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Forex Trading and the WMR Fix

Martin D.D. Evans*

November 2014

Second Draft

Abstract

Since 2013 regulators have been investigating the activities of some of the world's largest banks around the setting of daily benchmarks for forex prices. These benchmarks are a key linchpin of world financial markets, providing standardize prices used to value global equity and bond portfolios, to hedge currency exposure, and to write and execute derivatives' contracts. The most important of these benchmarks, called the "London 4pm Fix", "the WMR Fix" or just the "Fix", is published by the WM Company and Reuters based on forex trading around 4:00 pm GMT. This paper undertakes a detailed empirical analysis of the how forex rates behave around the Fix drawing on a decade of tick-by-tick data for 21 currency pairs. The analysis reveals that the behavior of spot rates in the minutes immediately before and after 4:00 pm are quite unlike that observed at other times. Pre- and post-Fix changes in spot rates are extraordinarily volatile and exhibit strong negative serial correlation, particularly on the last trading day of each month. These statistical features appear pervasive, they are present across all 21 currency pairs throughout the decade. However, they are also inconsistent with the predictions of existing microstructure models of competitive forex trading.

Keywords: Forex Trading, Order Flows, Forex Price Fixes, Microstructure Trading Models
JEL Codes: F3; F4; G1.

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* Georgetown University, Department of Economics, Washington DC 20057 and NBER. Tel: (202) 687-1570 email: evansm1@georgetown.edu. Disclosure: The research reported here only uses publicly available data and was undertaken independently without compensation. I do, however, have an ongoing consulting relationship with a law firm involved in litigation related to the WRM Fix.

Introduction

In the summer of 2013 the financial press reported the existence of numerous regulatory investigations into the foreign currency (forex) trading activities of some of the world's largest banks. These on-going investigations by the European Commission, Switzerland's markets regulator Finma and the country's competition authority Weko, the UK's Financial Services Authority, the Department of Justice in the US, the Hong Kong Monetary Authority and the Australian Securities and Investment Commission, among others, center on the actions of the banks' forex traders around the time that benchmark currency prices are determined. The most widely used benchmarks are provided by the WM Company and Reuters, based on forex transactions around 4:00 pm GMT. These benchmarks are colloquially known as the "London 4pm Fix", "the WMR Fix" or just the "Fix". In June 2013 Bloomberg News reported that some forex traders at the world's largest banks had been allegedly colluding in an attempt to manipulate the Fixes, and that regulators were investigating the matter. Since then, very little information concerning the investigations has been made public.[1]

Benchmark interest rates and forex prices, like LIBOR and the Fix, are key linchpins of the world's financial markets. In particular, the Fix provide standardize currency prices that are used to value global equity and bond portfolios, to (dynamically) hedge currency exposure, to write and execute derivatives contracts, and administer custodial agreements. In light of this, the fact that so many financial regulators are investigating forex trading around the Fix suggests that the allegations of collusion are credible. What is much less clear is whether collusion, if indeed it took place, could have materially affected the determination of the Fix to the detriment of participants in the forex and other financial markets. This paper presents statistical evidence pertinent to this issue. In particular, I used a decade's worth of tick-by-tick data from 21 currency paris to study the behavior of the forex prices around the Fix. To be clear, this analysis does not provide any direct evidence on the allegations of the collusion being investigated by regulators. Instead it documents a set of facts about the behavior of forex prices around the Fix which may be juxtaposed against models of forex trading.

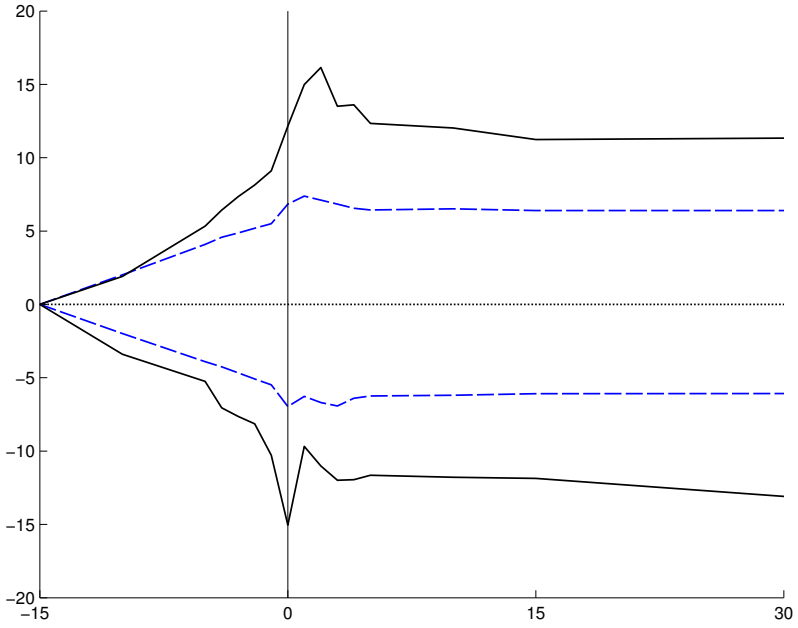
The sine qua non of the Fix is that it provides an accurate measure of the prices (i.e., spot rates) at which currency pairs trade around a specified time (4:00 pm GMT)[2]. This is true in the narrow sense that each Fix is computed from transaction prices in a currency pair during a 60 second window around 4:00 pm. But, interpreted more broadly, it is not the case. The central finding of my analysis is that the Fix benchmarks are very unrepresentative of the prices at which currency pairs trade in the hour or so around 4:00 pm. This finding holds true in all 21 currency pairs I examine (including the major currency pairs: e.g. USD/EUR, CHF/USD, USD/GBP and JPY/USD), and for every year between 2004 and 2013. It is also particular striking on the last trading day of every month. Initial news reports concerning the allegations of collusive behavior of banks' forex traders around the Fix showed instances where the prices from forex trades immediately around 4:00 pm looked very different from the prices several minutes earlier or later. My analysis shows that these examples of price movements around the Fix are far from unusual. On the contrary, they have been commonplace throughout the span of my data.

[1] There have been several news stories reporting the dismissal of forex traders from major banks, but the reasons behind these dismissals - particularly with respect to the regulators' investigations - were not disclosed.

[2] Hereafter, all times refer to GMT.

My main findings are most easily summarized with the aid of a plot. Figure 1 shows the average paths for the USD/GBP spot rate during the 15 minutes before and 30 minutes after the 4:00 pm.[3] The solid lines plot the average level of spot rates measured in basis points relative to their level at 3:45 pm from all end-of-month trading days between the start of 2004 and end of 2013. The dashed lines depict the analogous plots from all other (i.e. intra-month) trading days. The upper branch of the solid and dashed plots shows the average spot rate level on those days when rates rose in the 15 minutes before the Fix, the lower branch shows the level when rates fell.

Figure 1: USD/GBP Spot Rate Profiles Around the Fix



Notes: Solid lines plot the average path for the USD/GBP from 15 minutes before to 30 minutes after the 4:00 pm GMT from all end-of-month trading days between the start of 2003 and end 2013. The dashed lines plot the average path over the same interval on all other (intra-month) trading days. Paths are plotted in basis points relative to the USD/GBP rate at 3:45 pm GMT.

Several features of the plots in Figure 1 are representative of my main findings. The first concerns the difference between the level of the Fix and the prior level of spot rates. Figure 1 shows that relative to the 3:45 level, this difference is roughly ±15 basis points on average at the end-of-the month, and ±7 basis points on intra-month days. I refer to these differences as the pre-fix rate changes. My analysis shows that rate changes of these magnitude are very rare in normal trading. I use the eleven year span of the tick-by-tick data to construct precise estimates of the distribution of rate changes that arise in forex trading away from significant (recurrent) events, such as the Fix and the scheduled release of macro data. These estimated distributions summarize the behavior spot rates under "normal" trading conditions, and can be

[3]Hereafter I use the term "spot rate" when referring to the price at which a particular currency pair trades. The USD/GBP spot rates plotted here are computed from the mid-point of the bid and offer rates, see Section 2 for details.

used to calibrate the rate changes we observe in the minutes leading up the Fix. This calibration exercise reveals that the pre-fix rate changes routinely seen at the end of each month fall in the extreme tails of the rate-change distribution based on normal forex trading. For example, in the case of the USD/GBP, the change in rates between 3:45 and 4:00 at the end of each month appear in 95th percentile of the rate-change distribution six times more frequently than we see under normal trading conditions. This pattern applies across all the currency pairs, and across horizons ranging from one hour to one minute before the Fix. It is also evident, to a lesser degree, in the intra-month data. As Figure 1 shows, intra-month pre-fix rate changes are on average smaller than their end-of-month counterparts, but they still appear in the 95th. percentile of the rate-change distribution four times more frequently than in normal trading. In sum, the movements in spot rates leading up to the 4:00 pm Fix are extraordinarily volatile across all time periods and currency pairs.

My second main finding concerns the relation between spot rates leading up to 4:00 pm, the Fix benchmark, and rates after 4:00 pm. The plots in Figure 1 show that the average path for the USD/GBP spot rate at the end of the month slope in opposite directions either side of (a point close to) the 4:00 pm Fix. In other words there are partial reversals in rate changes around the Fix: on average rates tend to fall after rising towards the Fix, and rise after falling towards the Fix. These reversals are larger in end-of-month than intra month data (as shown in Figure 1) and are present in the rate-dynamics of all 21 currencies studied. Like the pre-fix rate changes, unusually large post-fix changes (i.e., rate changes from the Fix going forward) regularly occur at the end of each month. In the 15 minutes following the Fix they appear in the 95th percentile of the rate-change distribution at two to four times the rate we see under normal trading conditions. Statistically, reversals show up as negative correlations between pre-fix and post-fix rate changes. I find evidence of large statistically significant negative correlations for most currency pairs in end-of-month data over horizons ranging from one to 15 minutes. These findings stand in sharp contrast to the very small degree of serial correlation in the rate changes generated by normal forex trading.

The statistical evidence overwhelming indicates that for all currency pairs the behavior of spot rates around the Fix is very unusual. These findings have several important implications. First, they undermine the notion that the Fix benchmark provides a snapshot of the spot rates (forex prices) associated with normal trading activity during the day. This notion is implicit in the widespread use of the Fix as the "daily spot rate". In reality, however, the daily range for spot rates is similar in size to the time series changes in Fix benchmarks over months, quarters and longer. Moreover, Fix benchmarks generally fall towards the extremes of the daily range for spot rates. Together, these findings imply that the forex returns computed from the Fix benchmarks often materially differ from the returns on forex positions that were initiated and/or closed at times away from 4:00 pm on the same days. This means that the returns routinely studied in the international finance literature (computed from the Fix benchmarks) are at best noisy estimates of the returns achieved by actual investors.

My statistical findings also present a challenge to theories of trading behavior around the Fix. As Section 1 explains, there are particular institutional factors that weigh on the trading decisions of market participants around the Fix that are not present at other times during the trading day. These factors figure prominently in the anecdotal accounts of forex trading around the Fix reported in the financial press, but it is unclear whether such trading can account for the unusual behavior of spot rates we observe. Similarly, existing

microstructure models of the forex trading are silent on whether the unusual statistical characteristics of spot rates around the Fix can arise in an equilibrium when these institutional factors are present.

Currency trading around the WMR Fix has not been the focus of academic research, with the notable exception of Melvin and Prins (2011). They describe how currency hedging by portfolio managers generate forex trading around the Fix. Their empirical analysis focuses on the links between forex and equity returns in the G10 currencies between 1996 and 2009, particularly the effects of equity returns on forex volatility around the Fix. This paper provides a more detailed examination of the behavior of spot rates round the Fix across a wider rage of currency pairs that compliments the analysis in Melvin and Prins (2011).

The remainder of the paper is structured as follows. Section 1 describes the institutional details of the WMR Fix and discusses the implications of existing theoretical trading models for the behavior of spot rates around the Fix. Section 2 describes the data. My empirical analysis begins in Sections 3 and 4. Here I examine how the Fix benchmarks relate to the daily variations in spot rates, and document how rates behave under normal trading conditions. Sections 5 and 6, in turn, examine the behavior of spot rates in the minutes before and after 4:00 pm. Finally, in Section 7, I examine the trading implications of the spot rate reversals around the Fix. This analysis places an economic perspective on my statistical findings, and provides indirect evidence on the degree of competition in forex trading around the Fix. Section 8 concludes.

1 Background

1.1 Institutional Background

The WMR Fix was established as a key financial benchmark at the end of 1993. Morgan Stanley Capital International (MSCI) announced that from December 31st 1993 onwards it would use the benchmark forex prices compiled at 4:00 pm GMT by the WM Company and Reuters to value the foreign security positions in its MSCI equity indices[4] – indices widely used track the performance international equity portfolios. Since then, the Fixes have been incorporated into numerous other tracking indices[5] and derivatives[6]. WRM Fixes are the de facto standard for construction of indices comprising international securities. They are also routinely used to compute the returns on portfolios that contain foreign currency denominated securities as well as the value of foreign securities held in custodial accounts. WMR Fixes are now computed every half-hour for 21 currency pairs and hourly for 160 currency pairs, but the 4:00 pm Fix remains the single most important benchmark forex price each day. My analysis focuses exclusively this particular benchmark.

Although forex markets operate continuously, trading activity is heavily concentrated around European business hours for most currency pairs (exceptions include Asian currencies where trading is concentrated earlier in the day). Thus the 4:00 pm Fix occurs towards the end of the daily window where there are a large number of potential counterparties available to participate in forex trades for major currency pairs. This is an important feature of the Fix. Market participants wanting to trade in the minutes following the Fix will

[4]Initially, the Fix benchmarks were used to compute the MSCI indices for all but the Latin American countries. After 2000 they were used for all the country indices.

[5]Recent examples include: Dow Jones Islamic Market, Global Real Estate (FTSE EPRA/NAREIT) and Global Coal (NASDAQ OMX) indices.

[6]See, for example, the USD volatility warrants issued by Goldman Sacks; Wiener Borse AG fInancial futures and CME spot, forward and swaps.

face spreads between bid and offer rates offered by potential counterparties that are comparable to spreads earlier in the day, but in the next hour or so (with exact timing depending on the particular currency pair) spreads widen as the number of counterparties shrinks. Generally speaking, forex trading becomes increasing costly (in terms of spreads) as one moves later into the day past the 4:00 pm Fix.

The Fix is computed over a one minute window that starts 30 seconds before 4:00 pm. The methodology is described on the WMR website (http://www.wmcompany.com) as follows:

> Over a one-minute Fix period, bid and offer order rates from the order matching systems and actual trades executed are captured every second from 30 seconds before to 30 seconds after the time of the Fix. Trading occurs in milliseconds on the trading platforms and therefore not every trade or order is captured, just a sample. Trades are identified as a bid or offer and a spread is applied to calculate the opposite bid or offer.
>
> Using valid rates over the Fix period, the median bid and offer are calculated independently and then the mid rate is calculated from these median bid and offer rates, resulting in a mid trade rate and a mid order rate. A spread is then applied to calculate a new trade rate bid and offer and a new order rate bid and offer. Subject to a minimum number of valid trades being captured over the Fix period, these new trade rates are used for the Fix; if there are insufficient trade rates, the new order rates are used for the Fix.

Two aspects of this methodology are noteworthy. The first concerns the source of the bid and offer forex rates. The electronic trading platforms run by Reuters and Electronic Broking Services (EBS) (now owned by ICAP) are the main trading venues for dealer-banks in the forex market. EBS is the primary trading venue for EUR/USD, USD/JPY, EUR/JPY, USD/CHF and EUR/CHF, and Reuters Matching is the primary trading venue for commonwealth (AUD/USD, NZD/USD, USD/CAD) and emerging market currency pairs.[7] The WMR Fix uses either platform as the primary data source depending on the currency pair, and rates from Currenex as a secondary source for validation. In recent years forex trading platforms have proliferated so that a wider array of (tradable) bid and offer rates are available to market participants than just those sourced by the Fix methodology. Thus the Fix should be viewed as a benchmark computed from a subset rather than the universe of forex rates available in the one minute window around 4:00 pm.

The second aspect concerns the computation of the trade benchmark. A careful reading of the methodology reveals that no account is taken of trading volume. This means that the transaction price recorded as the result of the submission of a market order to buy or sell forex valued at 20 million USD has exactly the same weight in computing the benchmark as an order valued at 200 million USD. Moreover, the methodology takes no account of order flow (i.e., the difference between the value of market orders to buy forex and sell forex within a time interval). Order flow during the one minute Fix window may be strongly positive or negative, but this fact will not be reflected in the Fix benchmark (provided there are enough buy and sell market orders to compute the median bid and offer trade rates).

The existence of the 4:00 pm Fix per se would not be of any great significance were it not for the fact that market participants face strong economic incentives to trade forex in and around the Fix window. It

[7] Throughout, I use market abbreviations for currencies: e.g., U.S. Dollar (USD), Euro (EUR), Swiss Franc (CHF), Japanese Yen (JPY), British Pound (GBP), Australian Dollar (AUD), Canadian Dollar (CAD) and New Zealand Dollar (NZD). I also follow market conventions when quoting spot rates in direct or indirect form, e.g. EUR/USD rather than USD/EUR.

is hard to overstate the importance of this point. If the Fix were calculated every day according to the methodology described above and archived as a data series, its existence would have no economic relevance for the behavior of the forex market. Fixes would simply be snap shot measures of forex rates around 4:00 pm that could be useful for research. One could argue about whether the methodology could be improved, but these would be arguments about measurement rather than arguments about how the existence of the Fix affected actual market activity. Of course, in reality, the Fixes aren't simply archived. Instead they are used in real time to value other securities, such as equity portfolios and derivatives. Market participants face strong incentives to trade in and around the Fix precisely because the Fixes are used for real-time valuation purposes.

The trading incentives created by the existence of the Fix originate with two groups of market participants. The first comprises investors wishing to hedge some of the currency risk associated with their holdings. As Melvin and Prins (2011) stress, fund managers with cross-boarder equity investments are important members of this group. Because the performance of their investments are often tracked against the returns on the MSCI indices that use the Fix, many managers will want to reduce the tracking error of their own portfolios by choosing to hedge some of their (forex) exposure to the Fix. In principle this hedging could take place continuously through the adjustment of forex forward positions, but in practice most managers adjust their currency hedge positions once a month, usually on the last trading day of the month. This hedging activity produces orders to purchase or sell forex. And, since the managers are concerned with tracking the MSCI indices, they want their forex orders to be filled at the Fix to minimize the tracking error in their own portfolio's performance.

As a concrete example, suppose the UK based mutual fund manager holds part of his portfolio in US equities. At the end of last month the US position had a value of 1 billion USD. The manager also maintains a 50 percent forex hedge ratio against this position, which was short 500 million USD at the end of last month. Now suppose that the value of the US equity portfolio rises by five percent during the current month to a value of 1050 million USD on the day prior to the end of the month. In this situation, the manager would want to increase his short USD position by 25 million, so on the last day of the month he would place an order to sell 25 million USD with a dealer-bank. This order could be submitted as a standard forex order, to be filled immediately by the dealer-bank at the best bid rate for the USD/GBP prevailing in the market (say on Reuters Matching). Alternatively, the manager could submit a "fill-at-fix" forex order, which specifies that the order to sell 25 million USD should be filled at the Fix benchmark rate established at 4:00 pm.[8] By market convention, fill-at-fix orders must be submitted to dealer-banks before the 3:45 pm. Consequently, the submitter of such an order faces a good deal more uncertainty about the exact rate at which the order will be filled than with a standard forex order.[9] Nevertheless, a fill-at-fix order will be preferable to the fund manager because it guarantees that the GBP value of the adjusted hedge portfolio matches 50 percent of the equity position valued in GBP at the new USD/GBP Fix benchmark.

This example illustrates how the use of the Fix in valuing equity portfolios combines with the desire of fund managers to (partially) hedge forex risk to produce fill-at-fix forex orders leading up to the Fix. The

[8]The actual rate received by the manager will also include a spread adjustment to the Fix benchmark depending on whether the order was to buy or sell foreign currency. The fill-at-fix contract may specify the spread reported by WMR or one set by the dealer-bank.

[9]As we shall see, the volatility of spot rates between 3:45 and 4:00 pm is several orders of magnitude higher than the volatility of rates during the (fraction of) seconds between the submission and filling of a standard forex order.

use of the Fix benchmarks in derivative contracts produces a similar incentive to submit fill-at-fix orders from other investors wishing to partially hedge their derivative positions. Thus, the existence of the Fixes and their use in real-time valuation produces a hedging incentive for the submission of fill-at-fix orders before 3:45 pm. These incentives are particularly strong at the end of the month.

The second group of market participants affected by the Fix are the dealer-banks that accept fill-at-fix forex orders. As noted above, fill-at-fix orders differ from standard forex orders because the dealer-banks agree to fill them at the Fix benchmark rate at least 15 minutes before that rate is determined. Thus, in effect, the dealer-banks are offering a guarantee that the order will be filled at particular point in time whatever the prevailing rates (as represented by the Fix) might be.[10] By contrast, in accepting a standard forex order the dealer-bank undertakes to fill the order immediately at the best available prevailing rate.[11] Of course, such guarantees represent a source of risk to the dealer-bank. Generally speaking, it is the desire to manage this risk that creates incentives for dealer-banks to trade in and around the Fix.

To understand these risk, consider the position of a dealer-bank that by 3:45 pm has on net fill-at-fix orders to purchase 200 million GBP in the USD/GBP market. Broadly speaking, there are three strategies available to the dealer-bank. The first is simply to fill the fill-at-fix orders immediately at the prevailing market rate. This strategy runs the obvious risk that the Fix benchmark will be established at a significantly different level than current rates. In this particular example, the dealer risks a fall in the USD/GBP rate between 3:45 and 4:00 pm, which would produce a (USD) trading loss because the 200 million GBP purchased at 3:45 would be sold on to the bank's fill-at-fix customers at a lower USD price established by the Fix. The second strategy is to purchase the 200 million GBP at a rate as close as possible to the Fix benchmark. This involves trading within the one minute Fix window, and even then, there is no guarantee that the actual rate at which the GBP purchase is made exactly matches the Fix benchmark (because the latter is an average of rates during the Fix window). The third strategy has two prongs: (i) purchase the 200 million GBP incrementally between 3:45 and 4:00 and (ii) take a speculative position in anticipation of a change in rates between 3:45 and 4:00. The first prong reduces the risk from a fall in the USD/GBP rate relative to the first strategy, but it cannot eliminate the risk entirely. Goal of the second prong is produce a trading profit that will cover the remaining slippage between the Fix benchmark and the (effective) rate at which the 200 million GBP were purchased.

Several aspects of the third trading strategy are particularly noteworthy. First, the strategy necessitates trades to establish and close out the speculative position in addition to the trades necessary to fill the fill-at-fix order. Consequently, there would be greater trading volume around the Fix if many dealer-banks follow this strategy than is necessary to simply process the fill-at-fix orders across the market. Second, the strategy requires an inclination on the part of dealer-banks to take speculative positions. Generally speaking, dealer-banks will be more willing to take such positions the more representative they believe their fill-at-fix orders are relative to others across the market. For if their orders are indeed representative, they provide information on the aggregate order flow that must be processed by the market between 3:45 and 4:00 pm. Consistent with large body of research, dealer-banks know that order flow is the dominant driver of spot rates (away from scheduled data releases), so they will be willing to take a speculative position to benefit from

[10] While these are not legally binding guarantees, it is very rare for fill-at-fix orders not to filled at the Fix benchmark rate.
[11] Dealer-bank could also accept a limit order where price-contingency replaces the immediacy feature of the forex order.

the anticipated impact of order flow on future rates. Under these circumstances, the trades used by dealers to initiate their speculative positions will be in the same direction as the trades they use to incrementally fill the fill-at-fix orders – a trading pattern referred to as "front running".

In sum, the economic relevance of the Fix arises from the fact that it is used in real-time valuation. This, in turn, creates incentives for atypical forex trading activity around the 4:00 pm. There is a strong hedging incentive for fund managers and derivative investors to submit fill-at-fix forex orders to dealer-banks before 3:45 pm, particularly at the end of the month. And, once these atypical forex orders are received, there are strong incentives for dealer-banks to trade in a way that mitigates the risk inherent in filling the orders. The key challenge in examining the behavior of the forex market around the Fix is understanding how this trading activity is reflected in the behavior of spot rates.

1.2 Theoretical Background

The institutional features described above do not, in and of themselves, provide an explanation for the behavior of spot rates around the Fix. The submission of fill-at-fix forex orders before 3:45 pm and their implications for risk-mitigating trades by dealer-banks do not comprise a trading theory that can account for the volatility and negative serial correlation in spot rate changes around the Fix found in the data. What we require, instead, is an understanding of how the decisions by all market participants (i.e., dealer-banks and others) give rise, in aggregate, to the unusual behavior of spot rates we observe. In short, we need a model of forex trading that incorporates the institutional features described above and delivers equilibrium spot rates with the same statistical characteristics as we find in the data.

The Portfolio Shifts (PS) model developed by Lyons (1997) and Evans and Lyons (2002) and extended in Evans (2011) provides some useful insights into the behavior of spot rates around the Fix. The model explains how the optimal trading decisions of a large number of dealer-banks drive the dynamics of spot rates over the trading day. In particular, it describes how dealer-banks trade with one-another after they have received and filled forex orders from investors (non-banks), and how resulting pattern of inter-dealer trading is reflected in the behavior of spot rates.

The first insight arises from the characteristics of the model's equilibrium. As in standard models, equilibrium (bid and offer) spot rates clear markets. In the context of a forex trading model this means that there must be willing counterparties to all currency trades. In addition, the spot rates at any point in time support an ex ante efficient risk-sharing allocation across all market participants. Efficient risk-sharing requires that the marginal utility from holding forex (either a single currency or a portfolio) is the same across all market participants in every possible state of the world. This allocation is achieved at the end of each trading day in the PS model because the spot rate reaches a level where the entire stock of forex is held by (non-bank) investors. This aspect of the model's equilibrium accords well with the fact that dealer-banks do not hold substantial overnight forex positions. Risk-sharing also affects the determination of spot rates earlier in the trading day. Specifically, they adjust to levels consistent with market clearing and participants' forecasts for the end-of-day rates conditioned on common information. This doesn't mean that the intraday spot rates necessarily follow a random walk. In fact they don't in the PS model. In equilibrium there can be predictable patterns in rates that lead market participants to take (different) speculative positions, so long as in aggregate this speculative behavior is consistent with market clearing.

The relevance of these theoretical implications for the behavior of spot rates around the Fix is straightforward. When viewed from the perspective of the whole market, the hedging incentives to trade at the Fix are likely to produce changes in the distribution of forex holdings across non-bank participants. Thus, from the perspective of the PS model, trading around the Fix should establish a level for the spot rate at which the post-fix distribution of forex holdings achieves an efficient risk-sharing allocation. To see what this would mean in practice, consider the following examples.

Suppose that while individual dealer-banks receive positive and negative net fill-at-fix purchase orders for USD against GBP, in aggregate the orders net to zero. Furthermore, for the sake of clarity, let us assume that all dealer-banks hold their desired forex positions at 3:45 pm and that no other participants submit standard forex trades around the Fix. Under these circumstances, the PS model implies that the Fix benchmark will equal the (mid-point) of the bid and offer rates at 3:45 pm because those rates are consistent with an efficient risk-sharing allocation of forex after the Fix. Dealer-banks are able to fill their fill-at-fix orders by trading with each other at 4:00 pm without generating unwanted long or short positions, and post-fix forex holdings of non-banks will be at desired level because spot rates remain unchanged between 3:45 and 4:00 pm. Moreover, in the absence of external factors generating further changes in the desired forex holdings of non-banks, spot rates should remain at the level of the Fix for the remainder of the trading day.

Under other circumstances the aggregate imbalance in fill-at-fix orders will necessitate the establishment of a equilibrium spot rate that differs from the 3:45 pm rate. Now the fill-at-fix orders can only be filled if dealer-banks as a group take either a long or short position, so the spot rates generated by inter-dealer trading in the seconds around 4:00 pm do not represent the equilibrium rate at the end of the day's trading. Instead there must be an further change in the spot rate to a level at which dealers can find non-bank participants with which they can trade away their unwanted long or short forex positions. The observed behavior of spot rates around the Fix depends on the speed of this process. If it takes place within the one minute Fix window, the benchmark will closely approximate the end-of-day equilibrium spot rate. In this case there would be a significant pre-fix change in spot rates between 3:45 and 4:00 pm and an insignificant post-fix change. Alternatively, if the process extends well beyond the end of the Fix window, there would be significant pre- and post-fix spot rate changes.

In sum, the PS model provides an insight into why the Fix benchmark may be at a somewhat different level than spot rates before and after 4:00 pm. Simply put, spot rates appear volatile around the Fix because they are adjusting to a new distribution of desired forex holdings by non-banks participants.

The second important insight from the PS model concerns the trading behavior of dealers. In the model dealer-banks use information contained in the forex orders they receive from non-bank investors to forecast future movements in spot rates from which they establish speculative positions via their trades with other dealer-banks. The forex orders received by individual dealer-banks have forecasting power because they represent a noisy signal concerning the new distribution of desired forex holdings by non-bank investors that the future equilibrium spot rate must accommodate. Importantly, the model shows that dealer-banks trade in the same direction when establishing their speculative positions as the incoming forex orders they receive from non-banks. So if a dealer-bank received a order to purchase GBP with USD, say, he would in turn purchase GBP from other dealers to set up a long speculative position in the GBP in anticipation of a rise in the USD/GDP spot rate. This trading behavior does not constitute front running because the dealer-bank

fills the investor's order before establishing the speculative position. Nevertheless, the dealer-bank would want to trade in exactly the same manner if instead the investor's order was filled at a later point in time. In this sense the PS model provides a rationale for why dealer-banks would establish speculative positions via trades that would appear to front run fill-at-fix forex orders. Front running arises as an optimal trading strategy by dealer-banks who understand that the fill-at-fix orders contain (imprecise) information about the future level of the spot rate consistent with an efficient risk-sharing allocation of forex holdings across market participants at the end of the trading day.

