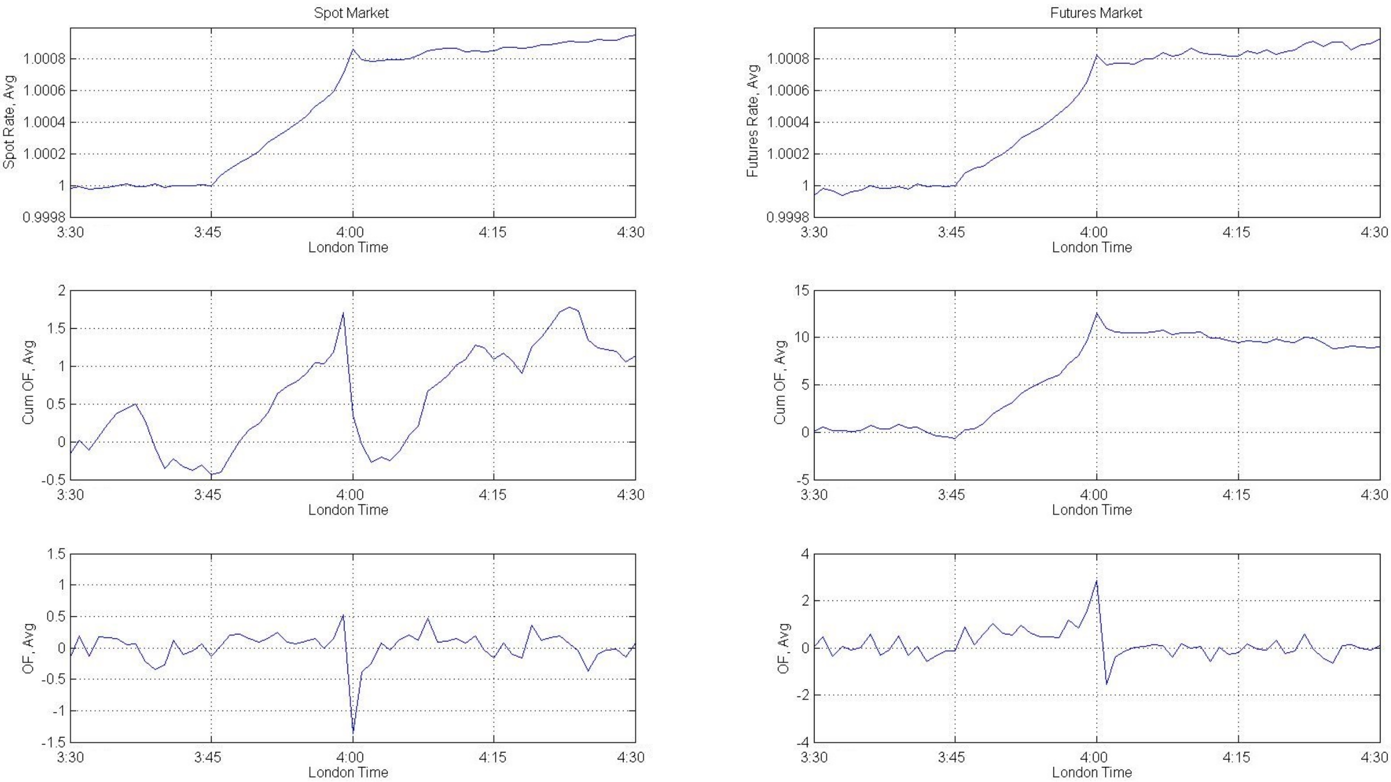

Figure 36: NZD/USD Price-Flow Dynamics around the Fix
(Full Sample Period, Negative Spot Price Movement before the Fix.)