Four key points arise from this insight. First, the presence of front running is not in and of itself an indicator of Pareto inefficiency in forex trading. It could be part of dealer-banks' optimal trading strategies in the equilibrium of a forex trading model where the spot rate achieves a level consistent with an efficient risk-sharing allocation by the end of the trading day. Second, the presence of front running by dealer-banks need not affect the behavior of spot rates. Limiting the size of dealer-banks speculative positions in the PS model would not change the behavior of equilibrium spot rates during the day, but it would make acting as a dealer-bank less attractive to potential market participants. Third, the size of dealer-banks speculative positions (and hence the degree of front running) depend critically on the perceived precision of their spot rate forecasts. Risk-averse dealer-banks understand that their forecasts are based on imprecise inferences about the new distribution of desired forex holdings across all non-bank participants, and so choose the size of their speculative positions to balance expected profits against the risk of actual losses. Under these circumstances, information about the orders received by other dealer-banks would be economically valuable to any individual dealer-bank because it would improve the precision of its spot rate forecasts and reduce the risk associated with taking a particular position.

The forth and final point concerns the relation between front running and serial correlation in spot rate changes. In the PS model, spot rates jump directly to their end-of-day equilibrium level immediately after dealer-banks trade to establish their speculative positions. Thereafter, they remain at the same level even as the speculative positions are unwound and any undesired dealer-banks forex holdings are traded away to non-banks. Consequently there is no serial correlation in spot rate changes between the time when individual dealer-banks receive forex orders from investors and the end of the daily trading. This fact undermines the idea that the existence of front running *must* lead to negative serial correlation in spot rate changes. It also means that the PS model cannot provide a complete explanation for the behavior of spot rates around the Fix.

Could front running produce a negative serial correlation in equilibrium spot rate changes in another trading model? Possibly, but the model would have to limit the ability or inclination of market participants to exploit the predictability in spot rate movements. In the presence of negative serial correlation all participants will generally have an incentive to take long (short) speculative positions follow a fall (rise) in rates, so it will be impossible to find the counterparties necessary for the trades that initiate the positions unless speculative trading is limited to a subset of market participants. Alternatively, some participants must have a strong, overriding incentive to act as counterparties to the speculative trades of others. Section 7 considers further the incentive to take speculative positions that exploit the negative serial correlation in spot rate changes around the Fix.

In summary, the PS model of forex trading provides a number of insights into the possible factors driving

the behavior of spot rates around the Fix. In particular, it provides insights into the source of spot rate volatility and the possible presence of front running by dealer-banks. That said, the PS model (and other forex trading models) does not provide an "off-the-self" explanation for the negative correlation between pre- and post-fix spot rate changes that appears to be a prominent feature of the end-of-month data - a point I return to in Section 7 below.

2 Data and Statistical Methods

2.1 Data Sources

I use data from two sources. The daily Fix benchmarks are taken from Datastream. The intraday spot rate data comes from Gain Capital, a provider of electronic Forex trade data and transaction services, and the parent company for the retail trading portal Forex.com. Their data archive includes tick-by-tick bid and offer rates for a wide range of currencies, some starting as far back as 2000. In this study I focus on the spot rates for 21 currency pairs: the four majors involving the U.S. Dollar (USD/EUR, CHF/USD, USD/GBP and JPY/USD) and 17 further rates that use either the Euro, Pound or Dollar as the base currency. These rates are listed in column (i) of Table 1. Columns (ii) and (iii) report the span and scope of the tick-by-tick data for each rate. For 11 currency pairs I use a decade of tick-by-tick bid and offer rates starting at midnight on December 31 st., 2003. Continuous data is not available for the other currency pairs in 2004 – 2007 so I use tick-by-tick rates starting after midnight on December 31st 2007, when continuous data becomes available. The data samples for all the currency pairs end at midnight on December 31 st., 2013. As column (iii) shows, the time series for each currency pair contains tens of millions of data points. Each series contains a date and time stamp, where time is recorded to the nearest 1/100 of a second, and a bid and offer rate. Unlike standard time series, the time between observations is irregular, ranging from a few minutes to a hundredth of a second.

Gain Capital aggregates data from more than 20 banks and brokerages in the Forex market to construct the bid and offer rates for each currency pair. To gauge how accurately these data represent rates across the Forex market, Gain provides a comparison of the mid-point between its bid and ask rates with the mid-point for the best tradable bid and ask rates aggregated from 150 market participants by an independent firm, Interactive Data Corporation GTIS. These comparisons (available on line at http://www.forex.com/pricing-comparison.html) show very small differences between the two mid-point series in current data, typically less than one pip.[12]

As a further check on the accuracy of the Gain data, I compared the mid-points from the tick-by-tick data with the 4:00 pm Fix benchmarks on each trading day in the sample. Recall that the Fix benchmarks are computed as the mid point of the median bid and ask rates across multiple transactions in one minute window that starts 30 seconds before 4:00 pm. For comparison I computed an analogous mid-point from the median of the bid and ask rate data on every trading day covered by each currency pair. Differences

[12]In the Forex market a "pip" typically refers to the fourth decimal place in a spot rate, i.e., the difference between a EUR/USD rate of 1.3745 and 1.3743 is three pips. Rates involving the JPY are an exception to this convention, where a pip refers to the second decimal; e.g. there is a two pip difference between the JPY/USD rates of 107.42 and 107.44. In my analysis I report differences between rates in basis points (i.e., 1/100 of a percent) rather than pips to facilitate comparisons across different currency pairs.

between this mid-point and the Fix represent the tracking error of the Gain data relative to the rates used to determine the Fix.[13]

Table 1 reports the percentiles of the tracking-error distribution, measured in basis points relative to the Fix benchmark, for each of the currency pairs I study. Since the behavior of spot rates around the Fix on the last trading day in each month have been subject to particular scrutiny by the financial press, I separate the tracking errors on these days from the errors on other trading days and report percentiles for both the intra- and end-of-month distributions. Table 1 shows that the tracking errors in the Gain data are typically very small. The center panel of the table shows that the vast majority of intra-month tracking errors are within ± 2 basis points. This represents a high level of accuracy. For perspective, column (xii) reports the average spread between the bid and ask rates for each currency pair between 3:00 and 5:00 pm GMT. Clearly, most of the tracking-error distributions lie within these average spreads. The distributions for the end-of-month tracking errors are a little more dispersed: the 5'th. and 95'th. percentiles reported in columns (ix) and (xi) are larger (in absolute value) than their counterparts in the intra-month distributions (see columns (v) and (vii)). That said, the vast majority of the end-of-month tracking errors are still very small, both in absolute terms and relative to the average spreads.

Table 1 also reports the number of trading days used to compute the tracking-error distributions in columns (iv) and (viii). In my analysis below I only use the Gain tick-by-tick data on days where the time-stamps for each bid and ask rate can be exactly matched to GMT. Unfortunately, this is not always possible. There are days where the bid and ask rates with time-stamps that should correspond to 4:00 pm are clearly far from the Fix, so there must be a recording error in the Gain archive. I do not use any of the Gain data on these days. The different trading day numbers reported in columns (iv) and (viii) reflect the effects of this data verification process as well as differences in the data spans across currency pairs.

In summary, the statistics in Table1 show that once the accuracy of the time-stamps in the Gain data has been verified, the tick-by-tick rates around the 4:00 pm very closely match the rates used in computing the actual Fix. Importantly, the tracking errors documented here are much smaller in magnitude than the changes in rates we will examine in the periods before and after the 4:00 pm, so the Gain data provides an accurate measure of how forex rates behave across the market around the Fix.

2.2 Statistical Methods

The statistical methods I use below are chosen to highlight how the behavior of spot rates around the end-of-month Fixes differ from their behavior around intra-month Fixes, and other times. To accommodate the fact that the time series for intraday rates are irregularly spaced (i.e., the time between consecutive observations differs from observation to observation), I use a set of "observation windows" that define market events in clock time around the 4:00 pm. The set of observation windows are shown in Table 2. They range in duration from 11 hours starting at 7:00 am and ending at 6:00 pm, to just two minutes between 3:59 and 4:01 pm. For each window on every trading day with reliable Gain data I compute statistics that summarize the behavior of the mid-point rate (i.e., the average of the bid and offer rates) within the window. These statistics include the first and last rates, the maximum and minimum rates.

[13] All calculations are undertaken using Matlab.

Table 1: Data Characteristics

				Intra Month Trading Days				End-of-Month Trading Days				
	FX Rate	Data Span	Prices (millions)	Number	Tracking Error Distribution Percentiles (basis points) 5%	50%	95%	Number	Tracking Error Distribution Percentiles (basis points) 5%	50%	95%	Average Spread (basis points)
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)	(xi)	(xii)
A:	EUR/USD	2004-13	55.370	2420	-1.113	0.055	1.209	117	-1.232	0.109	1.771	1.708
	CHF/USD	2004-13	51.966	2258	-1.510	0.060	1.761	106	-2.462	0.058	2.345	3.477
	JPY/USD	2004-13	38.931	2204	-1.268	0.140	1.790	104	-3.241	0.207	2.608	2.771
	USD/GBP	2004-13	60.859	2421	-1.087	0.083	1.200	116	-1.258	0.051	2.566	2.285
B:	CHF/EUR	2004-13	37.858	2373	-1.144	0.000	1.145	116	-2.135	0.000	1.243	2.160
	JPY/EUR	2004-13	78.813	2421	-1.538	0.021	1.542	117	-4.939	0.090	2.822	2.622
	NOK/EUR	2008-13	15.780	1291	-1.710	0.008	2.015	62	-2.624	0.252	3.829	4.449
	NZD/EUR	2008-13	56.633	1414	-2.211	0.079	2.381	68	-2.927	0.284	3.844	7.018
	SEK/EUR	2008-13	17.424	1288	-1.643	-0.010	1.551	59	-2.336	-0.089	1.980	3.584
C:	AUS/GBP	2008-13	68.169	1476	-1.209	0.225	1.730	69	-2.695	0.544	4.016	4.773
	CAD/GBP	2008-13	57.455	1478	-1.180	0.293	1.777	71	-1.676	0.371	2.578	4.841
	CHF/GBP	2004-13	83.686	2417	-1.476	0.087	1.634	116	-3.412	0.020	2.013	4.152
	EUR/GBP	2004-13	41.643	2339	-1.651	0.114	2.176	115	-2.302	0.157	2.523	3.208
	JPY/GBP	2004-13	88.578	2418	-1.564	0.020	1.582	116	-2.612	0.137	2.378	4.090
	NZD/GBP	2008-13	58.216	1409	-2.197	0.089	2.350	67	-2.529	0.397	5.046	9.738
D:	AUS/USD	2004-13	49.016	2398	-1.601	0.144	2.283	116	-2.373	-0.117	2.053	3.171
	CAD/USD	2004-13	36.163	2404	-1.461	0.138	1.864	116	-1.909	0.256	2.821	3.576
	DKK/USD	2008-13	66.719	1305	-0.696	0.081	0.825	59	-0.779	0.115	0.996	1.244
	NOK/USD	2008-13	55.350	1306	-1.696	0.071	2.152	62	-3.983	0.602	3.999	4.738
	SEK/USD	2008-13	58.296	1297	-1.811	0.053	1.792	59	-2.783	0.101	2.067	4.048
	SGD/USD	2008-13	10.567	1200	-1.440	0.000	1.517	61	-1.980	0.168	1.982	3.671

Notes: Columns (i) - (iii) show the data span and the number of quotes (in millions) for each of the currency pairs in the data set. Columns (iv) and (viii) report the number of intra-month and end-of-month trading days for which there are intraday quotes, respectively. Quote errors on each day are defined as the difference between the mid-point of the average bid and ask quotes computed over a 30 second window centered on 4:00 pm and the Fix benchmark. Quote errors are expressed in basis points. Columns (v) - (vii) and (ix) - (xi) show the 5th., 50th. and 95th. percentiles of the quote error distribution computed on all intra-month and end-of-month trading days. Column (xii) reports the average spread (in basis points) between the bid and ask quotes between 3:00 and 5:00 pm.

Table 2: Observation Windows

Window	Start Time	End Time	Duration
(i)	7:00 am	6:00 pm	11 hrs
(ii)	3:00 pm	5:00 pm	2 hrs
(iii)	3:30 pm	4:30 pm	1 hr
(iv)	3:45 pm	4:15 pm	30 mins
(v)	3:50 pm	4:10 pm	20 mins
(vi)	3:55 pm	4:05 pm	10 mins
(vii)	3:56 pm	4:04 pm	8 mins
(viii)	3:57 pm	4:03 pm	6 mins
(ix)	3:58 pm	4:02 pm	4 mins
(x)	3:59 pm	4:01 pm	2 mins

I also use the Gain data to constructed empirical distributions for intraday spot rate dynamics away from the Fix. To build these distributions I pick a random starting time between 7:00 am and 6:00 pm on any day from the span of the intraday time series for a specific rate. I then use this time as the starting time for nine observation windows that range in duration from two hours to two minutes. These randomly selected windows correspond to windows (ii) to (x) in Table 2. If any of the randomly selected windows cover the Fix or the release of U.S. macro data at 8:30 am EST, I discard the starting time. If not, I compute and record the same series of statistics for each of the nine windows (again using mid-point rates). This process is repeated 10,000 times to build up the empirical distribution of the rate statistics away from the Fix. It is important to exclude observation windows that cover the scheduled releases of U.S. macro data when constructing these empirical distributions because the releases are often accompanied by large rate changes. These empirical distributions provide a benchmark to quantify differences between the behavior of spot rates around the Fix and other periods of normal trading activity.

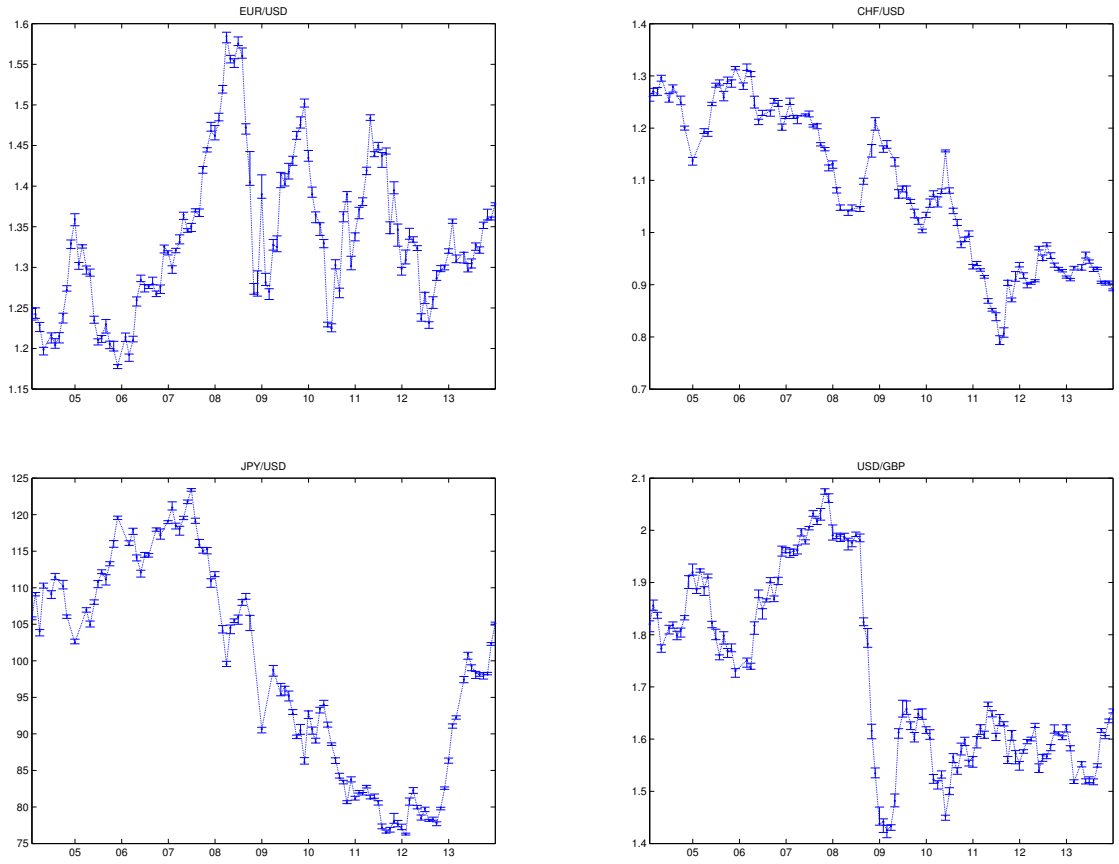
In the next 4 sections I examine the behavior of rates around the Fix. To begin I take a macro perspective. Fix benchmarks are routinely used to identify the daily spot rates from which the time series of exchange rates over months, years and decades are constructed, yet they are derived from spot rates contained in a very narrow window of daily trading activity. Section 3 examines the implications of this limitation. Next, in Section 4, I describe the behavior of spot rates under normal trading conditions. This analysis establishes empirical metrics that are used when I study the behavior of rates immediately before and after 4:00 pm in Sections 5 and 6, respectively.

3 Daily Trading Ranges and the Fix

The forex market operates continuously, without any set opening or closing times, but in reality most trading is heavily concentrated on weekdays between approximately 7:00 am and 6:00 pm GMT. In contrast, the

spot rates used to compute the Fix come from a tiny window of daily trading activity: 30 seconds either side of 4:00 pm. Consequently, each day's Fix provides limited information on the rates at which currencies trade throughout the trading day. Here I examine the implications of this limitation when studying the behavior of spot rates over days, months and longer horizons.

Figure 2: Major Currency Fixes with Daily Trading Range

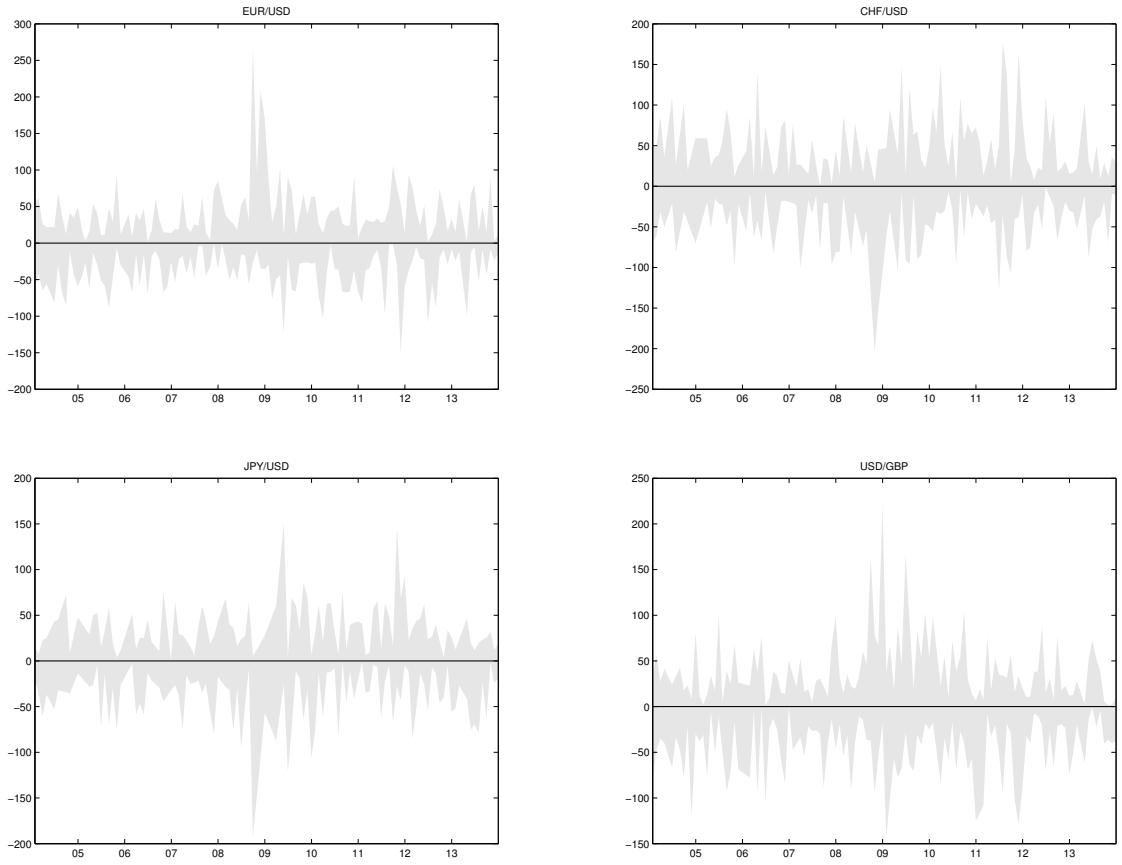


Notes: Time series for the Fix at the end of each month with upper and lower limits of daily trading range.

The Fix benchmarks are routinely used as daily rates when constructing time series for spot exchange rates over days, months or years. Figure 2 plots monthly time series for the spot rates of the four major currency pairs using the end-of-month Fixes between the end of 2003 and 2013. The plots also show the upper and lower limits for (mid-point) rates between 7:00 am and 6:00 pm GMT on the last trading day of each month. As these plots clearly indicate, the low frequency variations in the level of each spot rate (between one and five years in duration) are orders of magnitude larger than the daily rate ranges. Thus the low frequency time series characteristics of spot rates appear robust to the use of the Fix to identify the end-of month rates. One way to visualize this is to imagine alternative plots where the end-of-month rate is pinned down by a randomly chosen point within the daily trading range. The plots would undoubtedly look a little different from one month to the next, but they would still closely track the long swings shown in Figure 2. The Appendix contains analogous plots for the other 17 exchange rates that exhibit the same

features as the plots in Figure 2. In sum, therefore, the use of the Fix to identify the daily spot rate does not materially affect how we view the evolution of exchange-rate *levels* over long horizons.

Figure 3: Daily Trading Ranges around the Fix



Notes: Each panel plots the daily price range at the end of each month as a band around the Fix price in basis points. The upper and lower edges of the band are equal to $(\ln P_t^h - \ln P_t^f)10000$ and $-(\ln P_t^f - \ln P_t^l)10000$, respectively; where P_t^f is the Fix price, P_t^h is the maximum price and P_t^l is the minimum price between 7:00 am and 6:00 pm GMT on day t.

While daily spot rate ranges are small compared to the long-term swings in the level of rates, they are nevertheless sizable. Figure 3 illustrates this point for the major currency pairs. Here I plot the daily range at the end of each month as a band around the Fix in basis points. Thus the upper and lower edges of the band are equal to $10000(\ln S_t^{max} - \ln S_t^{fix})$ and $-10000(\ln S_t^{fix} - \ln S_t^{min})$, respectively; where S_t^{fix} is the Fix benchmark, S_t^{max} is the maximum rate and S_t^{min} is the minimum rate between 7:00 am and 6:00 pm on day t. As the plots clearly show, the ranges are sometimes as large as a couple of hundred basis points (particularly during the 2008-2009 financial crisis), and are often at least a hundred basis points. Notice, also, that the bands are rarely symmetric around zero because the Fix is often far from the center of the daily range; a point I shall return to below. As in Figure 2, these plots are representative of the bands for the other currency pairs shown in the Appendix.

One way to judge the economic significance of the daily spot rate ranges is to compare them against prior changes in the Fix over different horizons. For this purpose, I compute the range-to-change ratio

$\mathcal{R}_n = (\ln S_t^{max} - \ln S_t^{min})/|\ln S_t^{fix} - \ln S_{t-n}^{fix}|$ at the end of each month for horizons n of one month, one quarter and one year. $\mathcal{R}_n$ is just the ratio of the daily range (in percent) on day t to the absolute value of the percentage change in the Fix from day $t-n$ to day t. Table 3 reports the 50th. and 90th. percentiles of the empirical distributions for $\mathcal{R}_n$ at three horizons for all the currency pairs. As the table shows, for all the currency pairs both the 50'th. and 90'th. percentiles fall as the horizon rises from one month to one year. This is indicative of the leftward shift in the $\mathcal{R}_n$ distributions as n rises, which is not at all surprising. What is surprising are the size of ratios. To understand why, suppose an investor initiated a position at the Fix at the end of last month that was closed out at today's Fix, a month later, with a 1 percent return. If $\mathcal{R}_n = 0.5$ today, and the investor had the discretion to close out the position at any time between 7:00 am and 6:00 pm, he could have potentially achieved a return as large as 1.5 percent or as small as 0.5 percent, depending on where today's Fix was set relative to the daily range. In this sense the median values for $\mathcal{R}_n$ imply that monthly and quarterly returns computed from Fix benchmarks are "typically" rather imprecise measures of the return an investor might have received had they initiated and/or closed their positions away from the Fix on the same days. Moreover, on at least ten percent of the days covered by the sample, returns computed from the Fix could have been very imprecise. As the right hand columns of Table 3 show, the 90'th. percentiles of the $\mathcal{R}_n$ distributions are in many cases above one. In these instances it is possible that the return an investor received on a position initiated at the Fix but closed away from the Fix would have a *different sign* from one closed at the Fix.

The results in Table 3 make clear that forex returns computed over macro-relevant horizons are sensitive to the time of day that positions are initiated and closed. Unless investors are known to only execute their forex trades at the Fix, conventional measures of returns on forex positions that use the Fix as the daily exchange rate are *potentially* very imprecise measures of the returns actual investors received from positions initiated and closed on the same days. Of course the exact level of imprecision depends on far the rates received by the investor on their transactions to initiate and close the position differ from the Fix. These calculations require trading data on individual investors. In contrast, most of the research literature on the carry trade, forward premium puzzle, and international portfolio diversification implicitly assumes that the ability to trade away from the Fix has no material affect on Forex returns over macro horizons. At the very least, the results in Table 3 cast some doubt on this assumption.

The results in Table 3 also provide a perspective on why so many forex trades are executed at the Fix. When an investor sells a foreign currency denominated security (e.g. a stock or bond) held in a custodian account, the proceeds from the sale are used to purchases domestic currency that is credited to the investor's account. The results in the Table 3 show that the (domestic currency) return the investor ultimately receives could be materially affected if the custodian has discretion to choose the rate for the forex trade within the range on the day the security is sold. Indeed the choice of rate for such forex trades has been the subject of litigation between institutional investors (mutual and pension funds) and custodial banks.[14] One way to avoid such litigation is to eliminate discretion over the rate used in custodial forex trades by specifying that they are executed at the Fix. This arrangement increases the level of transparency in custodial trades for institutional investors and also produces a flow of orders into the forex market to execute trades at the Fix.

[14]See: Louisiana Municipal Police Employees' Retirement System et al v. JPMorgan Chase & Co et al, U.S. District Court, Southern District of New York, No. 12-06659; and Bank of New York Mellon Corp Forex Transactions Litigation in the same court, No. 12-md-02335.

Table 3: Range-to-Change Ratios

$$\mathcal{R}_n = (\ln S_t^{max} - \ln S_t^{min})/|\ln S_t^{fix} - \ln S_{t-n}^{fix}|$$

	horizons n	50th. percentile 1 month	50th. percentile 1 quarter	50th. percentile 1 year	90th. percentile 1 month	90th. percentile 1 quarter	90th. percentile 1 year
		(i)	(ii)	(iii)	(iv)	(v)	(vi)
A:	EUR/USD	0.430	0.222	0.107	2.016	1.646	0.611
	CHF/USD	0.460	0.224	0.203	2.527	1.518	1.418
	JPY/USD	0.369	0.207	0.084	2.230	1.420	0.372
	USD/GBP	0.536	0.312	0.168	5.184	2.071	0.989
	Average	0.449	0.241	0.141	2.989	1.664	0.848
B:	CHF/EUR	0.547	0.288	0.123	4.258	1.969	0.366
	JPY/EUR	0.367	0.214	0.094	3.460	1.144	0.596
	NOK/EUR	0.560	0.303	0.131	2.104	1.403	0.502
	NZD/EUR	0.405	0.192	0.114	1.561	0.907	0.738
	SEK/EUR	0.478	0.290	0.111	2.075	1.772	0.688
	Average	0.472	0.257	0.115	2.691	1.439	0.578
C:	AUD/GBP	0.372	0.177	0.116	2.991	1.115	0.982
	CAD/GBP	0.529	0.419	0.235	3.433	1.777	1.164
	CHF/GBP	0.451	0.278	0.123	2.616	1.567	0.558
	GBP/EUR	0.493	0.264	0.172	3.896	1.832	0.980
	JPY/GBP	0.383	0.227	0.096	1.181	0.903	0.959
	NZD/GBP	0.416	0.238	0.142	1.443	1.912	1.390
	Average	0.441	0.267	0.147	2.593	1.518	1.005
D:	AUD/USD	0.355	0.236	0.096	1.457	1.319	0.385
	CAD/USD	0.469	0.284	0.136	2.544	1.364	0.694
	DKK/USD	0.432	0.214	0.121	1.861	1.163	0.534
	NOK/USD	0.470	0.275	0.215	2.597	1.141	1.570
	SEK/USD	0.491	0.304	0.195	2.286	4.565	1.161
	SGD/USD	0.304	0.190	0.099	2.084	0.861	0.373
	Average	0.420	0.251	0.144	2.138	1.735	0.786

Notes: The table reports percentiles of the empirical $\mathcal{R}_n$distributions for each of the exchange rates listed on the left. Empirical distributions are constructed from the values for $\mathcal{R}_n$ computed at the end of each month for which reliable intraday rate data is available.

Table 4 reports statistical results that compliment the visual evidence in Figure 3 on the relation between the daily spot rate range and the Fix at the end of each month. The table provides information on the intraday rate ranges between 7:00 am and 6:00 pm, 3:00 and 5:00 pm, and between 3:30 and 4:30 pm on every day for which there is reliable data for each currency pair. Columns (i) and (ii) report the 50th. and 90th. percentiles of the empirical distribution for the range expressed in basis points; i.e., $10000(\ln(S^{max}) - \ln(S^{min}))$ where S^{max} and S^{min} are the highest and lowest (mid-point) rates within the range. The tail probabilities in columns (iii) and (iv) compare the Fix to the range on each day. Specifically, column (iii) reports the

fraction of days on which the ratio $(S^{fix} - S^{min})/(S^{max} - S^{min})$ is either below 0.1 or above 0.9, while column (iv) reports fraction on which the ratio is either below 0.05 or above 0.95.

An inspection of the statistics in Table 4 reveals several noteworthy features. First, there is remarkable similarity in the empirical range distributions across currency pairs. Column (i) shows that typical spot rate ranges (represented by the 50th. percentiles) from 7:00 am to 6:00 pm are between 70 and 80 basis points, fall to around 30 points between 3:00 and 5:00 pm, and are on average a little above 20 points between 3:30 and 4:30 pm. The 90th. percentiles for the range distributions are also very similar across most currency pairs, and are roughly twice the size of the 50th percentiles. Four currency pairs prove exceptions to this pattern: Distributions for the CHF/EUR and SGD/USD are shifted more to the left, while those for the NOK/USD and SEK/USD are shifted more to the right.

The second noteworthy feature concerns the effect of time on the range distributions. As one would expect, the distributions shift leftward and become more compact as the ranges are computed over shorter time windows. Notice, however, that the statistics in panel III are based from just one hour of trading activity whereas those in panel I come from 11 hours. If the sequence of intraday rates followed a random walk with a constant variance, the percentiles in panel I should be $\sqrt{11} \simeq 0.33$ times their counterparts in panel III. The table shows that this is approximately the case. This is surprising because the statistics in panel I encompass periods during which macro data are routinely released, whereas those in panel III come from the hour of trading around the Fix where releases do not occur. The factors affecting rates around the Fix appear comparable in their effects on the range of rates as the release of macro data. This is one piece of evidence documenting the atypical behavior of spot rates around the Fix.

The third feature concerns the tail probabilities reported in columns (iii) and (iv). As the table clearly shows, the Fix appears close to the edges of the price ranges far more often that we would expect if it were merely a randomly chosen point from the range. For a perspective, consider the position of an investor who is committed to undertaking a forex trade on a particular day and must decide whether to execute the trade via the submission of a standard (market or limit) order at a time close to 4:00 pm, or via the submission of a fill-at-fix order. The tail probabilities in panels II and III imply that the investor faces more rate uncertainty in orders filled at the Fix than from standard trades executed at a random time around the fix.

In summary, the results above show that the Fix provides limited information about the rates used in the execution forex trades on any particular day. The Fix is computed as an average of rates in a narrow one-minute window that cannot adequately represent the fully range of spot rates at which trades take place over the trading day. As a consequence, investors initiating and closing positions away from the Fix are quite likely to achieve returns over days, weeks and longer, that differ significantly from those computed over the same horizons using the Fix. Furthermore, the Fix should not be viewed as representing a randomly chosen spot rate from the intraday range on a particular day. Across all the currency pairs, the incidence of Fix benchmarks near the edge of the intraday spot rate range is far higher than would be the incidence of randomly chosen rates.

Table 4: Trading Ranges and the Fix

		I: 7:00 am -6:00 pm GMT				II: 3:00-5:00 pm GMT				III: 3:30-4:30 pm GMT			
		Range Distribution		Tail Probabilities		Range Distribution		Tail Probabilities		Range Distribution		Tail Probabilities	
		50%	90%	20%	10%	50%	90%	20%	10%	50%	90%	20%	10%
		(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv)
A: Majors	EUR/USD	73.049	133.130	0.304	0.210	32.923	64.408	0.408	0.270	22.312	44.659	0.392	0.251
	CHF/USD	79.157	142.709	0.321	0.216	35.972	68.733	0.396	0.253	24.611	48.101	0.359	0.232
	JPY/USD	66.341	120.889	0.304	0.197	29.651	59.880	0.373	0.243	20.715	39.984	0.346	0.234
	USD/GBP	68.880	129.649	0.279	0.177	29.767	59.391	0.357	0.228	20.757	42.069	0.338	0.213
	Average	71.857	131.594	0.302	0.200	32.078	63.103	0.384	0.248	22.099	43.703	0.359	0.232
B: EUR	CHF/EUR	32.996	90.981	0.340	0.222	15.306	41.911	0.334	0.208	11.164	30.955	0.315	0.184
	JPY/EUR	79.185	163.978	0.299	0.192	35.100	74.383	0.363	0.235	24.073	52.200	0.364	0.222
	NOK/EUR	61.523	121.154	0.272	0.163	28.879	55.579	0.277	0.167	20.754	41.480	0.246	0.156
	NZD/EUR	82.317	151.633	0.298	0.204	38.680	76.462	0.340	0.201	28.393	57.282	0.309	0.194
	SEK/EUR	65.110	129.011	0.260	0.153	29.969	57.276	0.283	0.174	22.076	41.735	0.250	0.166
	Average	64.226	131.352	0.294	0.187	29.587	61.122	0.319	0.197	21.292	44.730	0.297	0.185
C: GBP	AUS/GBP	79.906	155.525	0.294	0.202	36.362	74.123	0.361	0.230	26.683	57.060	0.338	0.205
	CAD/GBP	82.238	153.473	0.288	0.176	38.710	76.689	0.315	0.203	27.846	56.795	0.305	0.212
	CHF/GBP	66.053	133.963	0.286	0.190	28.722	59.177	0.357	0.220	20.951	43.033	0.333	0.209
	EUR/GBP	57.296	112.261	0.248	0.154	23.686	46.904	0.327	0.192	17.273	34.743	0.302	0.173
	JPY/GBP	81.113	165.301	0.293	0.177	34.818	75.997	0.347	0.232	24.917	54.822	0.325	0.212
	NZD/GBP	86.413	161.864	0.297	0.187	41.723	82.508	0.335	0.202	30.252	63.275	0.298	0.197
	Average	75.503	147.064	0.284	0.181	34.003	69.233	0.340	0.213	24.654	51.621	0.317	0.201
D: USD	AUS/USD	78.218	161.009	0.329	0.218	37.792	81.713	0.368	0.227	27.054	56.649	0.330	0.196
	CAD/USD	74.574	137.799	0.284	0.181	35.149	70.505	0.329	0.202	24.847	48.947	0.303	0.186
	DKK/USD	80.139	146.297	0.304	0.216	37.026	70.223	0.410	0.267	25.234	49.993	0.398	0.263
	NOK/USD	105.594	197.482	0.311	0.198	50.165	94.826	0.347	0.220	35.640	67.861	0.330	0.202
	SEK/USD	110.334	209.301	0.299	0.192	51.952	98.312	0.350	0.213	36.553	70.112	0.325	0.203
	SGD/USD	36.736	67.820	0.313	0.185	16.850	31.507	0.344	0.225	11.549	23.386	0.313	0.189
	Average	80.932	153.285	0.307	0.198	38.156	74.515	0.358	0.226	26.813	52.825	0.333	0.206

Notes: Columns (i) and (ii) report the 50th. and 90th. percentiles from the empirical distribution of the trading range (identified in the header of each panel) expressed in basis points; i.e., $(\ln(S^{max}) - \ln(S^{min}))10000$ where S^{max} and S^{min} are the highest and lowest mid-point rates within the range. Column (iii) reports the fraction of days in the sample that the ratio $(S^{fix} - S^{min})/(S^{max} - S^{min})$ is either below 0.1 or above 0.9. Column (iv) reports the fraction of the days when the ratio is either below 0.05 or above 0.95.

4 Spot Rate Dynamics Away from the Fix

In this section I examine the behavior of intraday spot rate dynamics away from the Fix. Table 5 reports statistics for the distribution of spot rate changes over horizons of five, fifteen, and thirty minutes. These statistics are computed from an empirical distribution of 10000 observations chosen at random times (away from the Fix) from the time series of intraday (mid-point) rates, $\{S_t\}$, for each currency pair (as described in Section 2.2). Columns (iii) - (vii) report statistics for the distribution of changes in the log rates expressed in basis points per minute, i.e.,$\Delta\ ^h s_t \equiv (\ln(S_{t+h}) - \ln(S_t)) * 10000/h$ for horizons $h = \{5, 15, 60\}$ minutes. Columns (viii) and (ix) report the first-order autocorrelation in$\Delta\ ^h s_t$ (i.e. $corr(\Delta^h s_{t+h}, \Delta^h s_t)$) and the p-value for the null of a zero autocorrelation, respectively. Column (x) reports the Kolmogorov-Smirnov (KS) test for the null that the two conditional distributions $f(\Delta^h s_{t+h}|\Delta^h s_t > 0)$ and $f(\Delta^h s_{t+h}|\Delta^h s_t \leq 0)$ are the same.[15] The p-value for the test is shown in column (xi).

As Table 5 shows, the rate-change distributions have several common characteristics across all the currency pairs. First, the dispersion in the rate-change distributions decline as the horizon rises. Columns (iii) and (iv) show that the absolute values for the 5th. and 95th. percentiles of the distributions fall as the horizon rise from five to 30 minutes. The change in dispersion is also reflected by the standard deviations shown in column (v), which fall as the horizon rises. Second, all the rate-change distributions are strongly leptokurtic. As column (vii) shows, the kurtosis statistics across all the currency pairs are large; much larger than the value of three for the implied by the normal distribution. These statistics indicate that atypically large changes in rates occur quite frequently away from the Fix and scheduled macro news releases.

The third feature concerns temporal dependence between rate changes. Column (viii) shows that rate changes display some small degree of autocorrelation. Across currency pairs, the autocorrelation is generally negative. This fact accounts for the declining dispersion of the rate-change distributions as the horizon rises, noted above. Although small in (absolute) value, the statistics in column (ix) indicate that many of the estimated autocorrelation coefficients are statistical signifiant at standard levels. There is also evidence of temporal dependence from the KS tests reported in column (ix). Under the null of temporal independence, future changes in rates should not depend on the sign of past changes, i.e., $f(\Delta^h s_{t+h}|\Delta^h s_t > 0) = f(\Delta^h s_{t+h}|\Delta^h s_t \leq 0)$. As column (x) shows, this null can easily be rejected at standard levels of significance for most currency pairs and horizons h.

[15] Two versions of the KS test can be found in the statistics literature. The one-sample KS test is a nonparametric test of the null hypothesis that the population cdf of the data is equal to the hypothesized cdf. The two-sample KS test is a nonparametric hypothesis test of the null that the data in two samples are from the same continuous distribution. Here I compute the two-sample KS test which uses the maximum absolute difference between the cdfs of the distributions of the two data samples. The test statistic is computed as $D = max_x \left(|\hat{F}_1(x) - \hat{F}_2(x)|\right)$ where $\hat{F}_1(x)$ is the proportion of the first data sample less than or equal to x, and $\hat{F}_2(x)$ is the proportion of the second data sample less than or equal to x. The KS test and its asymptotic p-value are computed with the Matlab "kstest2" function.

Table 5: Spot Rate Dynamics

		Spot Rate Changes (bps per minute)						Temporal Dependence			
		horizon	5%	95%	std	skew	kurtosis	Autocorrelation	p-value	Independence	p-value
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)	(xi)
A:	EUR/USD	5	-1.345	1.378	0.886	-0.033	8.777	-0.018	(0.137)	0.055	(0.000)
		15	-0.730	0.729	0.466	-0.122	7.694	-0.007	(0.587)	0.047	(0.002)
		30	-0.468	0.468	0.302	0.057	9.717	0.025	(0.037)	0.047	(0.001)
	CHF/USD	5	-1.481	1.532	0.968	-0.166	11.873	-0.021	(0.097)	0.051	(0.001)
		15	-0.774	0.787	0.511	-0.090	8.259	-0.036	(0.005)	0.046	(0.003)
		30	-0.510	0.492	0.318	-0.235	8.301	0.045	(0.000)	0.051	(0.001)
	JPY/USD	5	-1.259	1.265	0.818	-0.009	8.457	-0.044	(0.001)	0.049	(0.002)
		15	-0.657	0.672	0.429	0.310	8.110	-0.047	(0.000)	0.055	(0.000)
		30	-0.421	0.413	0.276	0.198	9.298	0.033	(0.007)	0.050	(0.001)
	USD/GBP	5	-1.317	1.338	0.915	0.285	12.967	-0.041	(0.001)	0.043	(0.006)
		15	-0.717	0.711	0.501	-0.421	20.581	0.028	(0.024)	0.026	(0.251)
		30	-0.460	0.473	0.329	-0.633	28.025	-0.049	(0.000)	0.047	(0.001)
B:	CHF/EUR	5	-0.818	0.889	0.630	0.213	33.326	-0.046	(0.000)	0.072	(0.000)
		15	-0.464	0.463	0.335	0.429	26.405	-0.004	(0.718)	0.057	(0.000)
		30	-0.301	0.282	0.212	0.465	23.065	-0.010	(0.416)	0.047	(0.002)
	JPY/EUR	5	-1.607	1.633	1.089	0.234	12.711	-0.007	(0.545)	0.039	(0.016)
		15	-0.895	0.885	0.585	0.397	11.241	-0.033	(0.007)	0.048	(0.002)
		30	-0.570	0.567	0.379	0.411	11.997	-0.008	(0.495)	0.034	(0.039)
	NOK/EUR	5	-1.232	1.402	0.854	0.251	9.228	0.035	(0.036)	0.036	(0.209)
		15	-0.697	0.747	0.487	0.162	9.704	0.005	(0.761)	0.017	(0.958)
		30	-0.446	0.484	0.319	-0.036	12.685	-0.068	(0.000)	0.083	(0.000)
	NZD/EUR	5	-1.695	1.699	1.170	0.349	15.685	-0.044	(0.006)	0.040	(0.104)
		15	-0.932	0.904	0.610	-0.188	9.959	-0.059	(0.000)	0.073	(0.000)
		30	-0.582	0.571	0.383	-0.806	17.827	-0.061	(0.000)	0.066	(0.000)
	SEK/EUR	5	-1.365	1.389	0.885	-0.148	8.334	0.046	(0.007)	0.036	(0.221)
		15	-0.730	0.778	0.488	0.087	8.384	0.017	(0.314)	0.048	(0.035)
		30	-0.503	0.484	0.321	-0.092	8.763	-0.039	(0.017)	0.072	(0.000)
C:	AUS/GBP	5	-1.683	1.821	1.230	-0.229	17.100	-0.110	(0.000)	0.047	(0.029)
		15	-0.918	0.929	0.639	-0.211	13.506	-0.022	(0.157)	0.017	(0.944)
		30	-0.581	0.591	0.420	-1.893	44.503	-0.097	(0.000)	0.043	(0.045)
	CAD/GBP	5	-1.709	1.722	1.152	-0.064	12.740	-0.085	(0.000)	0.040	(0.084)
		15	-0.931	0.913	0.604	0.080	8.627	0.010	(0.540)	0.029	(0.375)
		30	-0.602	0.580	0.392	-0.080	9.988	-0.129	(0.000)	0.051	(0.010)
	CHF/GBP	5	-1.388	1.390	0.943	0.051	13.442	-0.037	(0.003)	0.067	(0.000)
		15	-0.766	0.726	0.520	0.226	16.612	0.037	(0.003)	0.032	(0.074)
		30	-0.479	0.464	0.342	-0.877	28.940	-0.059	(0.000)	0.048	(0.001)
	EUR/GBP	5	-1.165	1.162	0.764	-0.193	9.183	-0.041	(0.001)	0.054	(0.001)
		15	-0.598	0.629	0.421	-0.147	15.589	0.035	(0.004)	0.019	(0.662)
		30	-0.401	0.418	0.282	0.324	21.871	-0.053	(0.000)	0.068	(0.000)
	JPY/GBP	5	-1.692	1.757	1.181	0.516	14.281	-0.039	(0.001)	0.045	(0.003)
		15	-0.913	0.952	0.640	0.338	16.520	0.013	(0.294)	0.048	(0.001)
		30	-0.578	0.612	0.419	-0.038	23.768	-0.048	(0.000)	0.053	(0.000)
	NZD/GBP	5	-1.877	1.938	1.314	0.264	15.240	-0.053	(0.001)	0.027	(0.491)
		15	-1.032	1.045	0.691	-0.605	16.852	0.022	(0.178)	0.051	(0.014)
		30	-0.648	0.633	0.456	-2.661	62.103	-0.159	(0.000)	0.083	(0.000)

Notes: see below.

Table 5: Spot Rate Dynamics (cont.)

		Spot Rate Changes (bps. per minute)						Temporal Dependence			
		horizon	5%	95%	std	skew	kurtosis	Autocorrelation	p-value	Independence	p-value
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)	(xi)
D:	AUS/USD	5	-1.693	1.687	1.160	0.086	18.120	-0.087	(0.000)	0.054	(0.000)
		15	-0.905	0.883	0.610	-0.088	12.623	-0.030	(0.015)	0.033	(0.075)
		30	-0.591	0.562	0.399	0.411	13.210	-0.041	(0.001)	0.034	(0.044)
	CAD/USD	5	-1.467	1.435	0.921	-0.085	8.762	-0.003	(0.789)	0.023	(0.428)
		15	-0.776	0.778	0.510	0.290	10.587	-0.025	(0.039)	0.053	(0.000)
		30	-0.505	0.488	0.329	-0.103	13.586	-0.044	(0.000)	0.043	(0.004)
	DKK/USD	5	-1.578	1.548	1.014	0.095	7.817	-0.015	(0.358)	0.050	(0.024)
		15	-0.822	0.831	0.536	0.094	6.901	0.012	(0.480)	0.048	(0.036)
		30	-0.567	0.549	0.351	-0.103	8.885	0.022	(0.187)	0.048	(0.025)
	NOK/USD	5	-2.089	2.184	1.352	0.094	6.047	0.011	(0.523)	0.032	(0.325)
		15	-1.176	1.184	0.747	0.168	6.938	0.000	(0.995)	0.031	(0.379)
		30	-0.730	0.784	0.490	-0.049	8.592	-0.048	(0.004)	0.031	(0.320)
	SEK/USD	5	-2.304	2.276	1.436	-0.076	6.168	0.012	(0.477)	0.023	(0.710)
		15	-1.215	1.204	0.783	0.211	8.700	0.012	(0.487)	0.047	(0.039)
		30	-0.810	0.784	0.511	-0.057	8.471	-0.012	(0.468)	0.025	(0.587)
	SGD/USD	5	-0.736	0.813	0.523	0.094	9.615	-0.027	(0.121)	0.059	(0.016)
		15	-0.434	0.432	0.278	-0.046	9.321	-0.036	(0.033)	0.043	(0.105)
		30	-0.284	0.285	0.181	0.128	8.823	-0.059	(0.000)	0.062	(0.003)

Notes: Columns (iii) - (vii) report statistics on the distribution of changes in the log spot rates over horizons h of 5, 15, and 30 minutes. The change in rates are expressed in basis points per minutes, i.e.,$\Delta\ ^h s_t \equiv (\ln(S_{t+h}) - \ln(S_t)) * 10000/h$ for $h = \{5, 15, 60\}$, where S_t is the mid-point rate at time t. All statistics are computed from 10000 starting times t sampled at random from the span of the available time series for each currency pair. Columns (viii) and (ix) report the first-order autocorrelation in$\Delta\ ^h s_t$ (i.e. $corr(\Delta^h s_{t+h}, \Delta^h s_t)$) and the p-value for the null of a zero autocorrelation, respectively. Column (x) reports the KS test for the null that the two conditional distributions $f(\Delta^h s_{t+h} | \Delta^h s_t > 0)$ and $f(\Delta^h s_{t+h} | \Delta^h s_t \leq 0)$ are the same. The asymptotic p-value for the null is shown in column (xi).

The temporal dependence of intraday rate changes documented in Table 5 might appear surprising to someone familiar with the statistical properties of asset price changes measured over much longer horizons (e.g., days, months or quarters). In particular, it would seem from the estimated autocorrelations that future rate changes are (to some degree) forecastable using past rates; an apparent contradiction of Weak-form efficiency. However, two caveats are in order. First, these correlations are computed from the mid-points of bid and ask rates. As such, the estimated autocorrelations do not imply that the future returns available to traders (i.e. changes in log rates that account for the bid/offer spread) can be forecast. As we shall see below, the forecastability of future forex returns adjusted for the spread is typically much less than the apparent forecastability implied by the estimated autocorrelation in mid-point rate changes. The second caveat concerns risk. Even in cases where there is forecastability for returns (adjusted for the spread), the precision of the forecast is very low. Traders taking speculative positions based on the forecasts would be exposed to significant risk of loss. Indeed, the risk of losses are so large relative to the expected gains, trading strategies exploiting forecastability would look very unattractive when judged by standard performance metrics like Sharpe ratios and Drawdown statistics. Section 7 examines the incentives facing traders to exploit serial correlation in spot rate changes in greater detail.

The statistics in Table 5 are based on the entire span of the time series of intraday rates for each currency

pair. This span covers a decade for 14 pairs during which the structure of trading in the forex market changed significantly. In addition, the data series span the 2008/9 world financial crisis. Consequently, it is possible that the characteristics identified above mask secular changes in the behavior of rates as forex trading institutions evolved and/or are unduly influenced by the atypical behavior of rates during the hight of the financial crisis.

The statistics in Table 6 shed light on these issues. Columns (iii) - (vii) and (viii) - (xii) report statistics on the distribution of rate changes (basis points per minute) between Jan 1st 2004 and Dec 31st. 2007, and between Jan 1st. 2010 and Dec. 31st. 2013.[16] Both of these subsamples cover periods that are far removed from the hight of the 2008/9 crisis. To examine the stability of the rate-change distribution across the two subsamples, I again use the KS test, and report its asymptotic p-value in the right-hand column of the table.

The statistics in Table 6 show that there has indeed been change in the rate-change distributions over the past decade. Formally, this can be seen from the very small p-values for the KS tests reported in column (xiv). A comparison of the statistics in columns (iii) - (vii) with those in (viii) - (xii) reveals that the tails of the distributions, measured by the percentiles and kurtosis, generally exhibit the largest differences across the two subsamples. In other words, the incidence and size of atypical rate changes appears to have evolved over the decade. That said, the majority of the statistics from the two subsamples are very similar. In particular, the standard deviations are similar in size and decline with the rise in the horizon in the same manner as their counterparts in Table 5. As above, this pattern is symptomatic of the generally negative autocorrelation in rate changes that is present in both subsamples. Estimated autocorrelations (unreported) are generally negative, and statistically significantly different from zero in the two subsamples, but the estimates are uniformly small (in absolute value), like those in Table 6.

Figure 4 provides visual evidence that compliments the statistics reported in Tables 5 and 6. The figure plots the rate-change densities for the four major currency pairs. Plot (i) in each panel shows density functions for$\Delta\ ^{h}s_t$ for $h = \{5, 15, 30\}$ minutes in green, blue, and red, respectively. Here we can clearly see how that dispersion of the densities increases as the horizon shortens from 30 to five minutes. Plot (ii) in each panel shows the distributions from the pre-2008 and post-2009 subsamples. On close inspection it is possible to see differences between the densities, but they are extremely small. Moreover, the densities from the subsamples do not look dissimilar to the densities in plot (i). Thus, while the differences between the subsample price-change distributions are statistically significant, the differences in the estimated densities do not appear economically important for the four major currency pairs. The Appendix shows that these similarities carry over to the other currency pairs. Despite the large institutional changes in forex trading over the past decade, the intraday dynamics of rates away from the Fix (and other scheduled announcements) appears to have been stable.

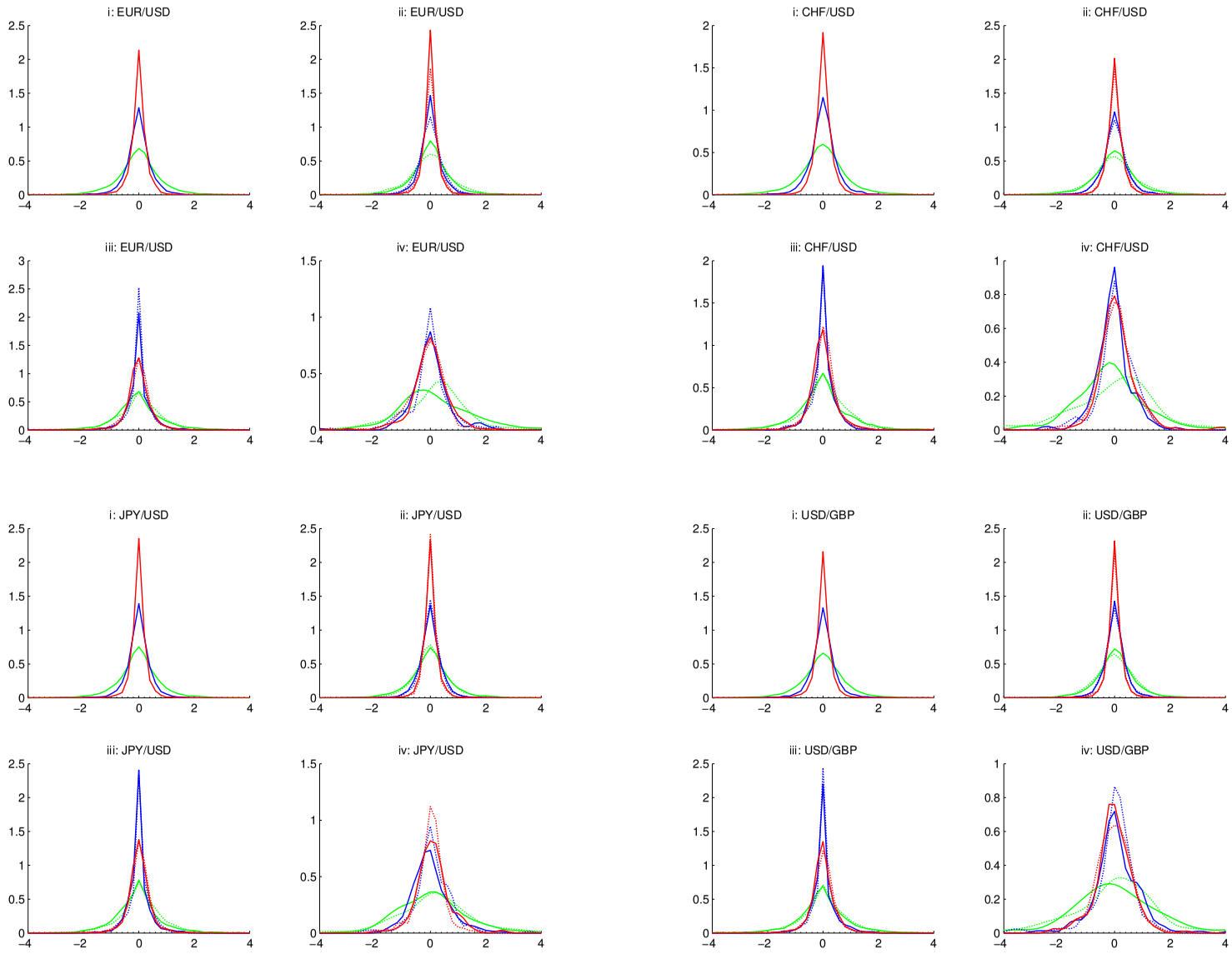
[16] I only include statistics for currency pairs with reliable intraday data starting in 2004.