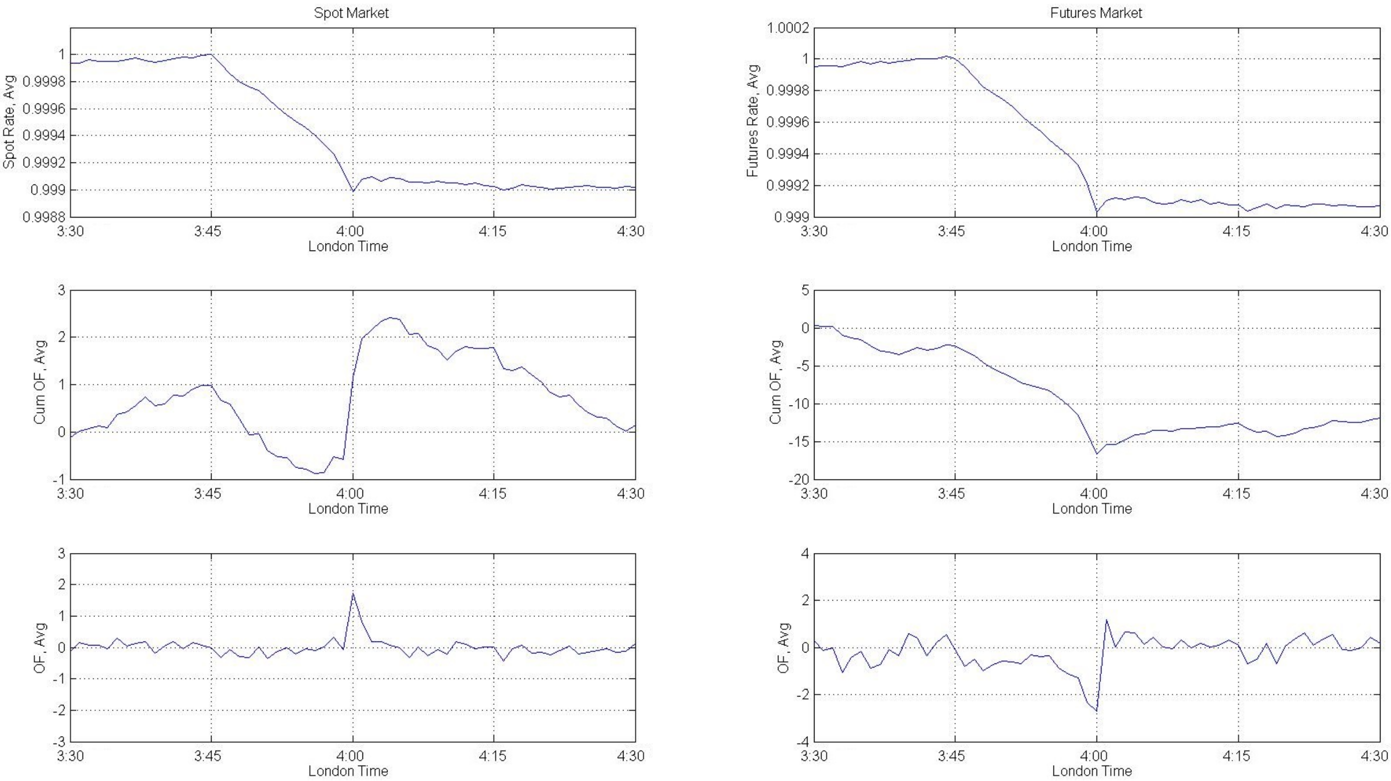

Figure 37: NZD/USD Spot & Futures Volatility

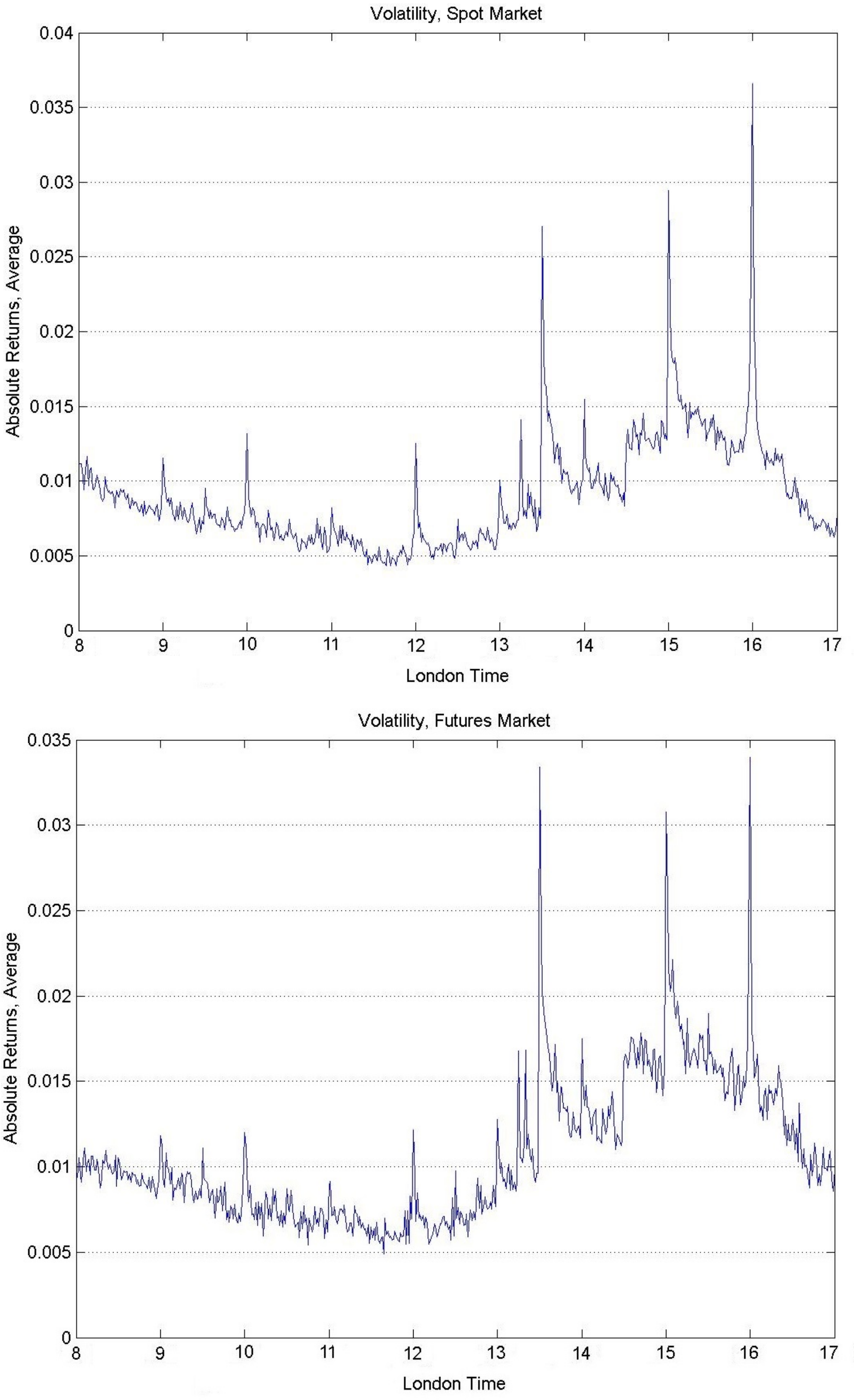

Figure 38: NZD/USD Spot & Futures Price Impact

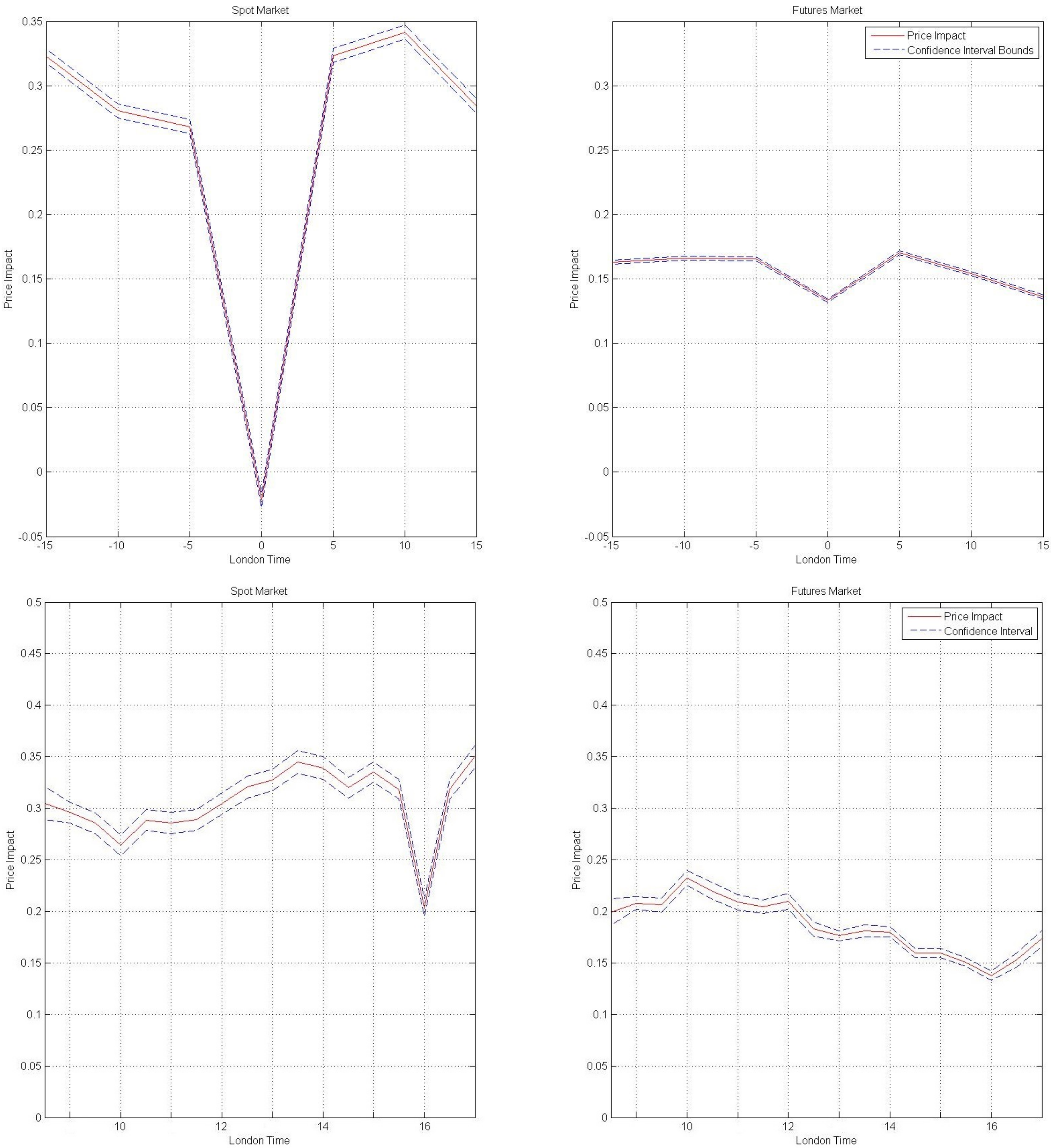

Figure 39: NZD/USD Price-Flow Dynamics around 09:30 am London Time.
(Full Sample Period, Positive Spot Price Movement.)