Table 6: Stability of Spot Rate Dynamics

			2004-2007					2010-1013					
		horizon	5%	95%	std	skew	kurtosis	5%	95%	std	skew	kurtosis	KS Test p-value
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)	(xi)	(xii)	(xiv)
A:	EUR/USD	5	-1.236	1.234	0.833	0.029	11.279	-1.369	1.462	0.890	0.193	6.333	0.000
		15	-0.671	0.636	0.436	-0.466	9.937	-0.727	0.737	0.463	0.135	6.094	0.001
		30	-0.671	0.636	0.282	-0.208	10.384	-0.478	0.487	0.299	0.267	5.886	0.000
	CHF/USD	5	-1.324	1.404	0.889	0.436	9.868	-1.580	1.528	1.012	-0.652	14.041	0.000
		15	-0.725	0.753	0.474	0.268	7.398	-0.805	0.767	0.522	-0.416	9.485	0.001
		30	-0.725	0.753	0.294	0.018	6.575	-0.530	0.489	0.325	-0.559	9.684	0.201
	JPY/USD	5	-1.235	1.312	0.829	0.151	8.780	-1.173	1.099	0.757	-0.174	9.364	0.000
		15	-0.658	0.673	0.428	0.007	7.115	-0.603	0.610	0.392	0.568	9.330	0.001
		30	-0.658	0.673	0.272	-0.291	9.113	-0.415	0.386	0.261	0.337	8.359	0.021
	USD/GBP	5	-1.261	1.216	0.887	0.506	18.506	-1.226	1.232	0.782	0.141	8.286	0.000
		15	-0.648	0.653	0.487	-0.854	35.074	-0.677	0.647	0.440	0.415	9.644	0.000
		30	-0.648	0.653	0.322	-1.450	49.030	-0.408	0.452	0.282	0.489	8.096	0.003
B:	CHF/EUR	5	-0.644	0.695	0.488	0.871	22.664	-1.059	1.082	0.764	0.014	31.187	0.000
		15	-0.360	0.382	0.267	1.205	32.256	-0.617	0.542	0.405	0.101	22.086	0.000
		30	-0.360	0.382	0.171	0.614	34.213	-0.371	0.371	0.253	0.433	17.937	0.000
	JPY/EUR	5	-1.360	1.331	1.000	0.562	23.980	-1.711	1.743	1.104	0.085	6.712	0.000
		15	-0.742	0.728	0.532	0.679	17.937	-0.943	0.967	0.595	0.339	8.313	0.000
		30	-0.742	0.728	0.352	0.562	20.992	-0.608	0.600	0.383	0.270	7.020	0.000
C:	CHF/GBP	5	-1.146	1.216	0.815	0.447	14.632	-1.496	1.392	0.987	-0.404	15.134	0.000
		15	-0.646	0.612	0.459	0.909	28.974	-0.803	0.738	0.532	-0.001	12.160	0.000
		30	-0.646	0.612	0.308	-1.634	62.633	-0.482	0.502	0.334	-0.101	9.787	0.001
	EUR/GBP	5	-0.895	0.903	0.667	-0.108	12.598	-1.147	1.215	0.761	-0.185	7.534	0.000
		15	-0.495	0.503	0.365	-0.516	25.800	-0.613	0.646	0.422	-0.228	11.588	0.000
		30	-0.495	0.503	0.244	0.968	46.873	-0.431	0.418	0.274	-0.210	7.546	0.000
	JPY/GBP	5	-1.533	1.547	1.144	0.952	22.271	-1.619	1.614	1.045	0.177	7.440	0.001
		15	-0.814	0.832	0.608	0.481	27.077	-0.880	0.919	0.573	0.466	9.680	0.007
		30	-0.814	0.832	0.405	-0.597	41.379	-0.538	0.598	0.372	0.391	9.238	0.038
D:	AUS/USD	5	-1.658	1.562	1.221	0.350	24.528	-1.557	1.559	0.968	-0.052	7.257	0.000
		15	-0.897	0.849	0.639	-0.161	16.309	-0.827	0.757	0.500	0.162	6.025	0.002
		30	-0.897	0.849	0.420	0.418	16.003	-0.511	0.500	0.323	0.365	7.591	0.001
	CAD/USD	5	-1.496	1.467	0.946	0.024	10.811	-1.207	1.217	0.782	-0.211	6.614	0.000
		15	-0.787	0.787	0.528	0.575	12.847	-0.700	0.650	0.416	-0.084	6.713	0.008
		30	-0.787	0.787	0.342	0.020	16.472	-0.419	0.415	0.264	0.004	7.356	0.004

Notes: Columns (iii) - (vii) and (viii) - (xii) report statistics on the distribution of changes in the log quotes over horizons h of 5, 15, and 30 minutes from quotes made between Jan 1st 2004 and Dec 31st. 2004, and between Jan 1st. 2010 and Dec. 31st. 2013. The change in quotes are expressed in basis points per minutes, i.e.,$\Delta\ ^h s_t \equiv (\ln(S_{t+h}) - \ln(S_t))10000/h$ for $h = \{5, 15, 60\}$. All statistics are computed from 10000 starting times t sampled at random. Column (xiv) reports the asymptotic p-value from the KS test of the null that the distributions from the two subsamples are the same.

Figure 4: Rate Change Densities



Notes: Plots (i) shows the density functions for$\Delta^{h} s_t$ for $h = \{5, 15, 30\}$ minutes in green, blue, and red, respectively. Plot (ii) shows the density functions$\Delta^{h} s_t$ from pre-2008 and post 2009 data with solid and dotted lines, respectively. Plots (iii) and (iv) show the conditional densities for $f(\Delta^h s_t | \Delta^h s_{t-h} > \kappa^+)$ (solid) and $f(\Delta^h s_t | \Delta^h s_{t-h} < \kappa^-)$ (dotted), where where κ^+ and κ^- denote the upper and lower percentiles of the price-change distribution, respectively: equal to {75%, 25%} in plot (iii) and {97.5%, 2.5%} in plot (iv).

5 Pre-Fix Spot Rate Dynamics

In now turn to the central focus of this study; the behavior of spot rates in the periods immediately before and after the 4:00 pm Fix. In this section I examine the pre-Fix behavior of rates between 3:00 and 4:00 pm using the distributions for rate-changes away from the Fix as a benchmark to identify atypical behavior.

Figure 5 shows the rate-change densities over windows of {60,15,5,1} minutes before 4:00 pm for the four major currency pairs. For each horizon and currency pair the figure plots the densities for spot rate changes away from the Fix (discussed in Section 4) together with the densities for the pre-Fix rate changes on intra-month and end-of-month days. The densities for the pre-Fix changes use the Fix as the end spot rate in each rate change. For example, the density for end-of-month five-minute pre-Fix change is estimated from the change in spot rates between 3:55 and 4:00 pm at the end of every month. The intra-month density is similarly estimated from intraday data on all the other days. Notice, also, that these densities are for rate changes expressed in basis points, rather than basis point per minute as in Figure 4.

Two features stand out from the plots in Figure 5. First, the behavior of pre-Fix rate changes are quite unlike that of rate changes associated with normal trading activity. As the plots clearly show, the estimated densities for the pre-Fix changes are quite different from the densities for rate-changes away from the Fix. It appears that many pre-Fix rate changes are atypical of the changes we observe at other times. This visual evidence is confirmed by KS tests for the equality of the pre-Fix and away-from-the-Fix distributions; they give very small p-values for all currency pairs and horizons.

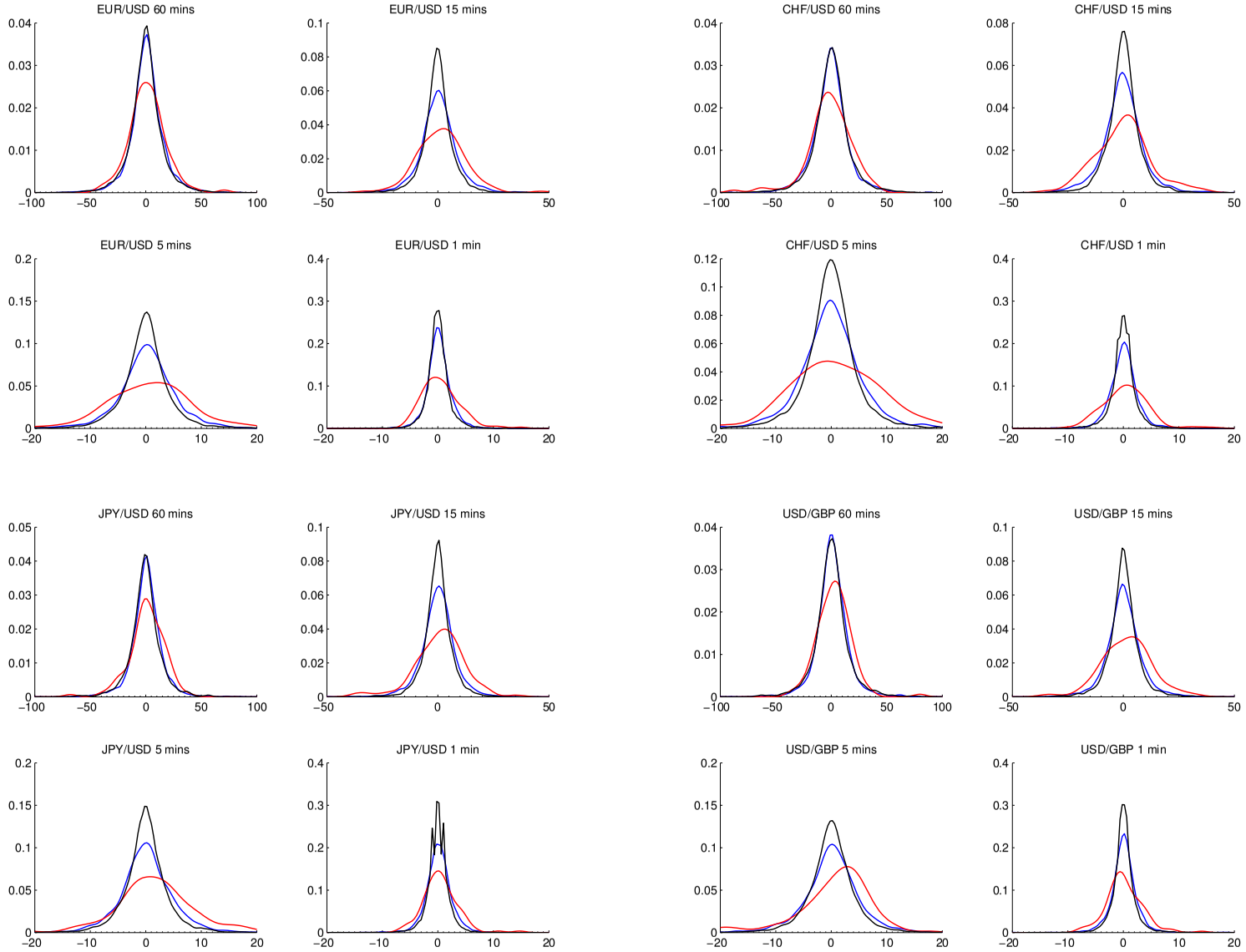
Second, the behavior of pre-Fix rate changes at the end of the month appear more atypical than those on other days. Recall from Section 1 that there is a strong hedging incentive for fund managers and derivative investors to submit fill-at-fix forex orders at the end of the month. The density plots show that this institutional factor has a material affect on the behavior of rates before the Fix. More specifically, the dispersion of pre-Fix rate changes at the end of the month is significantly larger than the dispersion of changes away from the Fix, and the dispersion of pre-Fix changes during the month. These differences are more pronounced at shorter horizons (particularly below 15 minutes). These density plots imply that the Fix established at the end of each month is quite often far from the rates at which forex was trading less than 15 minutes earlier, and that rate changes (over the same horizon) of a similar size are extraordinarily rare in trading away from the Fix. Importantly, this striking feature of the data applies to all 21 the currency pairs. As the Appendix shows, the plots in Figure 5 are representative of the plots for the other currency pairs.

How atypical are the spot rate movements before the Fix? To answer this question, I compare the pre-Fix rate changes to the tail probabilities from the distribution of rate-changes away from the Fix. Specifically, I compute the fraction of days where the absolution pre-Fix change is larger than the 95th. percentile of the distribution of absolute changes away from the Fix.[17] If pre-Fix changes are consistent with normal trading away from the Fix, they should be above the 95th. percentile on approximately one day in twenty (i.e., 5 percent of the time).

Table 7 reports the percentage of end-of-month and intra-month days on which the pre-Fix absolute basis point change in spot rates is larger than the 95th. percentile threshold across horizons ranging from one to 60 minutes. The results in the table are quite remarkable. Notice, first, that the incidence of unusually large

[17]The distribution of absolute rate changes away from the Fix is estimated from the same random sample of 10000 rates for each currency pair examined in Section 4.

Figure 5: Pre-Fix Rate Change Densities



Notes: Distribution for rate changes (in basis points) away from Fixes (black), intra-month pre-Fix (blue), and end-of-month pre-Fix (red).

Table 7: Tail Probabilities for pre-Fix Rate Changes

		I: End-of-Month						II: Intra-Month					
	horizon	60	30	15	10	5	1	60	30	15	10	5	1
		(i)	(ii)	(iii)	(iv)	(v)	(vi)	(i)	(ii)	(iii)	(iv)	(v)	(vi)
A:	EUR/USD	16.239	22.222	18.803	14.530	22.222	33.333	10.248	11.653	9.380	7.521	7.107	10.496
	CHF/USD	21.698	21.698	21.698	20.755	25.472	37.736	9.832	13.242	10.939	10.895	9.433	14.969
	JPY/USD	17.308	28.846	38.462	42.308	47.115	61.539	10.027	12.114	11.071	10.481	10.799	22.051
	USD/GBP	18.966	27.586	29.310	35.345	33.621	51.724	7.394	10.822	9.665	9.748	11.276	20.446
	Average	18.553	25.088	27.068	28.234	32.108	46.083	9.375	11.958	10.264	9.661	9.654	16.990
B:	CHF/EUR	18.966	23.276	25.862	28.448	29.310	33.621	7.375	9.987	9.819	11.125	11.589	15.086
	JPY/EUR	17.094	28.205	29.915	34.188	42.735	52.137	9.418	10.574	8.013	8.550	10.905	15.572
	NOK/EUR	16.129	29.032	24.194	35.484	35.484	58.065	10.070	14.330	14.562	14.795	19.597	29.202
	NZD/EUR	26.471	30.882	29.412	36.765	41.177	48.529	12.306	16.549	15.559	15.842	20.368	27.581
	SEK/EUR	16.949	25.424	30.509	38.983	45.763	45.763	9.472	13.975	16.149	15.761	15.450	29.115
	Average	19.122	27.364	27.978	34.774	38.894	47.623	9.728	13.083	12.820	13.215	15.582	23.311
C:	AUS/GBP	18.841	30.435	34.783	34.783	34.783	56.522	8.537	12.940	13.008	13.415	14.160	26.423
	CAD/GBP	19.718	28.169	30.986	29.578	38.028	39.437	9.811	14.614	16.238	16.847	22.463	30.176
	CHF/GBP	17.241	30.172	37.069	37.069	31.035	50.000	7.158	10.923	11.378	12.371	12.743	21.804
	EUR/GBP	21.739	31.304	40.000	41.739	37.391	50.435	6.926	10.603	12.399	11.372	12.185	22.488
	JPY/GBP	18.103	27.586	32.759	34.483	43.966	56.035	7.775	10.132	10.008	10.091	11.373	21.464
	NZD/GBP	17.910	25.373	25.373	23.881	26.866	47.761	9.865	13.272	12.420	14.195	21.221	30.518
	Average	18.926	28.840	33.495	33.589	35.345	50.031	8.345	12.081	12.575	13.048	15.691	25.479
D:	AUS/USD	22.414	28.448	23.276	29.310	32.759	46.552	10.092	12.427	11.259	11.426	13.136	19.516
	CAD/USD	23.276	31.897	29.310	30.172	34.483	43.966	11.273	16.722	15.183	14.642	16.889	26.040
	DKK/USD	13.559	15.254	10.170	11.864	18.644	30.509	10.575	10.881	6.820	7.433	7.126	10.575
	NOK/USD	8.065	22.581	19.355	25.807	29.032	46.774	9.724	12.481	9.954	11.792	12.864	24.043
	SEK/USD	13.559	20.339	23.729	23.729	33.898	40.678	9.792	12.336	11.334	10.948	11.411	22.282
	SGD/USD	8.197	11.475	9.836	14.754	16.393	19.672	7.833	9.667	8.917	9.500	10.083	18.667
	Average	14.845	21.666	19.279	22.606	27.535	38.025	9.881	12.419	10.578	10.957	11.918	20.187

Notes: Each cell reports the percentage of days in which the absolute basis point change in rates in the window before the Fix is larger than the 95th. percentile from the distribution of absolute basis point rate changes away from the Fix. Panel I reports the percentage for end-of-month rate changes, panel II the percentage for intra-month rate changes. Averages for the currencies in each block are reported in the last row.

pre-Fix rate changes is much higher at the end of the month than on other days. This pattern holds across all the currency pairs and over all the horizons. It reinforces the visual evidence in Figure 5 indicating that pre-Fix spot rate dynamics at the end of the month are different from other days. Second, the incidence of unusually large pre-Fix changes rises as the horizon shortens. This means that if we compare the level of the Fix with the level of rates in the prior hour on a randomly chosen day, we are likely to see an unusually large jump in rates shortly before 4:00 pm.

Perhaps the single most striking aspect of Table 7 concerns the high incidence of unusually large rate movements immediately prior to Fix. Examples of large price movements immediately before 4:00 pm on particular days for specific currencies have been reported in the financial press (see, e.g., Reuters 2013). The statistics in Table 7 show that unusually large pre-Fix rate changes are almost commonplace. For example, atypically large changes in the minute before the Fix on intra-month days occur at more than three times the rate that would be consistent with normal trading activity across the four major currency pairs, and at higher rates across the other currency pairs. The incidence of atypically large rate changes immediately before the Fix is even higher at the end of the month. At the one minute horizon atypical changes occur between four and twelve times the rate consistent with normal trading activity. These are remarkably high numbers. For two of the major currency pairs, the JPY/USD and USD/GBP, atypically large rate changes in the minute before 4:00 pm occur at more than ten times the rate consistent with normal trading activity.

It is also informative to examine the incidence of atypically large pre-Fix rate changes through time. For this purpose Table 8 reports the number of atypical changes (again using the 95th. percentile threshold) over a one minute horizon at the end of the month during each year covered by the dataset. P-values for the null hypothesis that the number of atypical end-of-month changes occurs by chance (based on the distribution of absolute rate changes in normal forex trading) are reported in parenthesis. As the table clearly shows, the high incidence of atypically large pre-Fix rate changes is not concentrated in a few years or currency pairs. On the contrary, it is pervasive. For example, in the case of the USD/GBP, there have been a high number of atypically large changes in every year between 2004 and 2013. In fact the numbers are so high in nine of the years that the probability of this representing rate movements from normal forex trading in USD/GBP in any year is less than 0.001 (i.e., less that one in one thousand). This repeated high incidence of atypically large pre-Fix rate changes is also evident in the JPY/USD, JPY/EUR, CHF/GBP, EUR/GBP, JPY/GBP,USD/USD and CAD/USD. The results in Table 8 also show that the peak incidence of atypically large rate changes did not occur around the world financial crisis. Aggregating across all 21 currency pairs, the peak year was 2010 with a total of 148.

Table 8: Pre-Fix Tail Events By Year (1 minute window)

		2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
A:	EUR/USD	2	5	1	6	5	6	6	3	4	2
		(0.165)	(0.000)	(0.600)	(0.000)	(0.000)	(0.000)	(0.000)	(0.028)	(0.003)	(0.138)
	CHF/USD	1	4	0	5	3	4	5	7	7	4
		(0.450)	(0.001)	(0.569)	(0.000)	(0.007)	(0.002)	(0.000)	(0.000)	(0.000)	(0.002)
	JPY/USD	3	4	7	11	5	6	9	8	4	7
		(0.011)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.003)	(0.000)
	USD/GBP	6	5	6	3	5	9	7	8	5	7
		(0.000)	(0.000)	(0.000)	(0.028)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
B:	CHF/EUR	4	1	1	3	4	4	9	7	0	6
		(0.003)	(0.550)	(0.550)	(0.028)	(0.003)	(0.003)	(0.000)	(0.000)	(0.540)	(0.000)
	JPY/EUR	6	4	4	7	8	8	9	5	5	5
		(0.000)	(0.002)	(0.002)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	NOK/EUR					1	8	8	10	6	4
						(0.200)	(0.000)	(0.000)	(0.000)	(0.000)	(0.002)
	NZD/EUR					8	7	5	4	5	4
						(0.000)	(0.000)	(0.000)	(0.003)	(0.000)	(0.002)
	SEK/EUR					1	4	7	6	5	6
						(0.200)	(0.003)	(0.000)	(0.000)	(0.000)	(0.000)
C:	AUS/GBP					10	9	8	6	5	2
						(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.138)
	CAD/GBP					6	5	6	4	4	3
						(0.000)	(0.000)	(0.000)	(0.003)	(0.003)	(0.021)
	CHF/GBP	4	3	4	5	7	7	8	7	7	7
		(0.003)	(0.021)	(0.002)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	EUR/GBP	3	3	4	4	7	8	9	7	8	6
		(0.028)	(0.021)	(0.002)	(0.003)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	JPY/GBP	4	3	4	8	7	9	10	6	6	9
		(0.003)	(0.021)	(0.002)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	NZD/GBP					6	8	7	6	4	2
						(0.000)	(0.000)	(0.000)	(0.000)	(0.003)	(0.138)
D:	AUS/USD	4	3	5	4	9	9	9	4	3	4
		(0.002)	(0.021)	(0.000)	(0.003)	(0.000)	(0.000)	(0.000)	(0.003)	(0.028)	(0.002)
	CAD/USD	4	3	5	7	6	5	4	3	7	8
		(0.003)	(0.021)	(0.000)	(0.000)	(0.000)	(0.000)	(0.003)	(0.028)	(0.000)	(0.000)
	DKK/USD					3	5	6	2	1	2
						(0.001)	(0.000)	(0.000)	(0.165)	(0.600)	(0.138)
	NOK/USD					2	8	6	6	4	4
						(0.015)	(0.000)	(0.000)	(0.000)	(0.003)	(0.002)
	SEK/USD					3	3	7	5	3	5
						(0.001)	(0.021)	(0.000)	(0.000)	(0.028)	(0.000)
	SGD/USD					2	3	3	1	1	2
						(0.015)	(0.028)	(0.028)	(0.600)	(0.600)	(0.138)

Notes: Each cell reports the number of months in each year that where the absolute change in rates in the 1 minute before the Fix falls in the 95th percentile of the empirical distribution of rate changes away from the Fix. P-values for the null that the number of months occurs by purely by chance are reported in parentheses.

To summarize, the results above show that the changes in forex rates observed immediately before the 4:00 pm Fix are extraordinarily unusual when compared to their behavior in normal trading away from the

Fix: rates regularly jump by an amount that is very rarely seen elsewhere. Moreover, the incidence of these atypically large pre-Fix rate changes is particularly high at the end of each month, appears pervasive across currency pairs and through time.

6 Post-Fix Spot Rate Dynamics

The high incidence of unusually large changes in spot rates immediately before Fix carries over into the behavior of rates after 4:00 pm. Table 9 reports the incidence of large post-Fix rate changes (starting at the Fix) over horizons of one to 60 minutes. As above I use the 95th. percentile threshold from the empirical distribution of absolute price changes away from the Fix to identify atypically large rate changes, and report their incidence for each of the exchange rate pairs at the end of each month and on other intra-month days.

The results in Table 7 show that the incidence of atypically large post-Fix rate changes differs from the incidence of the pre-Fix counterparts. For example, the statistics in Panel II show the incidence of unusually large rate movements falls as the horizon lengthens. At the one and five minute horizons, the incidence is approximately twice as high as we would expect to see in trading away from the Fix, but atypically large rate changes over 60 minutes occur at close to the normal frequency. By this metric, most of the unusual behavior in rates on intra-month days is confined to the first few minutes following 4:00 pm. In contrast, Table 7 showed that unusual rate behavior is evident up to 30 minutes before the Fix on intra-month days.

The behavior of the spot rates at the end of the month is distinctly different. As panel I of Table 9 shows, the incidence of atypically large rate changes is larger at all horizons. For most currency pairs, the incidence at the one minute horizon is at least four times higher than we would expect to see in normal trading, declining to between two and three times normal at the 30 minute horizon. While high, these incidence rates are well below those reported in Table 7 for pre-Fix changes over comparable horizons.

Together, the statistics in Tables7 and 9 clearly establish that rates are unusually volatile immediately before and after the Fix, particularly at the end of the month. I now consider how the pre- and post-Fix behavior of rates are linked. For this purpose I estimate the bivariate density for pre- and post-Fix rate changes at different horizons. More specifically, I estimate the bivariate density $g(\ln(S_{t+h}/S_t^{fix}), \ln(S_t^{fix}/S_{t-h}))$. In view of the results above, I focus on the behavior of rates at the end of each month, and so use the rates from those days to estimate the bi-variate density $g(.,.)$. Estimation uses a Gaussian Kernel with the bandwidth determined as in Bowman and Azzalini (1997).

Figure 6 shows the density functions for the four major currency pairs at horizons ranging from 15 to one minute. (Plots for the 17 other currency pairs are in the Appendix.) Each plot shows the contours of the estimated density, $g(.,.)$, where the pre- and post-Fix rate changes are expressed in basis points. Notice that the horizontal (pre-Fix) and vertical (post-Fix) axes have the same scale in each plot, but differ across plots. Each plot also shows a solid line that represents the projection (i.e. regression) of $\ln(S_{t+h}/S_t^{fix})$ on $\ln(S_t^{fix}/S_{t-h})$, denoted as $\mathcal{P}(\ln(S_t^{fix}/S_{t-h}))$. This line provides information on the intertemporal dependence between the pre- and post-Fix rate changes discussed below.

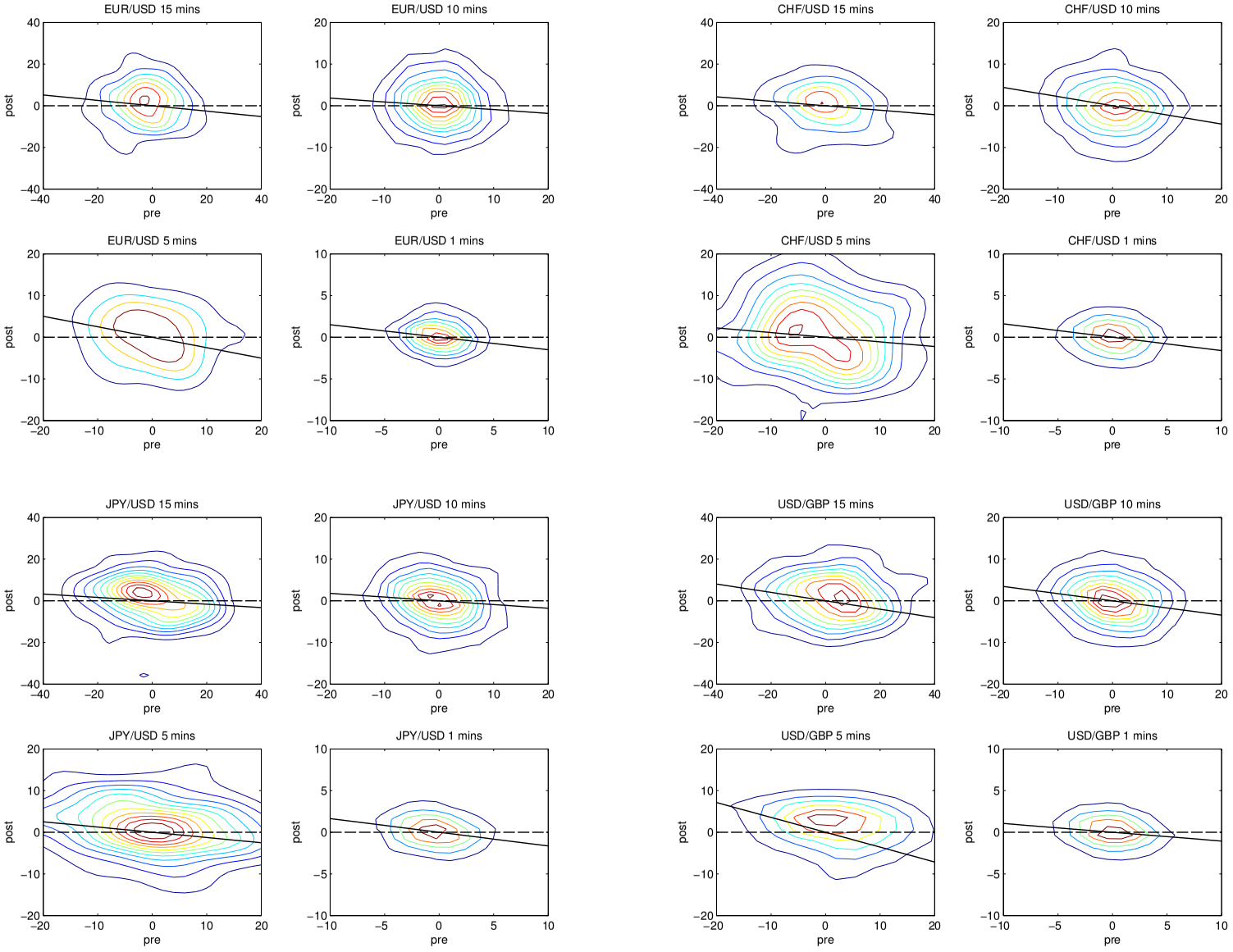
The plots in Figure 6 contain a lot of information about the behavior of spot rates immediately before and after the Fix. Consider, first, the general shape of the density contours. In all cases, the maximum width of each contour exceeds its maximum hight. This feature is present in the bivariate densities across

Table 9: Tail Probabilities for Post-Fix Rate Changes

		I: End-of-Month						II: Intra-Month					
	horizon	60	30	15	10	5	1	60	30	15	10	5	1
		(i)	(ii)	(iii)	(iv)	(v)	(vi)	(i)	(ii)	(iii)	(iv)	(v)	(vi)
A:	EUR/USD	5.983	14.530	15.385	11.966	17.094	20.513	4.917	9.711	9.298	8.554	8.554	6.157
	CHF/USD	6.604	15.094	18.868	17.925	18.868	26.415	4.827	9.965	9.699	8.946	8.193	6.997
	JPY/USD	4.808	18.269	16.346	20.192	21.154	21.154	4.492	8.439	8.893	9.392	8.394	9.483
	USD/GBP	5.172	15.517	14.655	14.655	13.793	18.103	3.965	8.137	7.228	7.683	8.922	6.939
	Average	5.642	15.853	16.313	16.184	17.727	21.546	4.550	9.063	8.779	8.644	8.516	7.394
B:	CHF/EUR	6.897	10.345	16.379	14.655	19.828	16.379	5.310	8.681	7.965	8.807	8.681	8.260
	JPY/EUR	4.274	12.821	16.239	14.530	18.803	25.641	5.370	8.468	7.600	8.674	8.798	7.435
	NOK/EUR	8.065	8.065	4.839	8.065	12.903	20.968	3.408	7.591	6.739	7.436	10.380	18.048
	NZD/EUR	10.294	22.059	16.177	19.118	26.471	41.177	5.375	8.911	7.638	7.992	10.113	11.245
	SEK/EUR	10.170	11.864	13.559	13.559	16.949	40.678	3.882	7.531	7.609	7.531	8.385	16.537
	Average	7.940	13.031	13.439	13.985	18.991	28.969	4.669	8.236	7.510	8.088	9.271	12.305
C:	AUS/GBP	7.246	20.290	23.188	20.290	28.986	26.087	5.488	7.859	6.911	7.656	7.114	8.537
	CAD/GBP	11.268	19.718	19.718	19.718	33.803	23.944	5.345	7.375	7.510	6.698	8.660	8.187
	CHF/GBP	6.897	11.207	14.655	17.241	20.690	21.552	3.889	7.199	7.613	7.737	8.440	9.102
	EUR/GBP	5.217	14.783	19.130	18.261	19.130	26.087	3.292	6.156	6.841	7.054	7.738	10.389
	JPY/GBP	3.448	11.207	15.517	13.793	15.517	14.655	4.839	7.568	8.189	6.989	8.519	7.610
	NZD/GBP	11.940	20.896	13.433	11.940	32.836	31.343	5.820	7.239	6.529	7.452	9.226	11.001
	Average	7.669	16.350	17.607	16.874	25.160	23.945	4.779	7.233	7.265	7.264	8.283	9.137
D:	AUS/USD	7.759	10.345	18.103	17.241	27.586	24.138	5.797	9.425	8.674	7.923	9.008	7.381
	CAD/USD	8.621	18.103	17.241	16.379	30.172	30.172	5.990	9.942	9.318	9.235	10.399	9.193
	DKK/USD	5.085	11.864	10.170	11.864	15.254	18.644	5.287	8.736	9.042	9.349	8.429	5.900
	NOK/USD	4.839	14.516	14.516	19.355	22.581	24.194	4.211	8.959	8.499	9.495	8.116	11.792
	SEK/USD	11.864	16.949	11.864	10.170	18.644	28.814	4.780	8.790	8.867	8.867	7.941	11.103
	SGD/USD	8.197	4.918	3.279	6.557	8.197	27.869	4.667	7.167	7.917	8.083	7.667	14.667
	Average	7.727	12.783	12.529	13.594	20.406	25.638	5.122	8.836	8.719	8.825	8.593	10.006

Notes: Each cell reports the percentage of days in which the absolute basis point change in rates in the window after the Fix is larger than the 95 percentile from the distribution of absolute basis point rate changes away from the Fix. Panel I reports the percentage for end-of-month rate changes, panel II the percentage for intra-month rate changes. Averages for the currencies in each block are reported in the last row.

Figure 6: Bivariate Pre- and Post- Fix Rate Change Densities



Notes: Each plot shows the contours of the estimated bivariate density for pre- and post-fix rate changes (in basis points) over horizons of 1 to 15 minutes. The solid line in each plot is the estimated regression line from the regression on the post-Fix rate change in the pre-Fix change. All estimates are based on end-of-month data.

all the currency pairs and at all horizons. Thus, rates are more volatile immediately before than after the Fix. The plots in Figure 6 also show that there is no simple monotonic relation between the horizon and the dispersion of the rate changes. While the dispersion at the one minute horizon is smaller than at the 15 minute horizon, for some currency pairs the pre- and post-Fix dispersions are larger at the five than ten minute horizons, (see, e.g. CHF/USD and JPY/USD). This pattern is noteworthy because there would be a monotonic relation between the (pre and post-Fix) dispersion and the horizon if log spot rates followed a martingale.

The most significant information conveyed by the plots in Figure 6 concerns the temporal dependence between the pre- and post-Fix rate changes. If post-Fix changes were distributed independently of the pre-Fix change, the contour plots would be symmetric around the horizon dashed line. This is clearly not the case for the four major currency pairs shown in Figure 6, nor is it so for any of the other 17 currency pairs. Although the details differ by currency pair and horizon, in general the contours appear as ellipses that are rotated clockwise around the point (0,0) (see, e.g., the contours for the USD/GBP at the ten-minute horizon). This pattern implies that positive post-Fix price changes are more likely than negative changes if they were preceded by a negative pre-Fix change, and vise-versa. Or, in terms of levels, if rates jumped up immediately before the Fix, they are more likely to jump downwards immediately afterwards than upwards. Similarly, rates are more likely to rise rather than fall immediately after 4:00 pm if they had fallen immediately before the Fix. In sum, therefore, the densities show that there is a tendency for rates to revert back towards their pre-Fix level immediately after 4:00 pm.

We can gauge the degree of rate reversion following the fix from the projection lines shown on each contour plot. By definition the projection allows us to spilt the post-Fix price change, $\ln(S_{t+h}/S_t^{fix})$, into a portion that is perfectly correlated with the pre-Fix change, the projection $\mathcal{P}(\ln(S_t^{fix}/S_{t-h}))$; and a projection error, η_{t+h}, that is uncorrelated with the pre-Fix change:

$$\ln(S_{t+h}/S_t^{fix}) = \mathcal{P}(\ln(S_t^{fix}/S_{t-h})) + \eta_{t+h}.$$

The plots identify $\mathcal{P}(\ln(S_t^{fix}/S_{t-h}))$ by the solid straight line. The vertical distances between the line and the contours represent the dispersion in η_{t+h} conditioned on a particular pre-fix price change $\ln(S_t^{fix}/S_{t-h})$. As Figure 6 clearly shows, the projection lines slope downwards (from left to right) at all horizons and across all four currency pairs. This pattern that is repeated across all the other 17 currency pairs. The steepness of these slopes identifies the degree to which pre-Fix changes in the level of rates are reversed following the Fix. For example, in the case of the USD/GBP, the projection line has a slope of approximately -0.4. This means that a 10 basis point fall in the USD/GBP rate in the five minutes before the fix is, on average, followed by a 4 basis point rise in the USD/GBP rate in the five minutes following the fix.

Table 10 provides more information on the projections across all 21 currency pairs. The table reports the estimated projection coefficients, their (heteroskedastic-consistent) standard errors, and the uncentered R^2 statistics for the projections over the horizons of {1, 5, 10, and 15} minutes. The estimated coefficients are uniformly negative, ranging in value from -0.08 to -0.61. More than half are statistically significant at the five percent level. The R^2 statistics measure the variance contribution of the projections to the post-Fix rate changes, $Var\left(\mathcal{P}(\ln(S_t^{fix}/S_{t-h}))\right)/Var\left(\ln(S_{t+h}/S_t^{fix})\right)$. As the table shows, these statistics are generally

Table 10: Post-Fix Projection Estimates

		15 Minutes			10 Minutes			5 Minutes			1 Minute		
		Coeff	Std Error	R^2	Coeff	Std Error	R^2	Coeff	Std Error	R^2	Coeff	Std Error	R^2
A:	EUR/USD	-0.129	(0.077)	0.018	-0.092	(0.094)	0.008	-0.251	(0.165)	0.060	-0.150	(0.082)	0.048
	CHF/USD	-0.107	(0.150)	0.009	-0.220	(0.172)	0.039	-0.112	(0.209)	0.015	-0.160	(0.138)	0.035
	JPY/USD	-0.081	(0.090)	0.011	-0.090	(0.064)	0.018	-0.126	(0.068)	0.051	-0.164*	(0.045)	0.173
	USD/GBP	-0.201	(0.118)	0.115	-0.172	(0.123)	0.090	-0.357	(0.255)	0.243	-0.105*	(0.046)	0.066
B:	CHF/EUR	-0.235*	(0.078)	0.113	-0.257*	(0.078)	0.140	-0.199	(0.107)	0.104	-0.096	(0.129)	0.020
	JPY/EUR	-0.375*	(0.154)	0.257	-0.386*	(0.159)	0.315	-0.467*	(0.168)	0.408	-0.605*	(0.200)	0.633
	NOK/EUR	-0.167*	(0.073)	0.089	-0.232*	(0.054)	0.207	-0.211*	(0.049)	0.162	-0.075	(0.110)	0.009
	NZD/EUR	-0.309*	(0.077)	0.307	-0.339*	(0.068)	0.381	-0.439*	(0.126)	0.447	-0.141	(0.118)	0.061
	SEK/EUR	-0.233*	(0.061)	0.209	-0.280*	(0.084)	0.218	-0.410*	(0.107)	0.307	-0.199*	(0.070)	0.068
C:	AUD/GBP	-0.303*	(0.042)	0.377	-0.324*	(0.037)	0.381	-0.431*	(0.050)	0.464	-0.031	(0.050)	0.008
	CAD/GBP	-0.038	(0.130)	0.002	-0.039	(0.115)	0.002	-0.344	(0.260)	0.079	-0.040	(0.103)	0.003
	CHF/GBP	-0.267*	(0.108)	0.161	-0.290*	(0.087)	0.198	-0.410*	(0.180)	0.298	-0.150	(0.085)	0.079
	EUR/GBP	-0.228*	(0.097)	0.134	-0.288*	(0.106)	0.202	-0.473*	(0.185)	0.365	-0.209*	(0.047)	0.168
	JPY/GBP	-0.147	(0.145)	0.066	-0.164	(0.133)	0.093	-0.256	(0.223)	0.149	-0.155*	(0.039)	0.179
	NZD/GBP	-0.397*	(0.049)	0.536	-0.413*	(0.041)	0.560	-0.505*	(0.053)	0.633	-0.246*	(0.075)	0.239
D:	AUD/USD	-0.247*	(0.056)	0.170	-0.279*	(0.068)	0.190	-0.256*	(0.106)	0.144	-0.124	(0.080)	0.061
	CAD/USD	-0.189*	(0.074)	0.069	-0.196*	(0.080)	0.084	-0.315*	(0.052)	0.140	-0.178*	(0.064)	0.071
	DKK/USD	-0.259*	(0.108)	0.054	-0.248	(0.138)	0.051	-0.312	(0.255)	0.079	-0.164	(0.102)	0.065
	NOK/USD	-0.135	(0.085)	0.029	-0.203*	(0.090)	0.057	-0.169	(0.089)	0.043	-0.079	(0.086)	0.014
	SEK/USD	-0.237*	(0.102)	0.111	-0.203*	(0.104)	0.063	-0.396*	(0.159)	0.161	-0.234*	(0.068)	0.126
	SGD/USD	-0.443	(0.238)	0.212	-0.142*	(0.211)	0.023	-0.313	(0.161)	0.156	-0.154	(0.309)	0.015

Notes: The table reports the estimated projection coefficient, its (heteroskedastic consistent) standard error, and the R^2 statistic from the projection of the post-fix rate change on the pre-fix change over the horizons shown at the top of each panel. The "*" indicates statistical significance at the 5 percent level. The right hand column of each panel reports the p-value for the KS statistic of the null that the post-Fix rate change distributions conditioned on the sign of the pre-Fix change are equal.

small (i.e. below 0.2). This indicates that most of the variation in post-Fix changes over time is attributable to projection errors that are uncorrelated with the pre-Fix changes. Notable exceptions to this pattern include the NZD/GBP, AUD/GBP, NZD/EUR and JPY/EUR rates. The R^2 statistics are good deal larger in these currency pairs; as high as 0.6 in the case of the NZD/GBP at the five-minute horizon. In these cases, rate reversion accounts for a significant fraction of the time series variation in post-Fix rate changes.

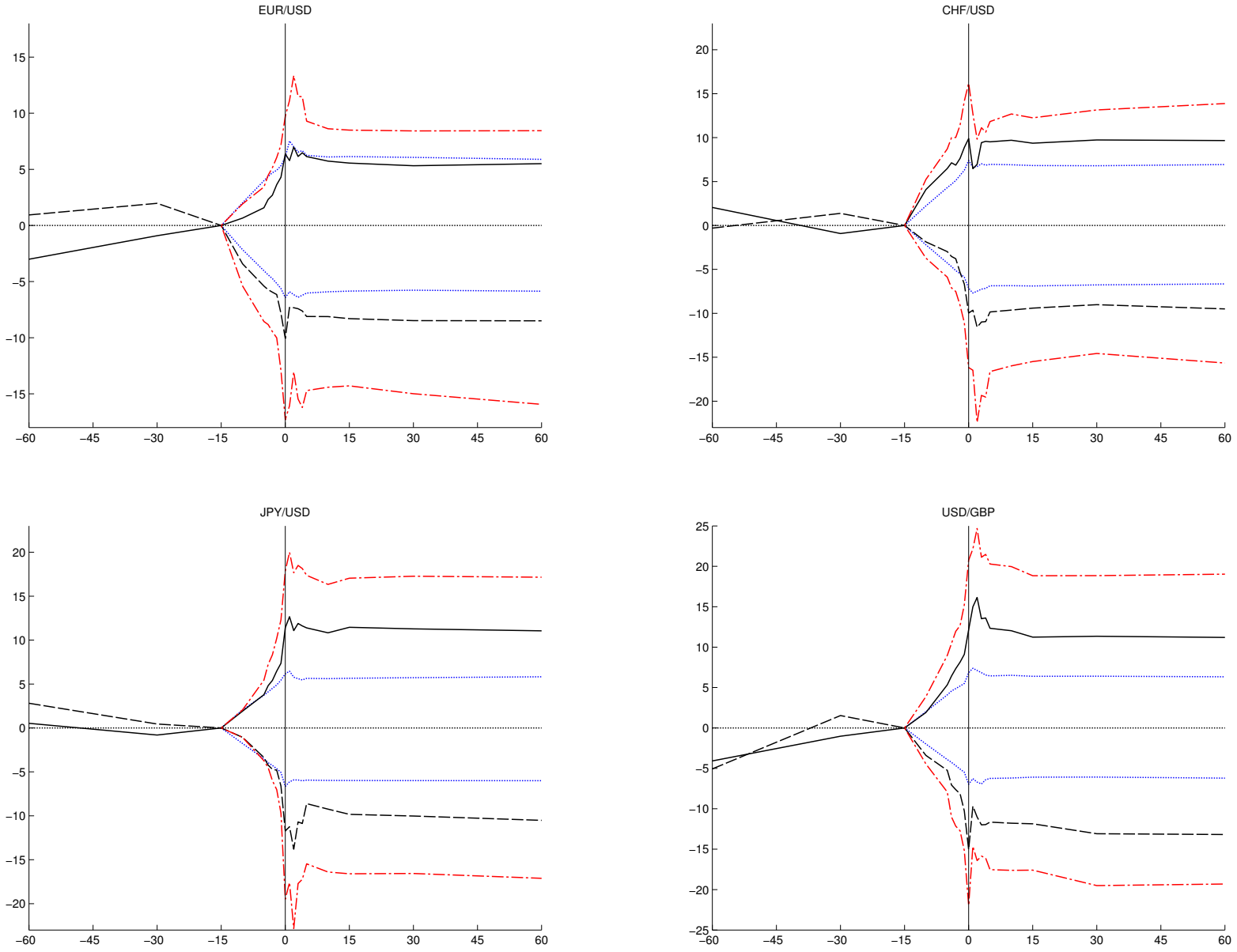
The projection coefficients shown in Table 10 provide one set of estimates for the average degree of rate revision following the Fix. By construction, these estimates assume that the rate revision is proportional to the pre-Fix rate change, and does not depend on whether rates rose or fell towards the Fix. Alternatively, we can estimate the size of spot rate revisions from the average path of rates after the Fix that are conditioned on the pre-Fix changes. For example, we can examine the average paths for spot rates conditioned on pre-Fix changes above or below certain thresholds. One advantage of this approach is that it can identify how the degree of rate revision varies as we move further beyond the Fix.

Figure 7 plots the average spot rate paths in the two hours around the 4:00 pm for the four major currency pairs. All the paths plotted in the figure are measured in basis points relative to the rate a 3:45 pm. The horizontal axis shows minutes after the Fix; so -15 corresponds to 3:45 pm and 0 corresponds to 4:00 pm (identified by the vertical line). Each plot shows six average spot rate paths that are conditioned on the change in rates between 3:45 and 4:00 pm. I condition on the pre-Fix changes at this horizon because 3:45 pm is the cut-off time for dealer-banks to accept fill-at-fix orders. The solid black line in each plot depicts the average rate path across all end-of-month trading days where the pre-Fix price change is positive. The dashed line depicts the analogous path when the pre-Fix change is negative. Average rate paths for intra-month days are shown by two dotted blue lines (the upper and lower lines are conditioned on positive and negative pre-fix price changes, respectively). The remaining upper and lower lines (drawn with dashes and dots) identify the average price paths on end-of-the month trading days where the pre-fix price change is in the 75th. and 25th. percentiles of the pre-fix price change distribution, respectively. For the sake of clarity, both the dotted and dash-dotted lines are hidden to the left of -15. As above, analogous plots for the other 17 currency pairs are in the Appendix.

The plots in Figure 7 provide a good deal of information about both the size and timing of the rate revisions following the Fix. Consider, first, the paths on intra-month days (shown by the blue dotted lines). These paths identify very small reversals during the first minute after the Fix (approximately equal to one basis point). Thereafter the paths a flat. These patterns are common across all the currency pairs. They are consistent with the idea that a new "equilibrium" rate is established based on the information contained in Fix-related trading almost immediately after 4:00 pm. This doesn't mean that rates remain at this level on any particular day, they do not. Rather it implies that all the relevant information contained in trading at (or immediately before) the Fix is fully assimilated into rates by approximately 4:01 pm so there is no systematic tendency for rates to rise or fall after that.

The rate paths from end-of-month trading days are quite different. Consistent with the statistics on pre-Fix rate volatility, changes in rates between 3:45 and 4:00 pm are larger (in absolute value). The plots also show that generally it takes longer for the new post-Fix equilibrium rate to be established, and that it tends to be further away from the extremum of the rate path. The differences between the end-of-month and intra-month paths is particularly clear cut in the case of the USD/GBP. Here the lowest average rate

Figure 7: Average Rate Paths Around the Fix



Notes: Average price path in basis points around 3:45 pm level conditioned on: (i) positive pre-fix changes (over 15 mins) at end of month (solid black); (ii) negative pre-fix changes (over 15 mins) at end of month (dashed black); (iii) pre-fix changes above the 75th. percentile of end-of-month distribution (upper red dashed dot); (iv) pre-fix changes in the 25th. percentile of end-of-month distribution (lower red dashed dot); (v) positive and negative pre-fix changes on intra-month days (upper and lower blue dots).

(across all days when prices fell towards the Fix) is 15 basis points below its level at 3:45 pm. Thereafter, rates immediately rebound by five basis points, before more falling back more slowly to produce a long-term reversal of approximately two basis points. On days when rates rise towards the Fix, the average increase is 15 basis points. Rates then fall back until 4:15 for a total long-term reversal of 5 basis points.

The plots in Figure 7 also show average rate paths following unusually large pre-Fix rate changes (i.e. those in the 75th. and 25th. percentiles of the empirical distribution) at the end-of-month trading days by the dashed-dotted lines. In some cases these paths identify larger rate revisions than occur on average across all end-of-month trading days, but in others the paths appear very similar. For example, in the case of the EUR/USD there is approximately five basis point revision following unusually large rises in rates towards the Fix, verses a revision of roughly one basis point on average across all end-of-month days. On the other hand, the paths for the USD/GBP show little difference in the size of the rate revisions following unusually large pre-Fix changes and other end-of-month trading days.

One final feature of Figure 7 deserves particular comment. The paths in all the plots are conditioned on the change in rates between 3:45 and 4:00 pm without regard to when rates changed within the 15-minute window. Thus, if most of the movement in rates occurred immediately before the Fix, say between 3:59 and 4:00 pm, the paths would be flat until a point just to the left of the vertical line. Instead, the paths in Figure 7 show that on average rates start "drifting" upwards or downwards soon after 3:45 pm. In other words, rates appear to "anticipate" whether the Fix will be above or below its level at 3:45 pm, and begin to move in that direction well before 4:00 pm. This form of "anticipatory" rate behavior is not seen at other times in the trading day.

7 Forex Trading Around the Fix

The behavior of forex rates around the 4:00 Fix is extremely unusual. When judged against the distribution of rate dynamics away from the Fix, both the volatility and serial dependence of pre- and post-Fix rate changes at the end-of-end month are quite extraordinary. This section provides an economic perspective on these statistical findings. In particular I examine whether the behavior of rates could be consistent with the effective and efficient intermediation of forex orders around the Fix.

At face value many of the results in Section 6 appear inconsistency with Weak-form efficiency, a basic measure of a well-functioning competitive market. In particular, the projection results in Table 10 and the rate paths in Figure 7 suggest that information contained in pre-Fix rates can be used to forecast rate movements after the Fix. More specifically, the projection coefficient estimates imply that, on average, end-of-month rates fall after the Fix if they rose beforehand; or conversely, rates rise after the Fix if they fell beforehand. Of course this forecasting pattern lies behind the average price paths in Figure 7. It suggests the simple end-of-month trading strategy of taking a long (short) position at 4:00 pm if rates fell (rose) towards the Fix. This strategy should generate positive returns on average, but actual returns on any day could be positive or negative depending on the gap between the Fix and the rate obtained when the position is closed. The question is: Would a trading strategy that exploits the forecastability of rates around the Fix be attractive to market participants?

To address this question, I computed the realized returns on trading strategies that initiated long and

short positions at the end-of-month Fix with durations of $h = \{1, 5, 15\}$ minutes. The long and short positions are selected according to the change in rates over the h minutes before the 4:00 pm Fix. Notice that this selection method does not require any estimation, so the returns I construct are from a strategy that could be executed in real time. For the sake of comparison, I also construct returns from the same strategy executed around all the intra-month Fixes.

I compute three performance measures to assess the attractiveness of the strategies to market participants: (i) the average return, (ii) the Sharpe Ratio and (iii) the Maximum Drawdown. The Sharpe Ratio is calculated as $SR = \frac{1}{\sqrt{252}} \left(\mathbb{E}_T[R_i] - 1 \right) / \sqrt{\mathbb{V}_t[R]}$, where R_i is the (gross) return on day i. $\mathbb{E}_T[.]$ and $\mathbb{V}_T[R]$ are sample the mean and variance from the T returns computed over the span of the data. Because returns are generated at the daily frequency, I include the $1/\sqrt{252}$ scale factor to "annualize" the ratio (using the convention that a year equals 252 trading days). Sharpe Ratios are widely used by financial market participants to judge the attractiveness of trading strategies. The Maximum Drawdown statistic is another widely-used measure. It is computed as the maximum percentage drop (i.e. from peak to trough) in the cumulated return from following the trading strategy over the span of data. As such, it provides a measure of downside risk.

Table 11 reports the performance measures for the trading strategies across all the currency pairs. The returns from strategies executed at the end of each month are reported in Panel I, those from strategies executed on intra-month days are shown in Panel II. Columns (i) - (iii) in Panel I show that average returns are generally positive for the end-of-the-month strategies. For some currency pairs, the returns are above ten percent (on an annualized basis). Average returns are also generally positive from the intra-month strategies (see Panel II), but they are good deal smaller. The difference between the end-of-month and intra-month strategies carries over to the Sharpe Ratios. All the ratios from the intra-month strategies are below 2.6, and most are below 2.0. Many of the Sharpe ratios from the end-of-month strategies are far higher, with a few ranging above 5.0. By this metric, the intra-month strategies look much more attractive than the intra-month strategies. They also appear more attractive in terms of the Drawdown statistics. The Drawdowns in the end-of-month strategies are generally one or two percent, whereas those from the intra-month strategies range from two to almost 18 percent.

The results in Table 11 do not support the presence of a strong economic incentive to exploit rate reversions around intra-month Fixes. Yes, the trading strategies for some currency pairs produce sizable average returns (see, e.g. CAD/USD and NZD/GBP), but they are also very risky because the post-Fix rate changes often differ from their forecast direction. Consequently, there does not appear to be a strong incentive for market participants to enter into trades at the Fix in a manner that would further ameliorate the temporal dependency between pre- and post-Fix rate changes observed in the intra-month data.

In contrast, there may be a stronger economic incentive to exploit the rate revisions around end-of-month Fixes. Panel I shows that strategies exploiting these rate reversions in many currency pairs produce significantly higher average returns and Sharpe ratios and smaller Drawdown statistics. Trading around the end-of-month Fixes appears to be more attractive than trading around the intra-month Fixes, but is it attractive enough to produce an economic incentive to trade?

The answer to this question largely depends on the size of the trading costs. Table 11 reports performance measures based on returns that use mid-point rates (i.e. the average of the bid and offer rates). As such,

Table 11: Trading Around the Fix

		I: End-of-month									II: Intra-month								
		Average Return			Sharpe Ratio			Max Drawdown			Average Return			Sharpe Ratio			Max Drawdown		
Horizon		15	5	1	15	5	1	15	5	1	15	5	1	15	5	1	15	5	1
		(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)
A:	EUR_USD	4.937	1.458	1.040	2.339	0.642	0.488	1.638	1.694	1.632	-1.732	-1.013	-1.686	-0.854	-0.554	-0.980	17.677	13.217	16.370
	USD_CHF	2.921	2.763	4.582	1.031	1.253	2.197	1.694	1.077	0.675	0.854	1.594	1.273	0.401	0.800	0.719	5.724	3.993	3.890
	USD_JPY	-0.167	0.812	0.233	-0.066	0.431	0.151	1.245	1.356	0.679	0.481	0.504	0.992	0.280	0.336	0.667	9.225	5.489	4.955
	GBP_USD	-0.866	0.077	-3.635	-0.325	0.042	-1.745	2.168	1.475	2.380	-0.655	0.192	0.254	-0.313	0.120	0.165	13.563	6.492	6.165
B:	EUR_CHF	4.113	4.302	3.698	3.271	4.413	5.158	0.552	0.363	0.200	1.087	1.725	1.606	0.799	1.423	1.452	2.696	2.359	2.259
	EUR_JPY	5.151	6.164	3.001	1.797	2.155	1.250	1.320	0.930	0.741	-1.161	-0.053	-0.875	-0.469	-0.014	-0.397	17.847	6.502	10.494
	EUR_NOK	4.153	7.449	4.806	2.027	4.399	2.738	0.569	0.343	0.477	3.735	3.370	2.664	2.088	1.959	1.657	1.479	2.303	2.111
	EUR_NZD	15.149	19.610	6.963	5.230	6.450	2.741	0.737	0.529	0.802	3.973	4.682	4.782	1.605	2.019	2.173	2.919	3.151	3.322
	EUR_SEK	7.755	2.585	4.502	2.560	0.806	1.687	0.772	1.006	0.513	2.774	2.761	0.128	1.547	1.698	0.091	3.114	1.688	2.513
C:	GBP_AUD	8.120	6.656	3.133	2.506	1.952	1.448	1.306	0.982	0.737	1.847	2.472	2.041	0.735	1.083	0.953	4.178	2.432	3.035
	GBP_CAD	-1.763	5.673	1.402	-0.494	1.787	0.530	2.166	1.427	1.300	3.701	4.333	3.420	1.542	1.975	1.686	3.722	1.945	2.468
	GBP_CHF	5.394	5.363	1.637	2.355	2.275	0.927	0.561	0.732	0.596	2.218	3.075	2.347	1.152	1.759	1.429	4.991	2.228	2.404
	EUR_GBP	10.430	10.719	8.761	3.589	3.934	3.237	0.602	0.439	0.456	1.751	2.282	1.674	1.191	1.676	1.312	2.046	1.361	1.634
	GBP_JPY	2.079	2.953	0.613	0.668	0.880	0.256	2.065	1.788	1.506	-0.075	1.061	0.974	-0.017	0.468	0.475	16.879	6.396	3.492
	GBP_NZD	6.635	11.502	10.890	1.735	3.037	4.476	1.427	1.291	0.865	4.778	6.356	5.862	1.794	2.533	2.389	2.653	2.796	2.436
D:	USD_AUD	11.277	14.382	10.443	4.133	5.086	3.904	1.234	0.923	0.920	0.200	0.535	1.006	0.091	0.240	0.465	12.621	11.112	7.103
	USD_CAD	5.002	11.987	10.907	1.700	4.334	4.108	1.451	0.977	0.801	5.006	5.349	3.845	2.275	2.635	2.032	3.992	2.515	3.832
	USD_DKK	9.011	3.603	1.680	3.484	1.854	1.018	0.883	0.893	0.663	0.760	0.665	0.736	0.344	0.328	0.373	4.303	5.188	6.624
	USD_NOK	2.595	6.245	10.719	0.753	2.012	5.169	1.630	1.008	0.311	3.851	3.119	2.964	1.215	1.081	1.124	2.748	5.158	3.826
	USD_SEK	5.276	-2.097	3.667	1.231	-0.476	0.993	1.496	2.892	1.214	3.567	2.207	0.278	1.148	0.744	0.113	3.868	4.621	7.964
	USD_SGD	2.516	2.596	0.719	2.177	2.658	0.841	0.609	0.304	0.427	1.546	1.914	2.205	1.427	2.015	2.386	1.155	1.263	0.730

Notes: Columns (i) - (iii) report the average return (in annual percent) from a trading strategy of holding a long (short) position for horizon $h = \{1, 5, 15\}$ minutes following the Fix if the Fix is below (above) the price level h minutes earlier. Columns (iv) - (vi) report the associated Sharpe ratios (annualized), while columns (vii) - (ix) show the maximum drawdown in percent from following the strategy on every end-of-month trading day (Panel I) and every intra-month trading day (Panel II).

they do not include the trading costs of entering a position at the Fix and exiting some minutes later. In reality, spreads collapse to almost zero in the 60-second window around 4:00 pm used in computing the Fix, so the Fix benchmark is a good approximation to the transaction price that traders would actually face when initiating a position at 4:00 pm. Thereafter spreads return to their normal level for the 20-30 minutes until daily trading activity declines. This pattern suggests that the typical rate facing a trader closing out a position from one to fifteen minutes after the Fix would be equal to the mid-point rate ± one half the normal spread between the offer and bid rates.