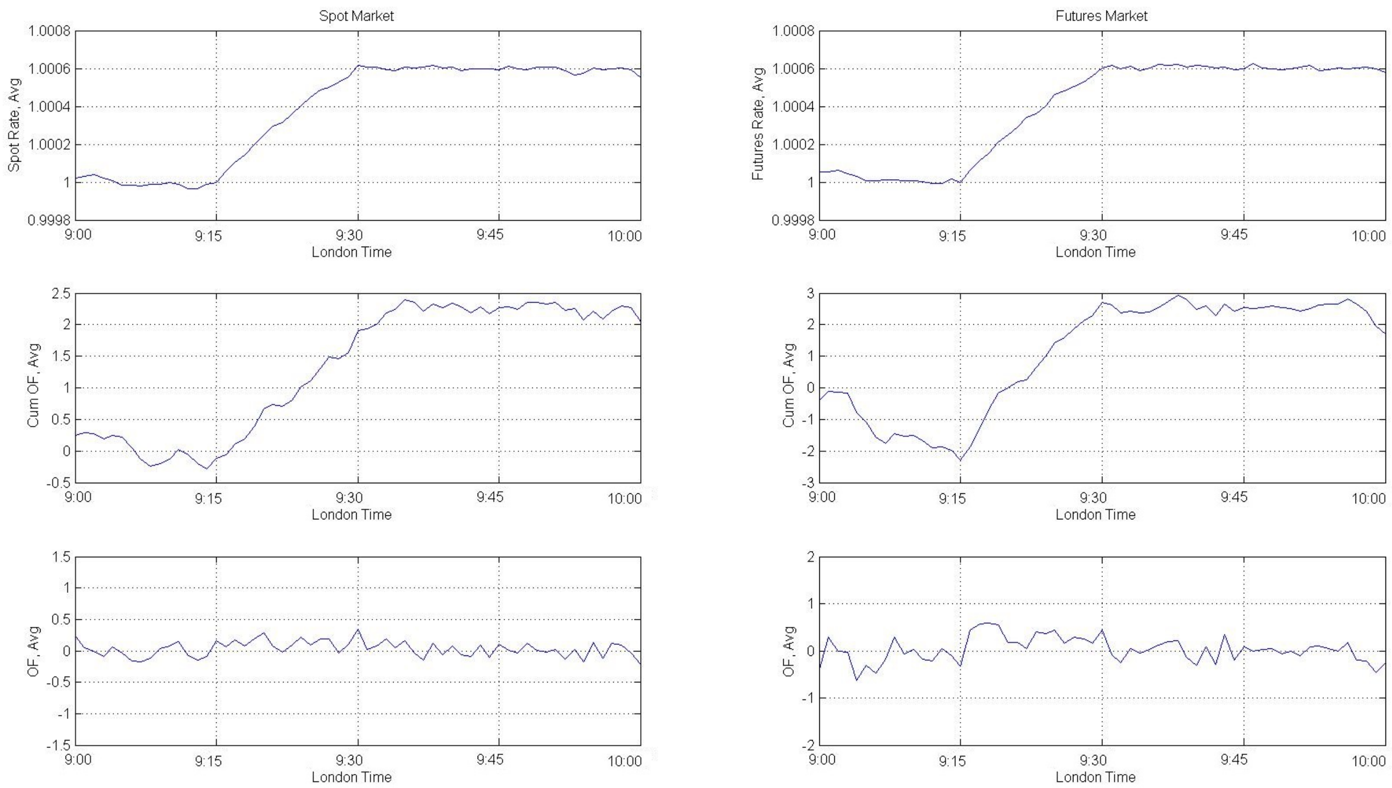

Figure 40: NZD/USD Price-Flow Dynamics around 09:30 am London Time.
(Full Sample Period, Negative Spot Price Movement.)

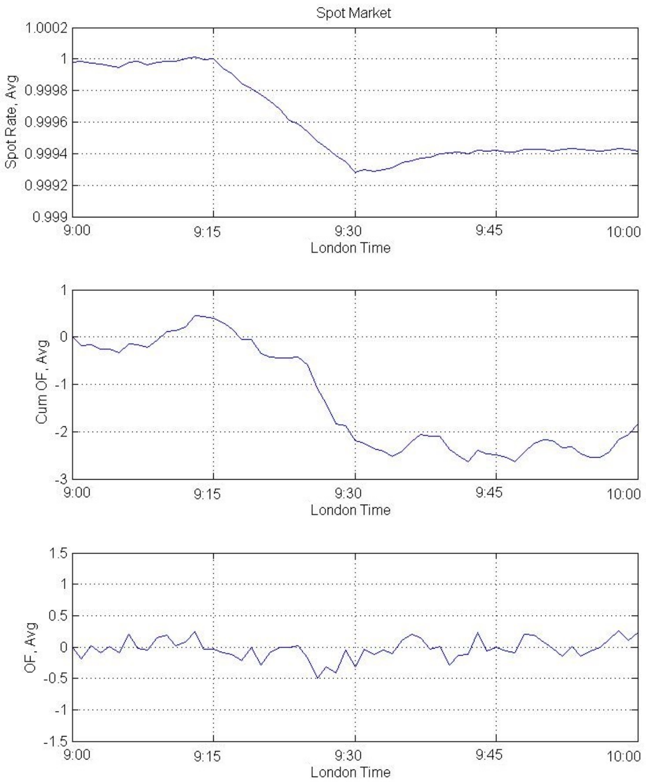

Figure 41: NZD/USD Price-Flow Dynamics around 3 pm London Time. (Full Sample Period, Positive Spot Price Movement.)