Table 12: Trading Around the Fix with Transaction Costs

		Average Return			Sharpe Ratio			Drawdown			Spread
Horizon		15	5	1	15	5	1	15	5	1	(Basis Points)
		(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)
A:	EUR_USD	2.807	-0.673	-1.090	1.335	-0.279	-0.489	1.998	1.931	1.852	1.708
	USD_CHF	-1.358	-1.515	0.303	-0.458	-0.669	0.155	1.935	1.273	0.871	3.477
	USD_JPY	-3.699	-2.720	-3.272	-1.694	-1.399	-2.000	1.799	1.835	1.486	2.771
	GBP_USD	-3.650	-2.682	-6.395	-1.415	-0.977	-3.079	3.007	1.858	3.321	2.285
B:	EUR_CHF	1.402	1.636	1.077	1.121	1.684	1.511	0.637	0.464	0.353	2.160
	EUR_JPY	1.959	2.972	-0.191	0.693	1.047	-0.067	1.615	1.207	1.039	2.622
	EUR_NOK	-1.360	2.029	-0.706	-0.650	1.205	-0.393	0.828	0.482	0.577	4.449
	EUR_NZD	6.247	10.585	-2.062	2.157	3.467	-0.792	0.951	0.618	1.711	7.018
	EUR_SEK	3.351	-1.818	0.097	1.115	-0.540	0.049	0.856	1.461	0.764	3.584
C:	GBP_AUD	2.244	0.781	-2.746	0.701	0.244	-1.244	2.074	1.016	1.665	4.773
	GBP_CAD	-7.687	-0.252	-4.362	-2.212	-0.063	-1.595	3.109	1.862	1.728	4.841
	GBP_CHF	0.242	0.267	-3.353	0.117	0.125	-1.867	1.745	1.122	2.011	4.152
	EUR_GBP	6.221	6.510	4.552	2.142	2.391	1.685	1.184	0.905	0.810	3.208
	GBP_JPY	-3.089	-2.216	-4.556	-0.953	-0.631	-1.795	3.385	2.694	3.278	4.090
	GBP_NZD	-5.669	-0.600	-1.420	-1.442	-0.138	-0.565	3.480	2.281	1.854	9.738
D:	USD_AUD	7.097	10.202	6.263	2.614	3.619	2.345	1.828	1.472	1.521	3.171
	USD_CAD	0.576	7.679	6.550	0.209	2.780	2.470	2.339	1.089	0.913	3.576
	USD_DKK	7.416	2.007	0.085	2.869	1.037	0.059	0.987	1.116	0.810	1.244
	USD_NOK	-3.413	0.236	4.709	-0.950	0.091	2.276	2.435	1.631	0.429	4.738
	USD_SEK	0.122	-7.250	-1.487	0.049	-1.699	-0.377	1.969	3.673	1.833	4.048
	USD_SGD	-1.898	-1.891	-3.490	-1.626	-1.920	-4.040	1.092	0.813	0.991	3.671

Notes: Columns (i) - (iii) report the average return (in annual percent) from a trading strategy of holding a long (short) position for horizon $h = \{1, 5, 15\}$ minutes following the end-of-month Fix if the Fix is below (above) the price level h minutes earlier. Columns (iv) - (vi) report the associated Sharpe ratios (annualized), while columns (vii) - (ix) show the maximum drawdown in percent from following the strategy on every end-of-month trading day. Returns are inclusive of trading costs, computed to be zero at the Fix and one half the average bid-ask spread (shown in column x) when the position is closed.

Table 12 reports the performance measures for the end-of-month trading strategy that include a trading cost of half the average spread estimated between 7:00 am and 6:00 pm GMT on every day in the data span. As the table clearly shows, the inclusion of this trading cost has a significant impact on the performance measures. Average returns are considerably lower; indeed, for many currency pairs they are now below zero. There are, however, a number of cases where average returns remain large a positive. For example, returns for the JPY/EUR, NZD/EUR, EUR/GBP, AUD/USD, CAD/USD, NOK/USD and DKK/USD at one or more horizons are sizable. The Sharpe Ratios and Drawdown statistics also appear quite attractive in many of these currencies.

The difference between the performance measures for the end-of-month strategies in Tables 11 and 12 show that the strength of the economic incentive to exploit rate revisions around end-of-month Fixes depends critically on trading costs. These costs differ from one market participant to another according to the trading venues they use, so it is impossible to compute a single performance measure (inclusive of trading costs) that is relevant to every market participant. Undoubtedly, some participants have access to trading platforms where spreads are much smaller than the average spreads reported in the Table 12. These participants face stronger economic incentives to exploit the rate revisions around the end-of-month Fixes than the performance measures in Table 12 suggest. For others, facing larger costs, the incentives are far weaker. Indeed, the performance measures in Table 12 indicate that they are absent for many of the currency pairs.

In summary, the performance metrics in Tables 11 and 12 suggest that for some currency pairs, most notably the NZD/EUR, EUR/GBP, AUD/USD and CAD/USD, market participants face strong economic incentives to adopt trading strategies exploiting rate revisions around end-of-month Fixes. For other currency pairs (including the four majors), the economic incentives are less clear cut because the metrics are far more sensitive to trading costs.

8 Conclusion

This paper has documented the atypical behavior of forex spot rates around the 4:00 pm Fix, particularly at the end of each month. The results show that across all time periods and currency pairs changes in rates before and after the Fix are regularly of a size rarely seen in normal trading activity. The pre- and post-Fix rate changes also display a strong degree of negative autocorrelation that is not found elsewhere during normal forex trading. As a consequence, there appears to be a strong economic incentive for market participant to adopt trading strategies that exploit the implied reversion in the rates (for some currency pairs) around the Fix.

These findings represent a challenge to standard forex trading models. Because the Fix is used in the real-time valuation of financial benchmarks and contracts, there is clear hedging motive to execute forex transaction at the Fix. Consequently, it is not a surprise that forex rates are unusually volatile in the 60-second Fix window around 4:00 pm. According to standard trading models (like the PS model discussed in Section 1), this is the period where rates should adjust to (unanticipated) aggregate market-wide order flow generated by hedging forex trades. What is surprising is the scale and timing. Volatility is so much higher than observed at other times, and rates start jumping around well before the Fix window. Standard trading models can only account for this level of volatility in the presence of very large (unanticipated) order flows, and cannot predict the anticipatory movements in the rates before the Fix. Also, the models cannot account for the strong negative correlation in rate changes around the Fix that appear to present attractive trading opportunities.

How, then, should we interpret these findings, particularly the autocorrelation in spot rate changes around the Fix? One possibility is simply that market participants were unaware of the trading opportunity it represented, but this not a compelling explanation. A disproportionately large amount of daily trading volume takes place during the minute or so around the Fix (approximately one percent of daily volume), so one would expect that many market participants focus on the behavior of spot rates during this period.

Alternatively, participants could have been aware of the trading opportunity, and (some) were exploiting it, but the effect of their trades on rates was offset be another countervailing factor. This seems a more plausible explanation, but it is impossible to investigate it further without detailed data on trading activity around the Fix.

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Appendix to Forex Trading and the WMR Fix

Martin D. D. Evans

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Table A.1: End-Of-Month Trading Ranges and the Fix

		I: 7:00-6:00 GMT				II: 3:00-5:00 GMT				III: 3:30-4:30 GMT			
		Range Distribution		Tail Probabilities		Range Distribution		Tail Probabilities		Range Distribution		Tail Probabilities	
		50%	90%	20%	10%	50%	90%	20%	10%	50%	90%	20%	10%
		(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv)
A: Majors	EUR/USD	76.794	119.249	0.268	0.167	38.834	75.895	0.351	0.177	28.676	52.211	0.313	0.164
	CHF/USD	94.853	154.358	0.319	0.183	47.528	81.867	0.367	0.163	31.707	64.957	0.361	0.204
	JPY/USD	73.341	119.288	0.312	0.142	37.440	76.826	0.341	0.203	27.451	55.131	0.308	0.214
	USD/GBP	81.742	135.705	0.286	0.160	41.052	78.282	0.405	0.251	30.964	68.833	0.309	0.214
	Average	81.683	132.150	0.296	0.163	41.213	78.217	0.366	0.199	29.700	60.283	0.323	0.199
B: EUR	CHF/EUR	35.235	90.774	0.272	0.149	19.247	45.610	0.267	0.189	14.603	35.722	0.265	0.170
	DKK/EUR	2.351	4.835	0.270	0.166	1.409	3.087	0.218	0.062	1.072	2.422	0.226	0.081
	JPY/EUR	82.624	154.654	0.243	0.154	43.303	91.082	0.300	0.158	32.059	76.211	0.288	0.174
	NOK/EUR	69.163	110.285	0.258	0.176	33.250	61.362	0.347	0.231	24.722	48.031	0.318	0.192
	NZD/EUR	87.416	150.125	0.321	0.216	49.377	94.327	0.323	0.259	36.202	70.396	0.315	0.194
	SEK/EUR	61.625	127.977	0.171	0.065	37.374	75.349	0.192	0.125	30.441	56.439	0.213	0.143
	Average[1]	67.213	126.763	0.253	0.152	36.510	73.546	0.286	0.192	27.605	57.360	0.280	0.175
C: GBP	AUS/GBP	91.081	167.789	0.268	0.154	47.206	86.571	0.312	0.174	39.020	71.700	0.289	0.173
	CAD/GBP	96.104	167.363	0.361	0.192	50.003	99.829	0.282	0.187	38.543	80.019	0.268	0.202
	CHF/GBP	75.872	143.806	0.226	0.165	34.745	79.824	0.329	0.253	27.241	66.374	0.297	0.176
	EUR/GBP	63.237	119.544	0.181	0.116	29.016	66.500	0.266	0.152	23.569	46.696	0.219	0.099
	JPY/GBP	95.379	160.330	0.339	0.200	47.713	101.746	0.322	0.220	34.551	85.630	0.309	0.181
	NZD/GBP	92.833	155.445	0.286	0.174	52.234	92.520	0.337	0.206	41.126	75.692	0.376	0.268
	Average	85.751	152.380	0.277	0.167	43.486	87.832	0.308	0.199	34.008	71.019	0.293	0.183
D: USD	AUS/USD	85.759	175.769	0.246	0.150	46.425	91.047	0.280	0.153	33.151	65.346	0.244	0.135
	CAD/USD	85.643	153.332	0.225	0.141	47.143	76.322	0.236	0.164	32.877	61.621	0.228	0.174
	DKK/USD	85.361	129.650	0.224	0.132	39.292	73.290	0.289	0.174	29.290	52.409	0.273	0.183
	HKD/USD	3.223	10.648	0.330	0.248	2.314	7.958	0.333	0.211	2.058	6.274	0.270	0.185
	NOK/USD	115.907	184.613	0.232	0.154	58.704	92.952	0.309	0.187	42.882	82.140	0.306	0.170
	SEK/USD	112.579	192.450	0.275	0.165	63.217	116.613	0.360	0.208	43.960	90.279	0.287	0.217
	SGD/USD	37.107	63.284	0.273	0.191	18.979	32.221	0.340	0.231	14.129	23.480	0.386	0.280
	Average[2]	87.059	149.850	0.246	0.155	45.627	80.407	0.302	0.186	32.715	62.546	0.287	0.193

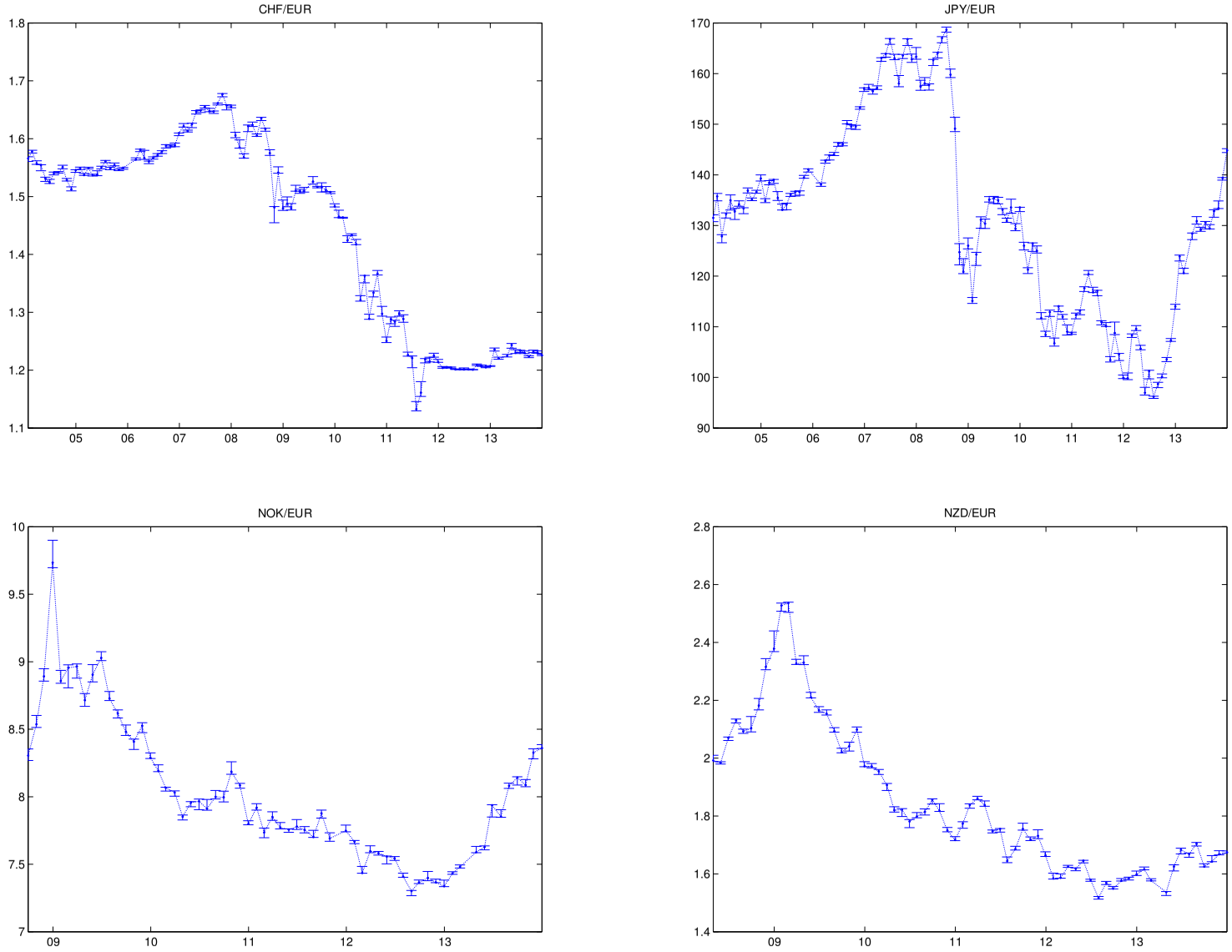
Notes: Columns (i) and (ii) report the 50th. and 90th. percentiles from the empirical distribution of the end-of-month trading range (identified in the header of each panel) expressed in basis points; i.e., $(\ln(P^h) - \ln(P^l))10000$ where P^h and P^l are the highest and lowest quotes (midpoint of bid and ask) within the range. Column (iii) report the fraction of days in the sample that the ratio $(P^f - P^l)/(P^h - P^l)$ is either below 0.1 or above 0.9. Column (iv) reports the fraction of the days when the ratio is either below 0.05 or above 0.95. Averages for the currencies in each block are reported in the last row (1: excludes DKK/EUR, 2: excludes HKD/USD).

Table A.2: Intra-Month Trading Ranges and the Fix

		I: 7:00-6:00 GMT				II: 3:00-5:00 GMT				III: 3:30-4:30 GMT			
		Range Distribution		Tail Probabilities		Range Distribution		Tail Probabilities		Range Distribution		Tail Probabilities	
		50%	90%	20%	10%	50%	90%	20%	10%	50%	90%	20%	10%
		(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv)
A: Majors	EUR/USD	72.664	133.544	0.305	0.212	32.311	64.024	0.411	0.276	22.000	44.306	0.395	0.253
	CHF/USD	78.339	141.763	0.321	0.219	35.631	68.119	0.396	0.256	24.300	47.568	0.360	0.234
	JPY/USD	66.044	121.030	0.304	0.200	29.283	59.179	0.376	0.244	20.271	39.128	0.348	0.235
	USD/GBP	68.381	128.790	0.280	0.177	29.223	57.764	0.357	0.230	20.340	41.082	0.339	0.213
	Average	71.357	131.282	0.302	0.202	31.612	62.272	0.385	0.251	21.728	43.021	0.360	0.234
B: EUR	CHF/EUR	32.896	91.019	0.346	0.225	15.084	41.673	0.335	0.209	10.994	30.413	0.317	0.186
	DKK/EUR	1.884	3.871	0.358	0.226	0.938	2.012	0.297	0.117	0.671	1.612	0.182	0.111
	JPY/EUR	79.043	163.981	0.301	0.196	34.769	73.595	0.369	0.243	23.843	51.180	0.367	0.224
	NOK/EUR	61.213	122.101	0.272	0.163	28.638	54.529	0.275	0.167	20.576	41.120	0.244	0.154
	NZD/EUR	81.948	151.939	0.304	0.206	38.488	76.247	0.345	0.205	28.206	56.326	0.313	0.197
	SEK/EUR	65.548	129.019	0.265	0.157	29.633	56.571	0.287	0.177	21.945	41.317	0.254	0.168
	Average[1]	64.130	131.612	0.297	0.189	29.322	60.523	0.322	0.200	21.113	44.071	0.299	0.186
C: GBP	AUS/GBP	79.466	155.353	0.295	0.205	36.084	73.708	0.365	0.233	26.107	56.145	0.339	0.205
	CAD/GBP	81.295	152.244	0.284	0.176	38.477	75.942	0.317	0.204	27.691	55.438	0.307	0.210
	CHF/GBP	65.698	133.619	0.290	0.191	28.449	57.954	0.359	0.218	20.563	42.024	0.333	0.209
	EUR/GBP	57.021	111.370	0.249	0.157	23.384	46.463	0.334	0.195	16.814	33.479	0.305	0.177
	JPY/GBP	80.681	165.320	0.292	0.177	34.177	75.072	0.349	0.233	24.465	52.827	0.325	0.213
	NZD/GBP	86.155	162.276	0.296	0.189	41.277	80.718	0.336	0.204	30.054	61.080	0.293	0.197
	Average	75.053	146.697	0.284	0.182	33.641	68.310	0.343	0.215	24.282	50.166	0.317	0.202
D: USD	AUS/USD	78.026	160.820	0.335	0.225	37.366	80.620	0.376	0.235	26.729	55.073	0.340	0.204
	CAD/USD	73.848	137.284	0.288	0.183	34.708	69.904	0.332	0.205	24.513	48.278	0.305	0.188
	DKK/USD	80.100	148.223	0.306	0.219	36.904	70.222	0.415	0.279	25.051	49.690	0.403	0.268
	HKD/USD	2.448	5.911	0.264	0.146	1.290	3.337	0.247	0.140	1.029	2.570	0.225	0.094
	NOK/USD	105.399	197.682	0.314	0.200	49.816	95.061	0.349	0.221	35.412	66.993	0.333	0.203
	SEK/USD	110.103	209.408	0.300	0.192	51.721	97.139	0.354	0.213	36.153	69.350	0.332	0.205
	SGD/USD	36.732	68.278	0.315	0.188	16.816	31.438	0.344	0.222	11.499	23.373	0.301	0.189
	Average[2]	80.701	153.616	0.310	0.201	37.889	74.064	0.362	0.229	26.560	52.126	0.336	0.209

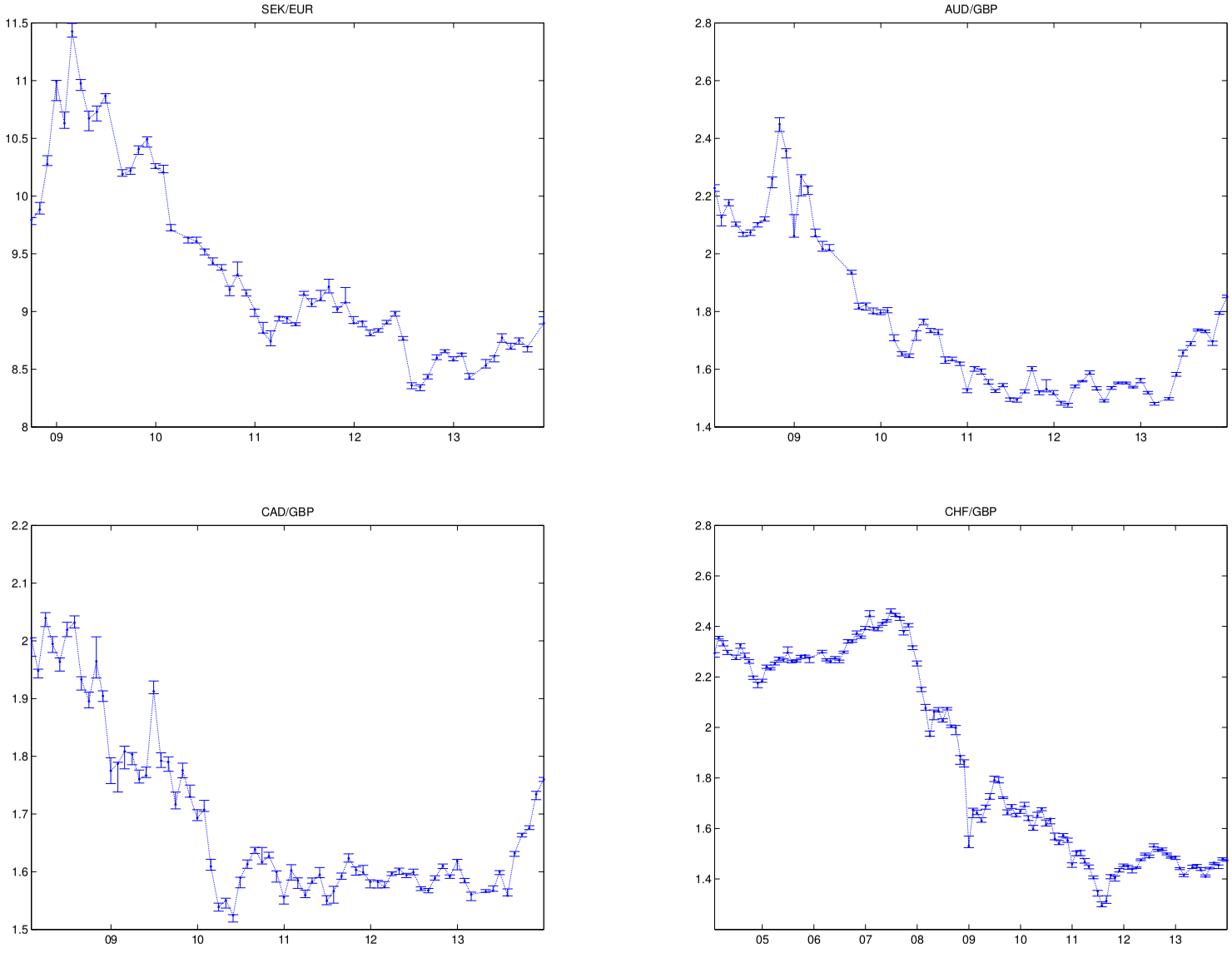
Notes: Columns (i) and (ii) report the 50th. and 90th. percentiles from the empirical distribution of the intra-month trading range (identified in the header of each panel) expressed in basis points; i.e., $(\ln(P^h) - \ln(P^l))10000$ where P^h and P^l are the highest and lowest quotes (midpoint of bid and ask) within the range. Column (iii) report the fraction of days in the sample that the ratio $(P^f - P^l)/(P^h - P^l)$ is either below 0.1 or above 0.9. Column (iv) reports the fraction of the days when the ratio is either below 0.05 or above 0.95. Averages for the currencies in each block are reported in the last row (1: excludes DKK/EUR, 2: excludes HKD/USD).

Figure A.1: Fixes with Daily Trading Range



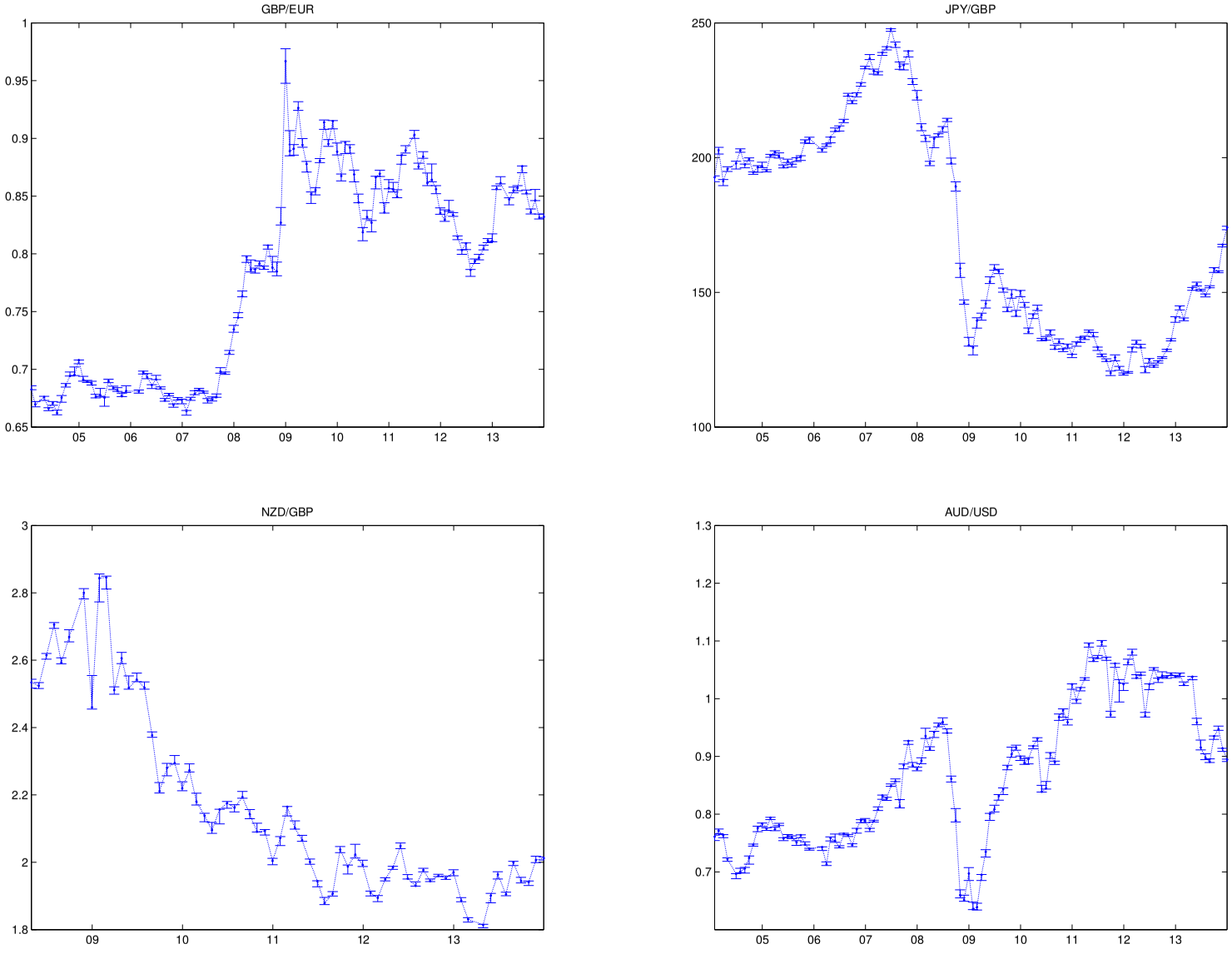
Notes: Time series for the fix at the end of each month with upper and lower limits of daily trading range.

Figure A.2: Fixes with Daily Trading Range



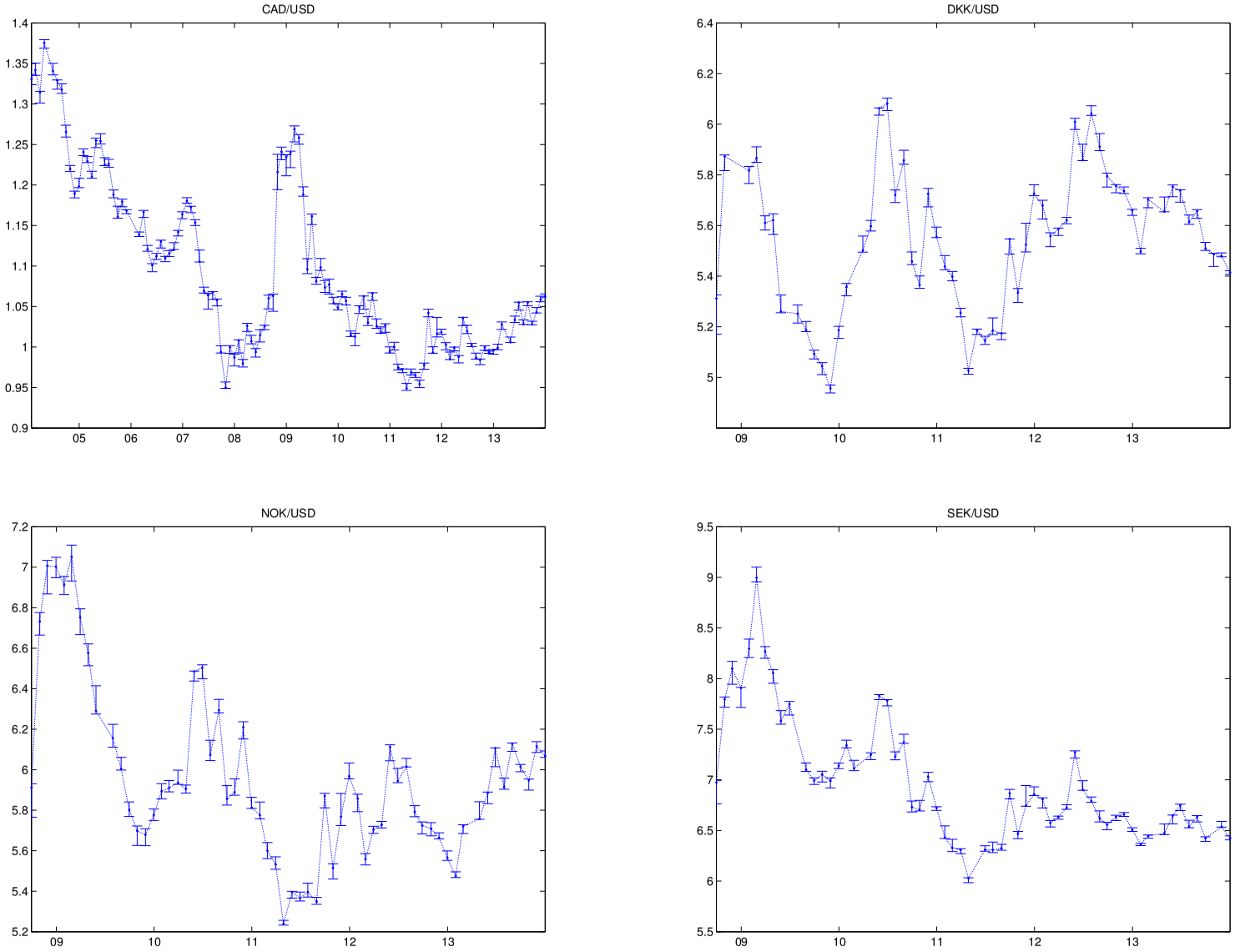
Notes: Time series for the fix at the end of each month with upper and lower limits of daily trading range.

Figure A.3: Fixes with Daily Trading Range



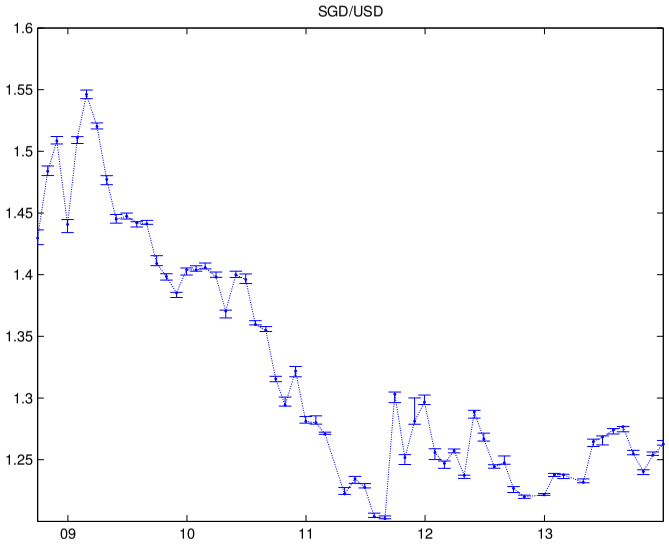
Notes: Time series for the fix at the end of each month with upper and lower limits of daily trading range.

Figure A.4: Fixes with Daily Trading Range



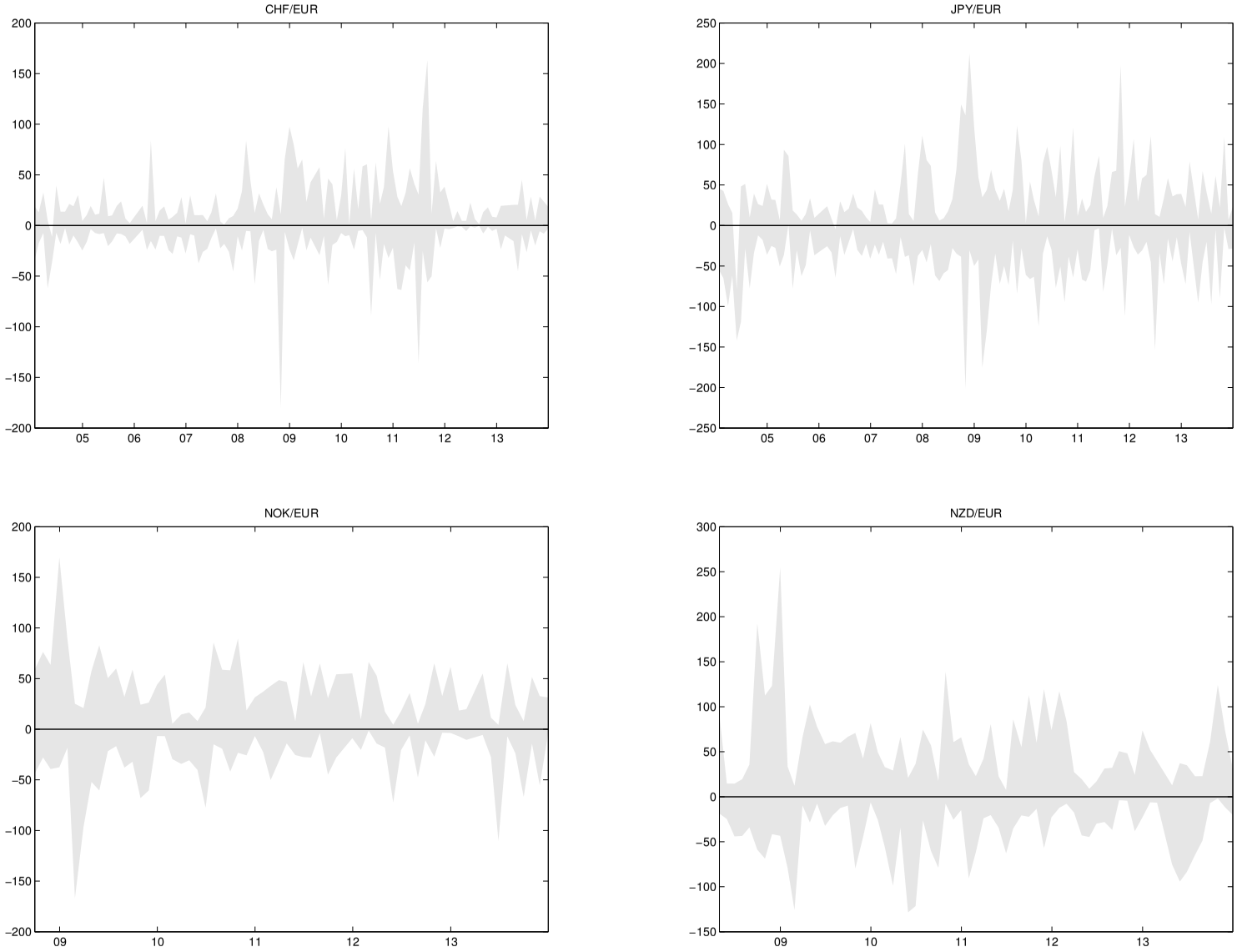
Notes: Time series for the fix at the end of each month with upper and lower limits of daily trading range.

Figure A.5: Fixes with Daily Trading Range



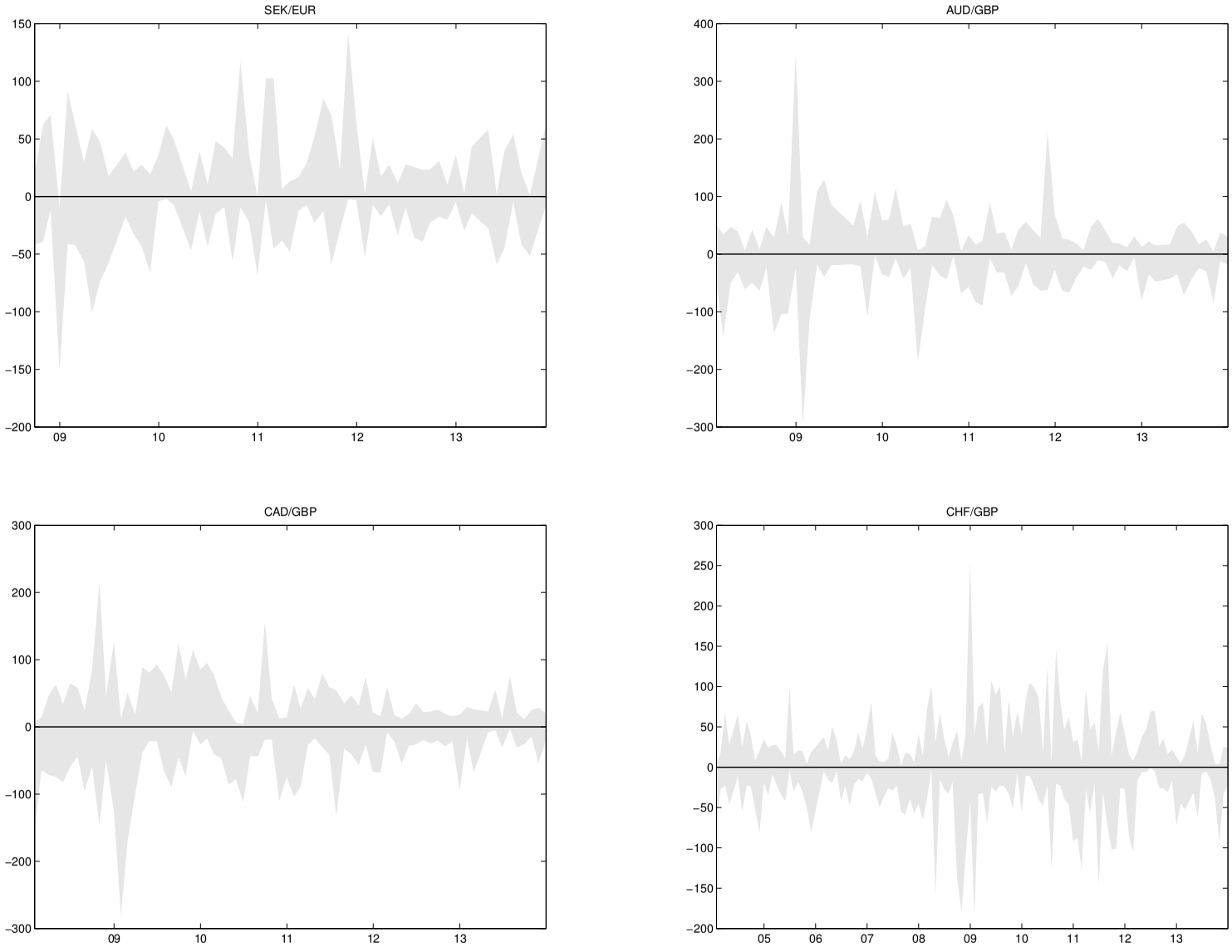
Notes: Time series for the fix at the end of each month with upper and lower limits of daily trading range.

Figure A.6: Daily Trading Range Around Fix



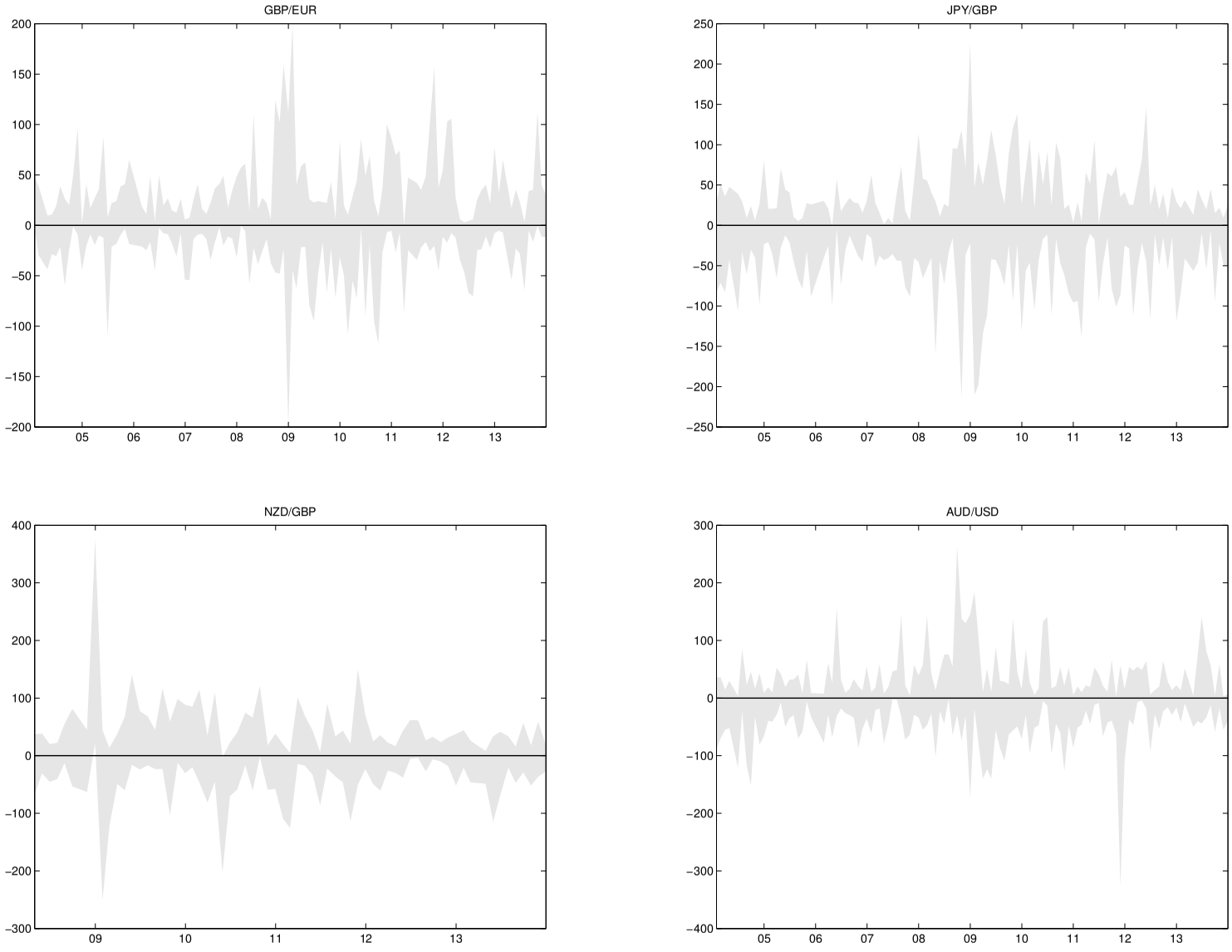
Notes: Time series for the fix at the end of each month with upper and lower limits of daily trading range.

Figure A.7: Daily Trading Range Around Fix



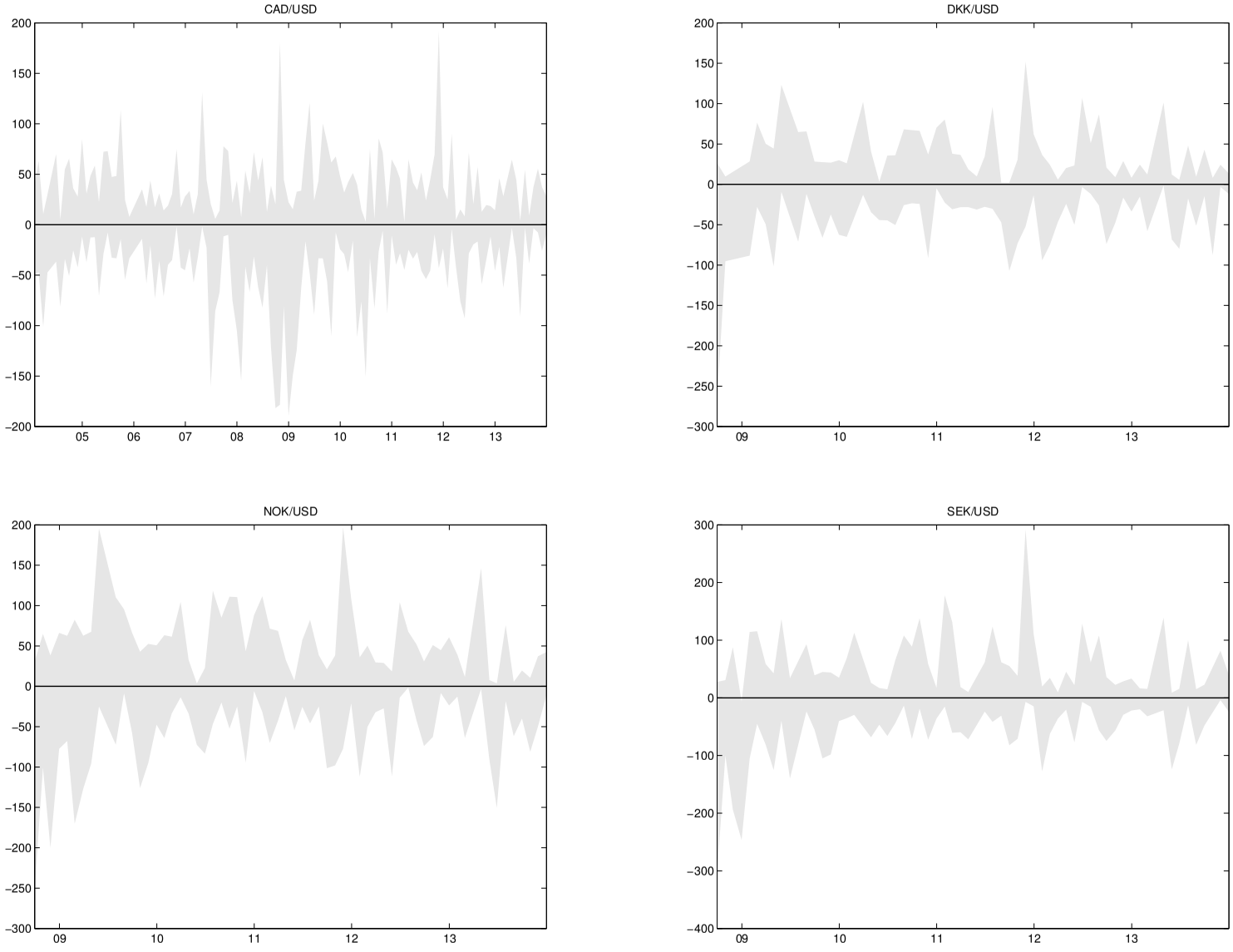
Notes: Time series for the fix at the end of each month with upper and lower limits of daily trading range.

Figure A.8: Daily Trading Range Around Fix



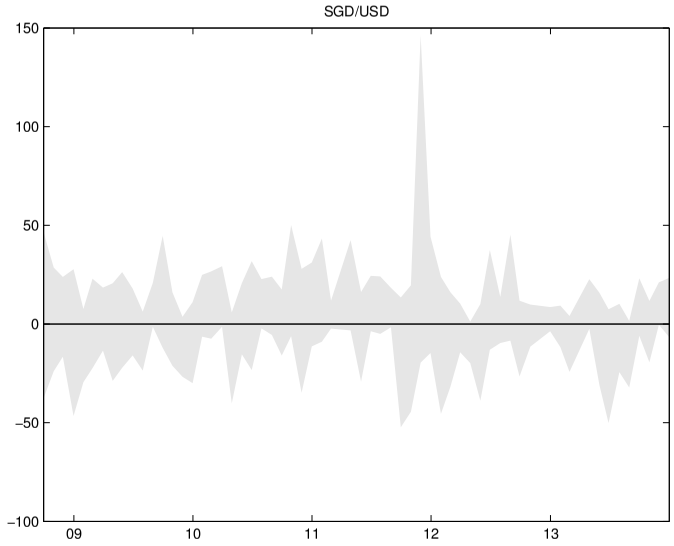
Notes: Time series for the fix at the end of each month with upper and lower limits of daily trading range.

Figure A.9: Daily Trading Range Around Fix



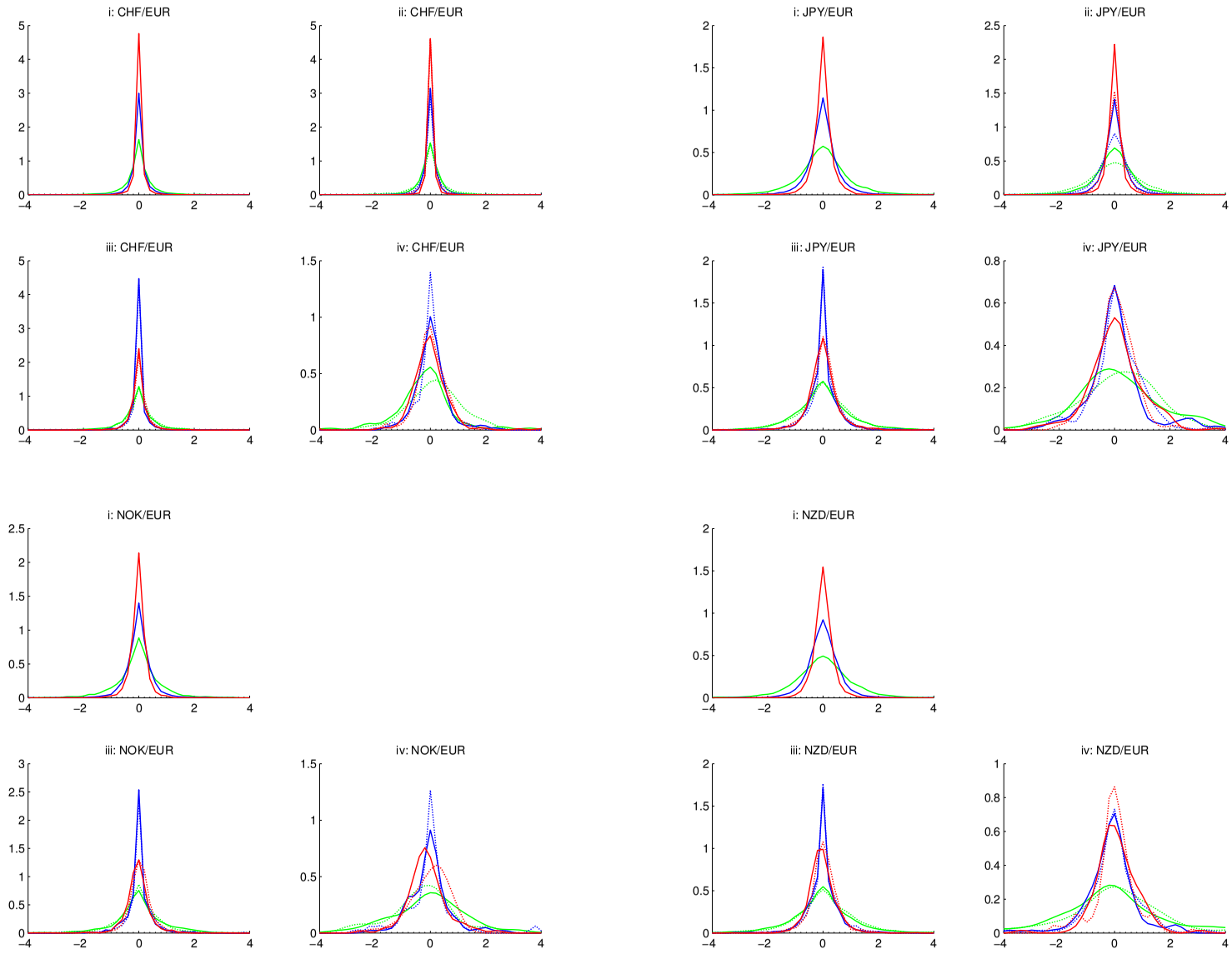
Notes: Time series for the fix at the end of each month with upper and lower limits of daily trading range.

Figure A.10: Daily Trading Range Around Fix



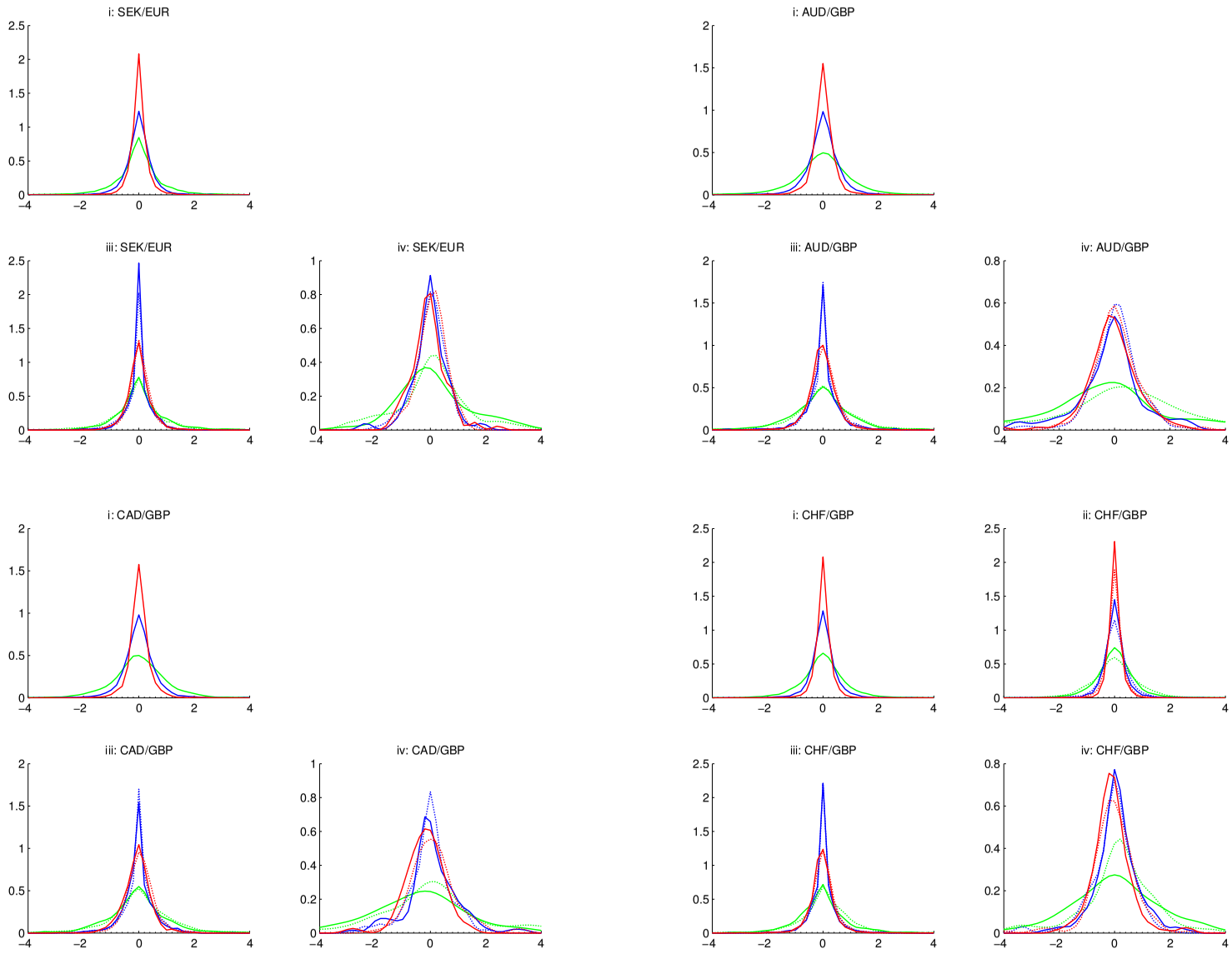
Notes: Time series for the fix at the end of each month with upper and lower limits of daily trading range.

Figure A.11: Rate Change Densities



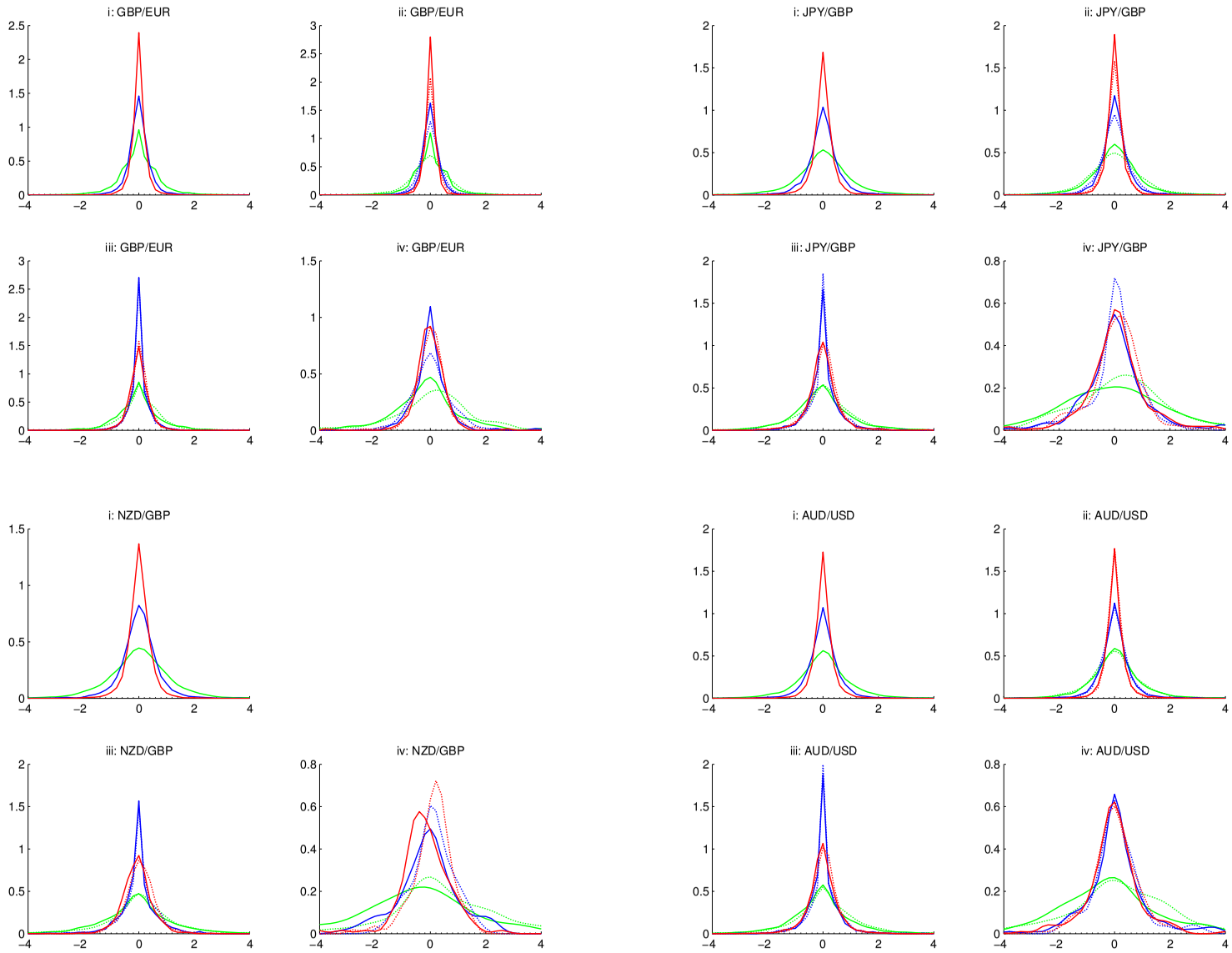
Notes: Panel i plots the density functions for$\Delta^{\ h}s_t$ for $h = \{5, 15, 30\}$ minutes in green, blue, and red, respectively. Panel ii plots the density functions$\Delta^{\ h}s_t$ from pre-2008 and post 2009 data with solid and dotted lines, respectively. Panels iii and iv plod the conditional densities for $f(\Delta^h s_t|\Delta^h s_{t-h} > \kappa^+)$ (solid) and $f(\Delta^h s_t|\Delta^h s_{t-h} < \kappa^-)$ (dotted) for $\{\kappa^+, \kappa^-\}$= {75%, 25%} (panel iii) and {97.5%, 2.5%} (panel iv).