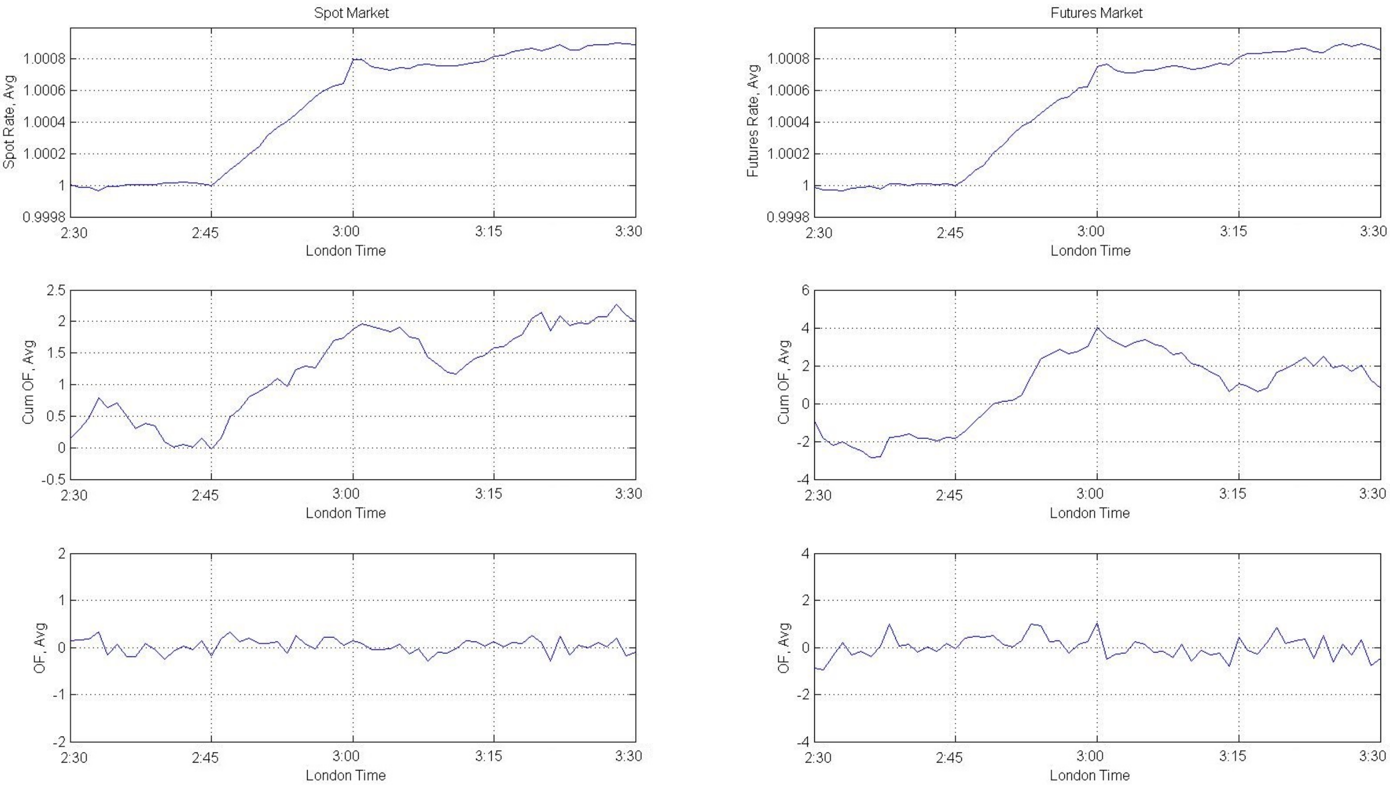

Figure 42: NZD/USD Price-Flow Dynamics around 3 pm London Time.
(Full Sample Period, Negative Spot Price Movement.)

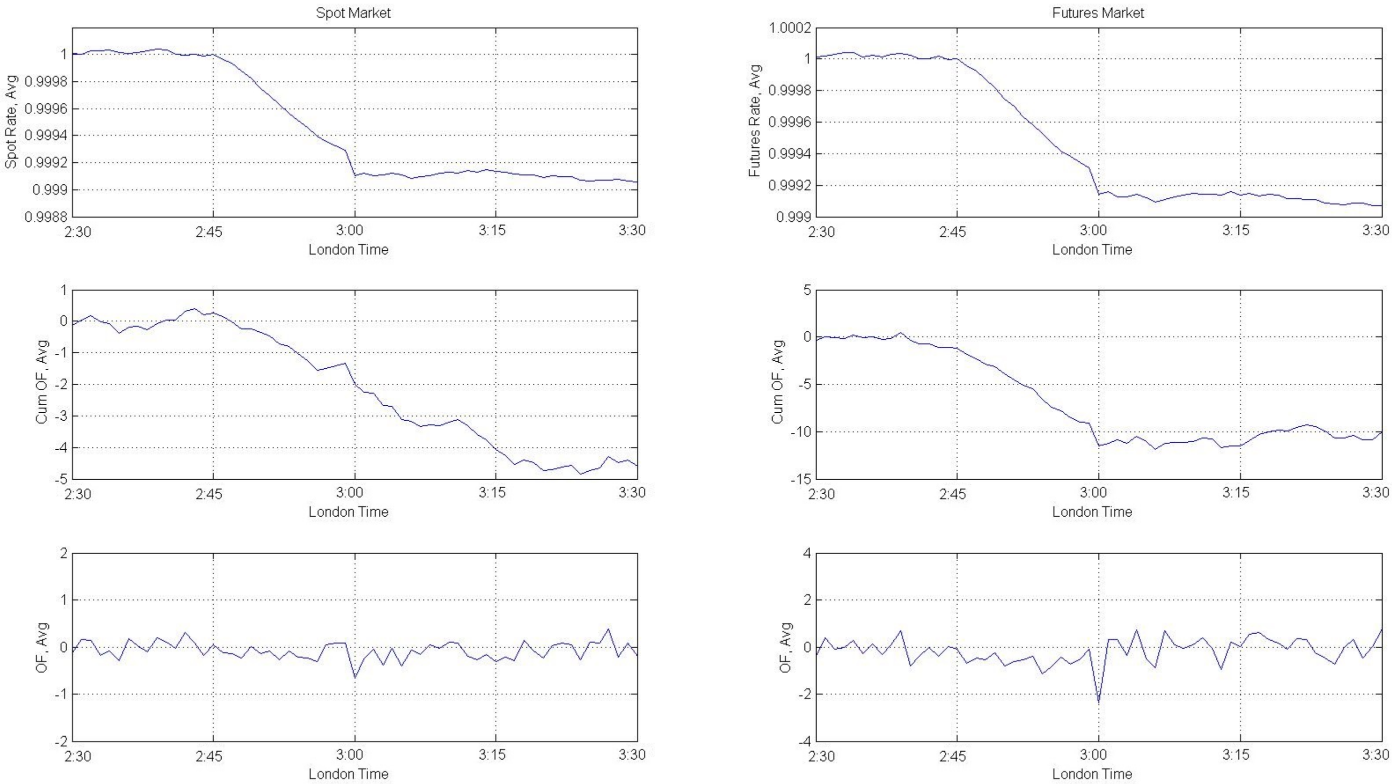

Figure 43: NZD/USD Price-Flow Dynamics around ECB Fix.
(Full Sample Period, Positive Spot Price Movement.)

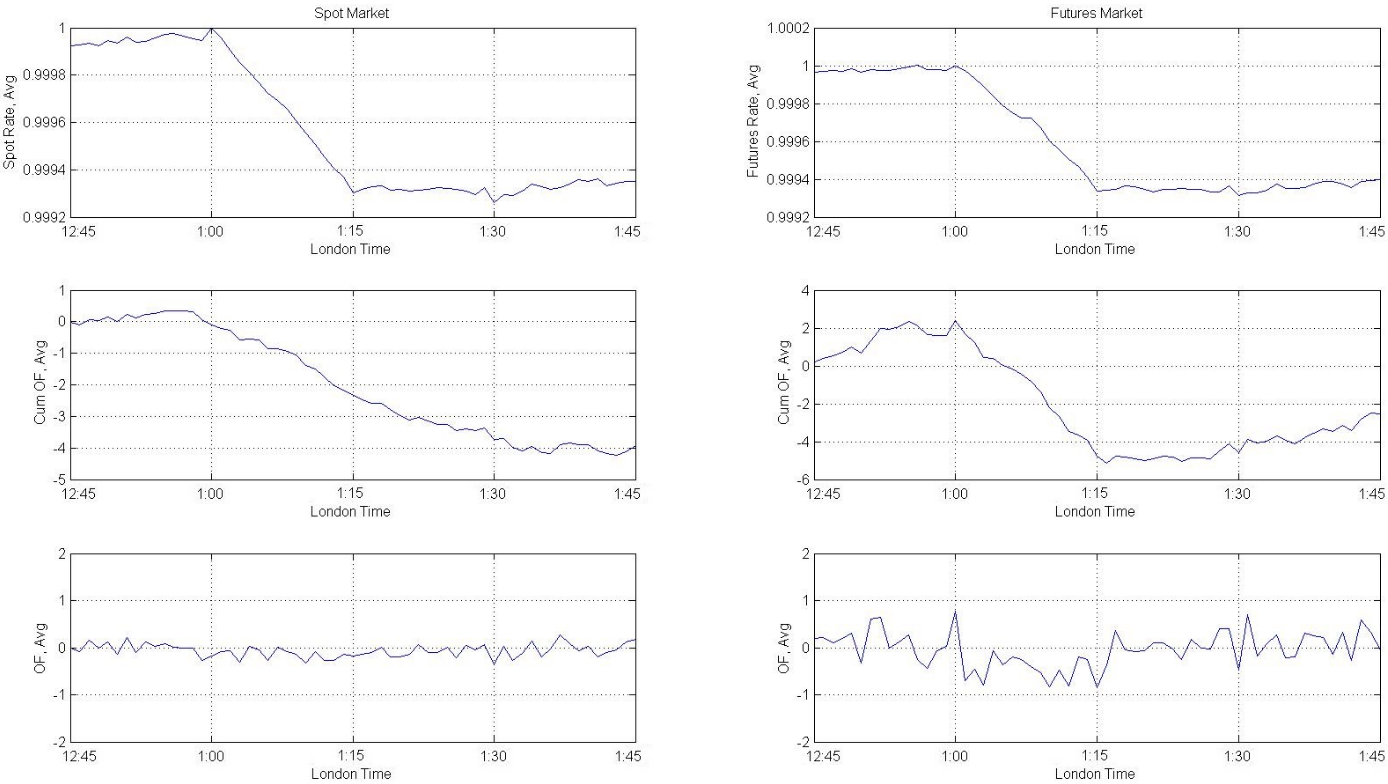

Figure 44: NZD/USD Price-Flow Dynamics around ECB Fix.
(Full Sample Period, Negative Spot Price Movement.)

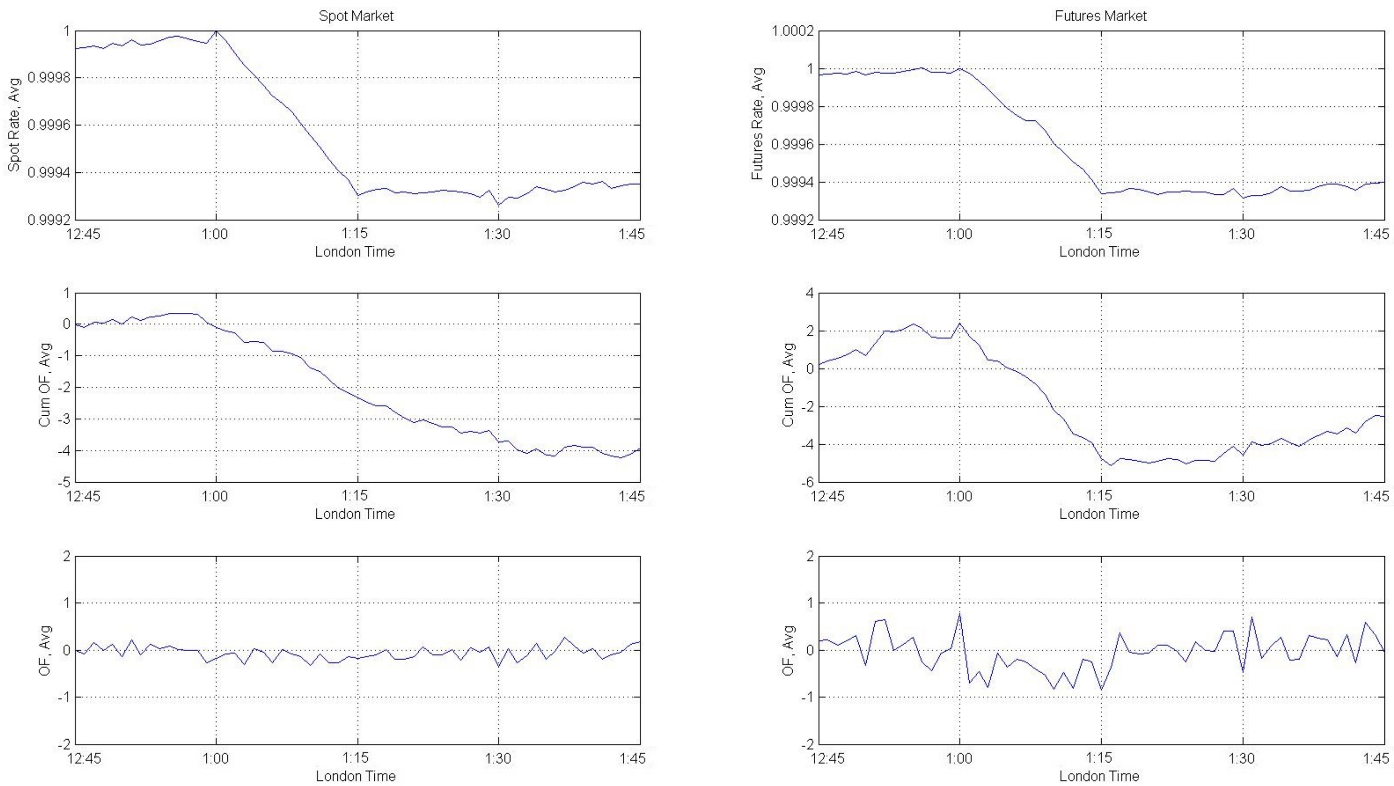

Figure 45: NZD/USD Basis (log)