Figure A.12: Rate Change Densities



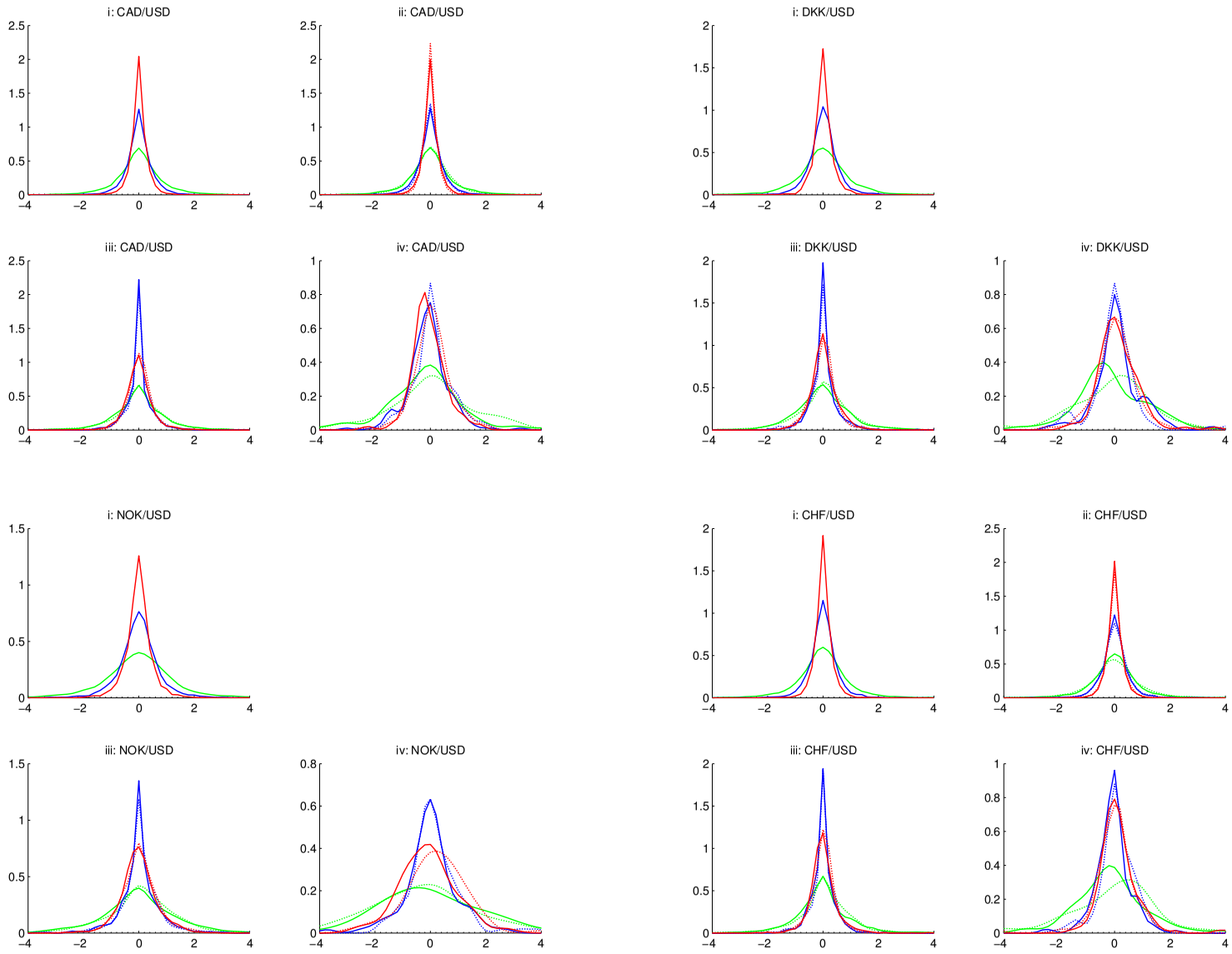
Notes: Panel i plots the density functions for$\Delta^{\ h}s_t$ for $h = \{5, 15, 30\}$ minutes in green, blue, and red, respectively. Panel ii plots the density functions$\Delta^{\ h}s_t$ from pre-2008 and post 2009 data with solid and dotted lines, respectively. Panels iii and iv plod the conditional densities for $f(\Delta^h s_t|\Delta^h s_{t-h} > \kappa^+)$ (solid) and $f(\Delta^h s_t|\Delta^h s_{t-h} < \kappa^-)$ (dotted) for $\{\kappa^+, \kappa^-\}$= {75%, 25%} (panel iii) and {97.5%, 2.5%} (panel iv).

Figure A.13: Rate Change Densities



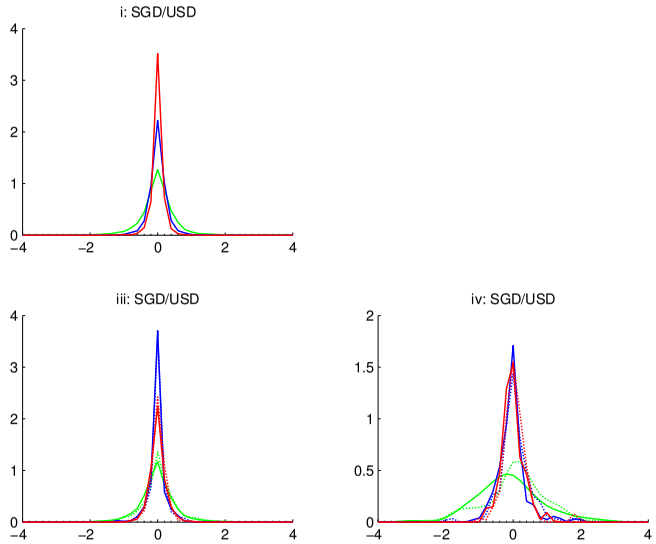
Notes: Panel i plots the density functions for$\Delta^{\ h}s_t$ for $h = \{5, 15, 30\}$ minutes in green, blue, and red, respectively. Panel ii plots the density functions$\Delta^{\ h}s_t$ from pre-2008 and post 2009 data with solid and dotted lines, respectively. Panels iii and iv plod the conditional densities for $f(\Delta^h s_t|\Delta^h s_{t-h} > \kappa^+)$ (solid) and $f(\Delta^h s_t|\Delta^h s_{t-h} < \kappa^-)$ (dotted) for $\{\kappa^+, \kappa^-\}$= {75%, 25%} (panel iii) and {97.5%, 2.5%} (panel iv).

Figure A.14: Rate Change Densities



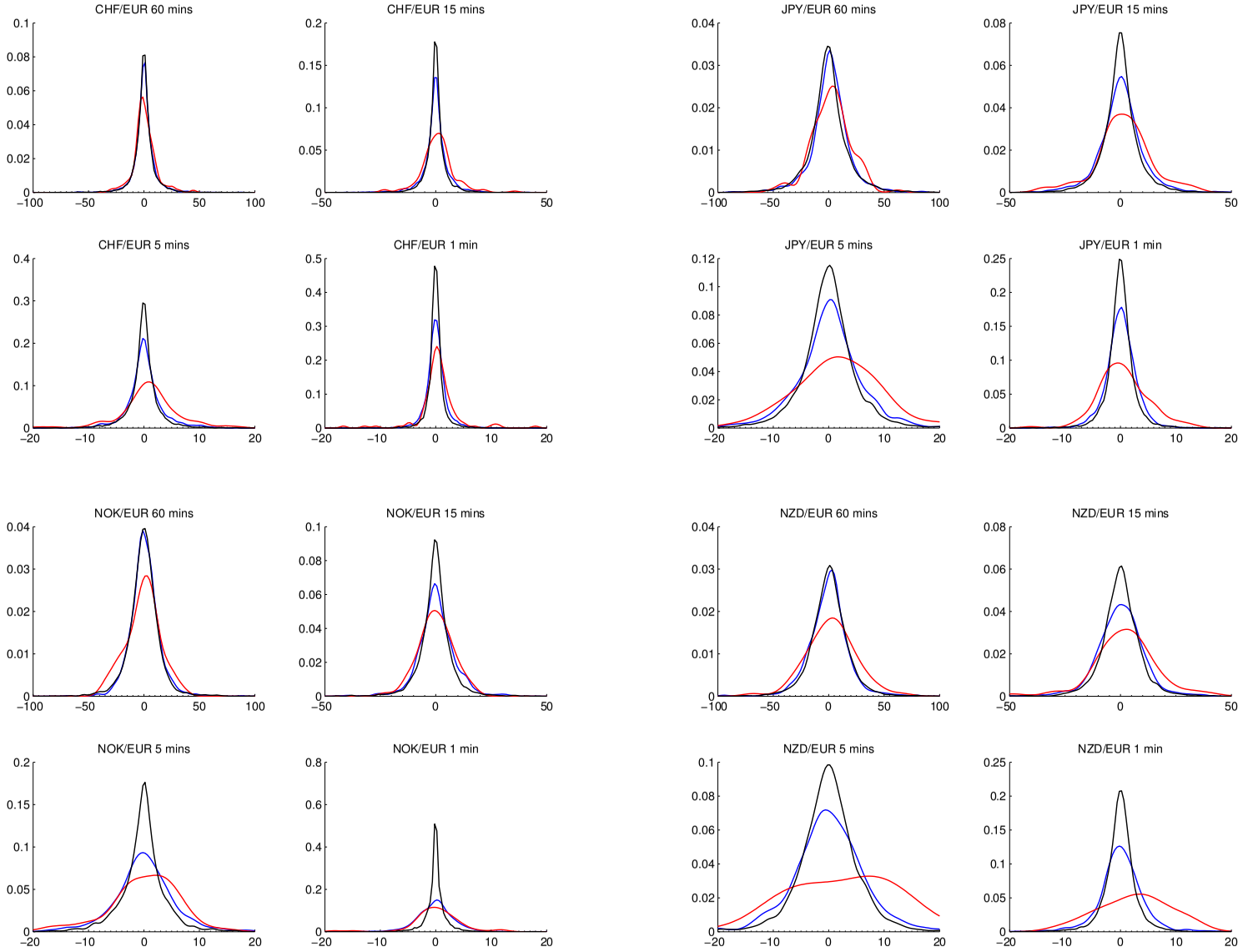
Notes: Panel i plots the density functions for$\Delta^{\ h}s_t$ for $h = \{5, 15, 30\}$ minutes in green, blue, and red, respectively. Panel ii plots the density functions$\Delta^{\ h}s_t$ from pre-2008 and post 2009 data with solid and dotted lines, respectively. Panels iii and iv plod the conditional densities for $f(\Delta^h s_t|\Delta^h s_{t-h} > \kappa^+)$ (solid) and $f(\Delta^h s_t|\Delta^h s_{t-h} < \kappa^-)$ (dotted) for $\{\kappa^+, \kappa^-\}$= {75%, 25%} (panel iii) and {97.5%, 2.5%} (panel iv).

Figure A.15: Rate Change Densities



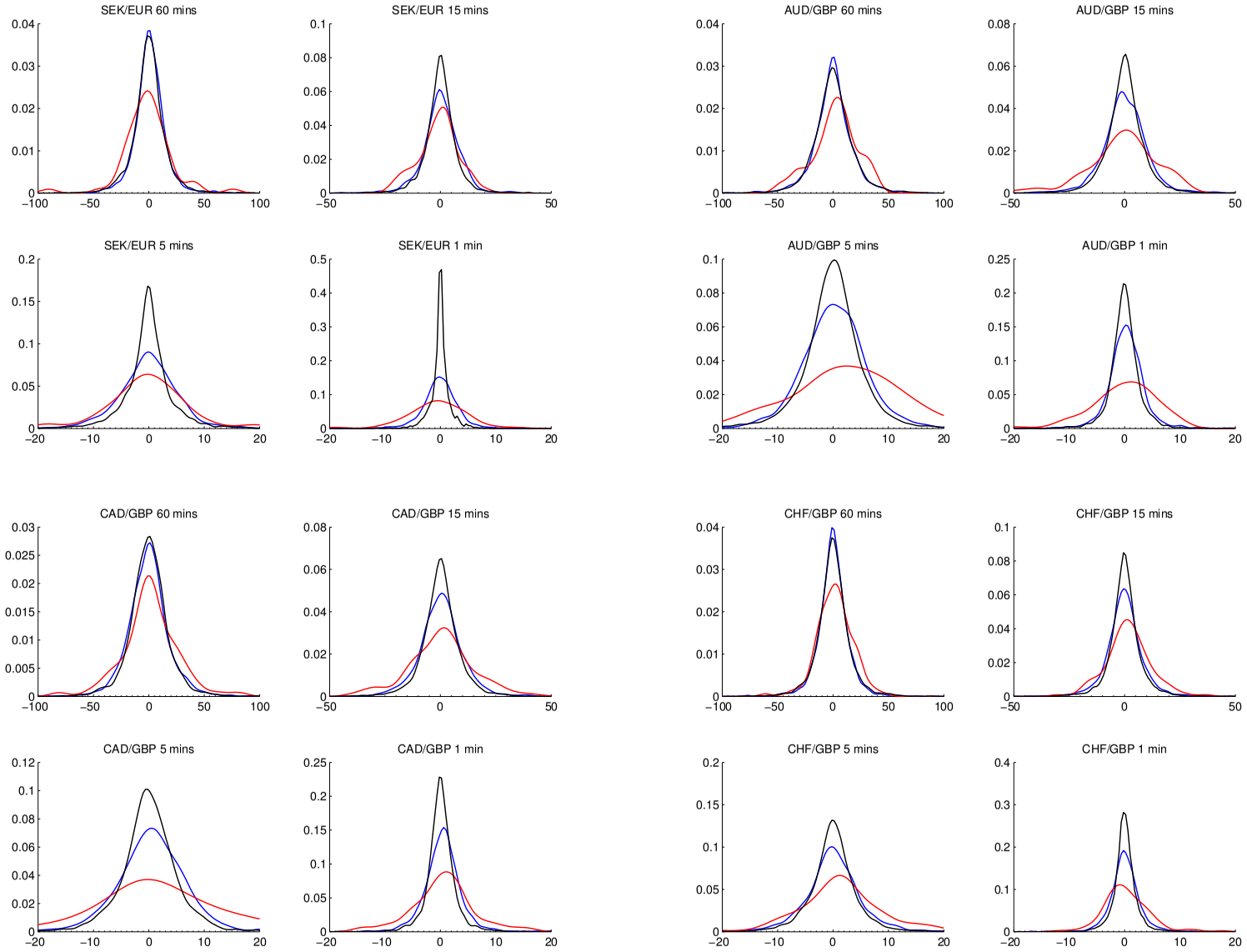
Notes: Panel i plots the density functions for$\Delta\ ^{h}s_t$ for $h = \{5, 15, 30\}$ minutes in green, blue, and red, respectively. Panel ii plots the density functions$\Delta\ ^{h}s_t$ from pre-2008 and post 2009 data with solid and dotted lines, respectively. Panels iii and iv plod the conditional densities for $f(\Delta^h s_t|\Delta^h s_{t-h} > \kappa^+)$ (solid) and $f(\Delta^h s_t|\Delta^h s_{t-h} < \kappa^-)$ (dotted) for $\{\kappa^+, \kappa^-\}$= {75%, 25%} (panel iii) and {97.5%, 2.5%} (panel iv).

Figure A.16: Pre-Fix Rate Change Densities



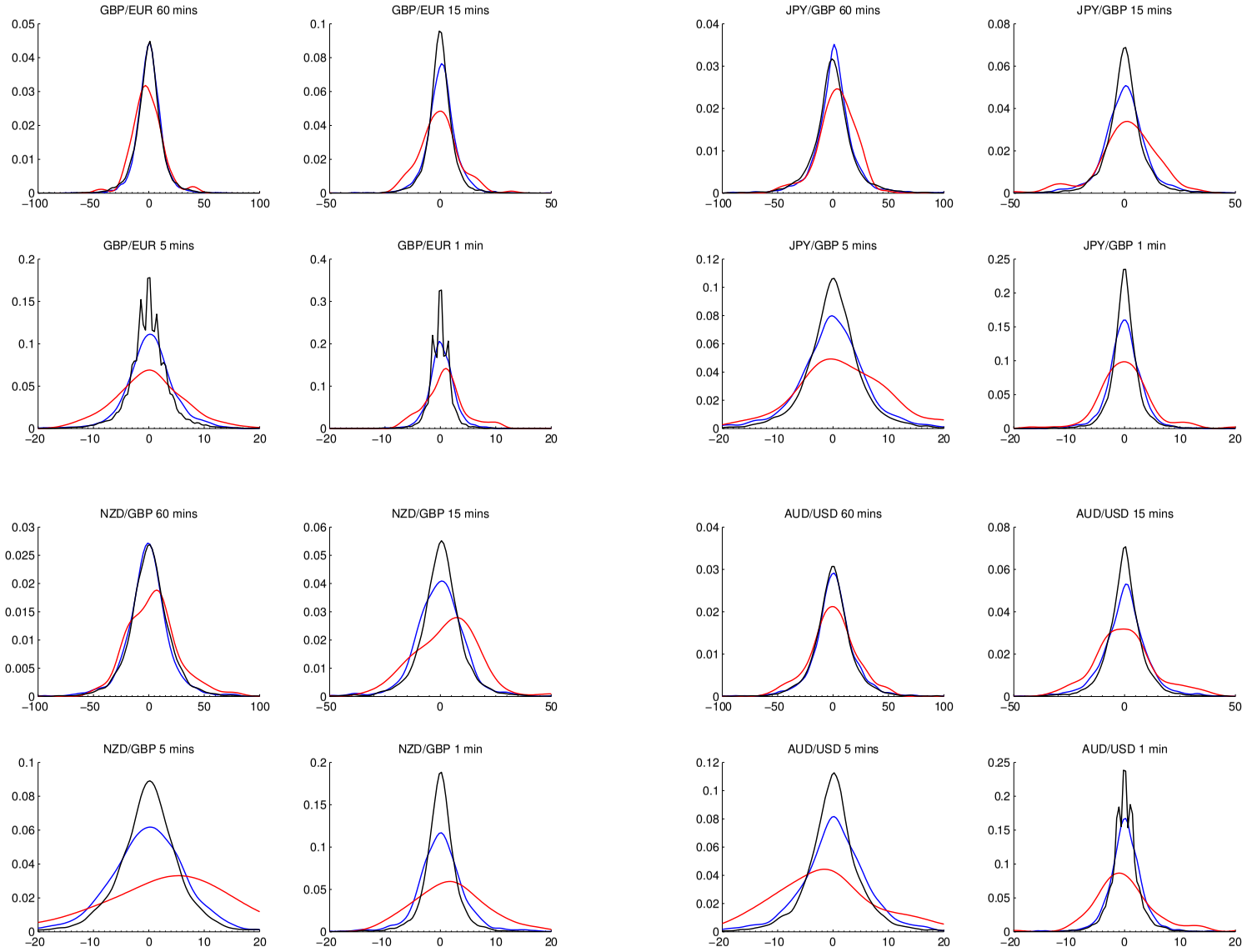
Notes: Densities of price changes (in basis points) away from Fix (black) intra-month pre-Fix (blue) and end-of-month pre-Fix (red).

Figure A.17: Pre-Fix Rate Change Densities



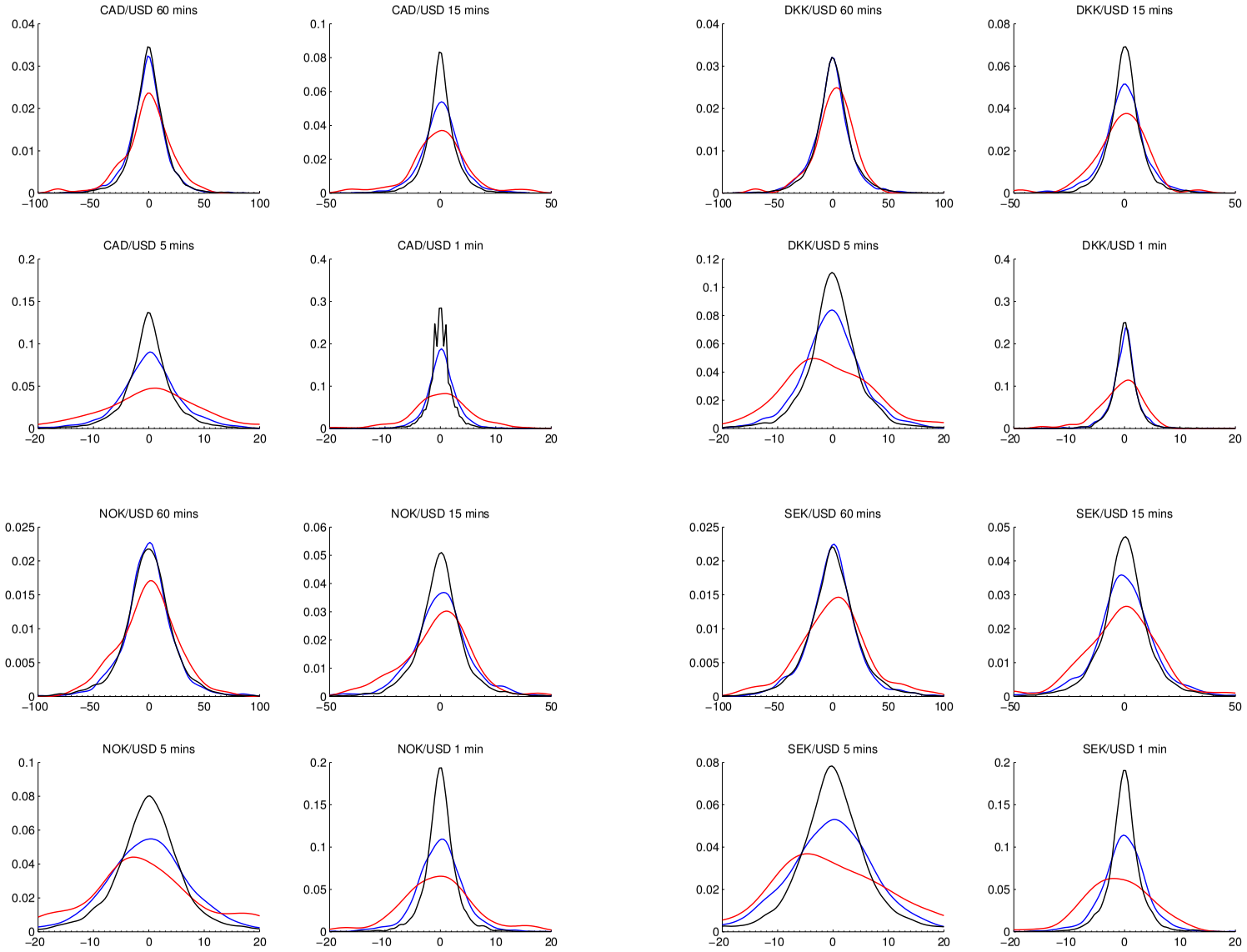
Notes: Densities of price changes (in basis points) away from Fix (black) intra-month pre-Fix (blue) and end-of-month pre-Fix (red).

Figure A.18: Pre-Fix Rate Change Densities



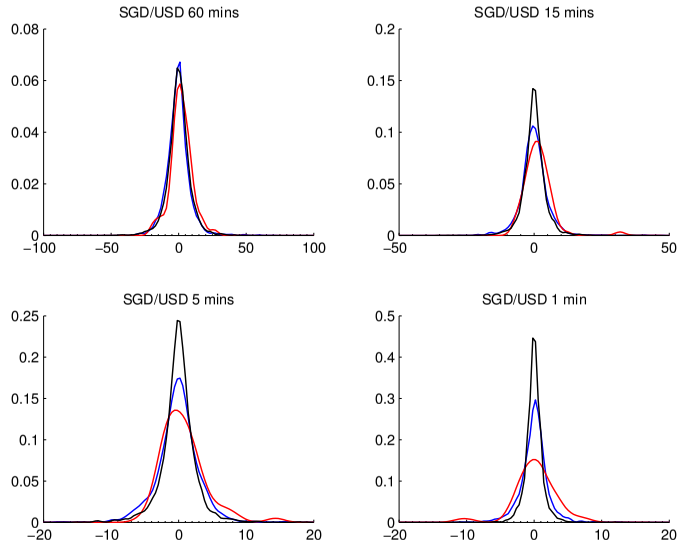
Notes: Densities of price changes (in basis points) away from Fix (black) intra-month pre-Fix (blue) and end-of-month pre-Fix (red).

Figure A.19: Pre-Fix Rate Change Densities



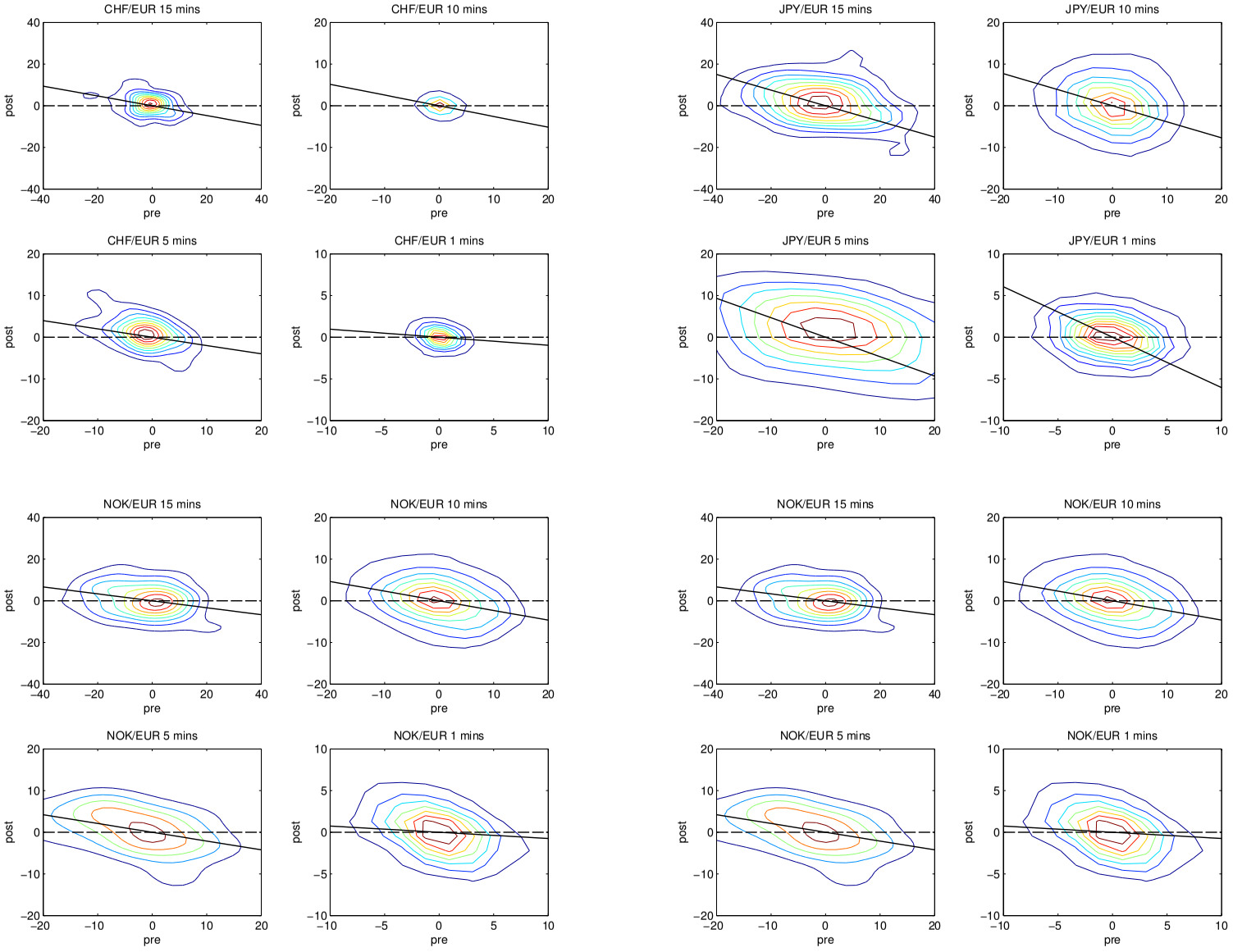
Notes: Densities of price changes (in basis points) away from Fix (black) intra-month pre-Fix (blue) and end-of-month pre-Fix (red).

Figure A.20: Pre-Fix Rate Change Densities



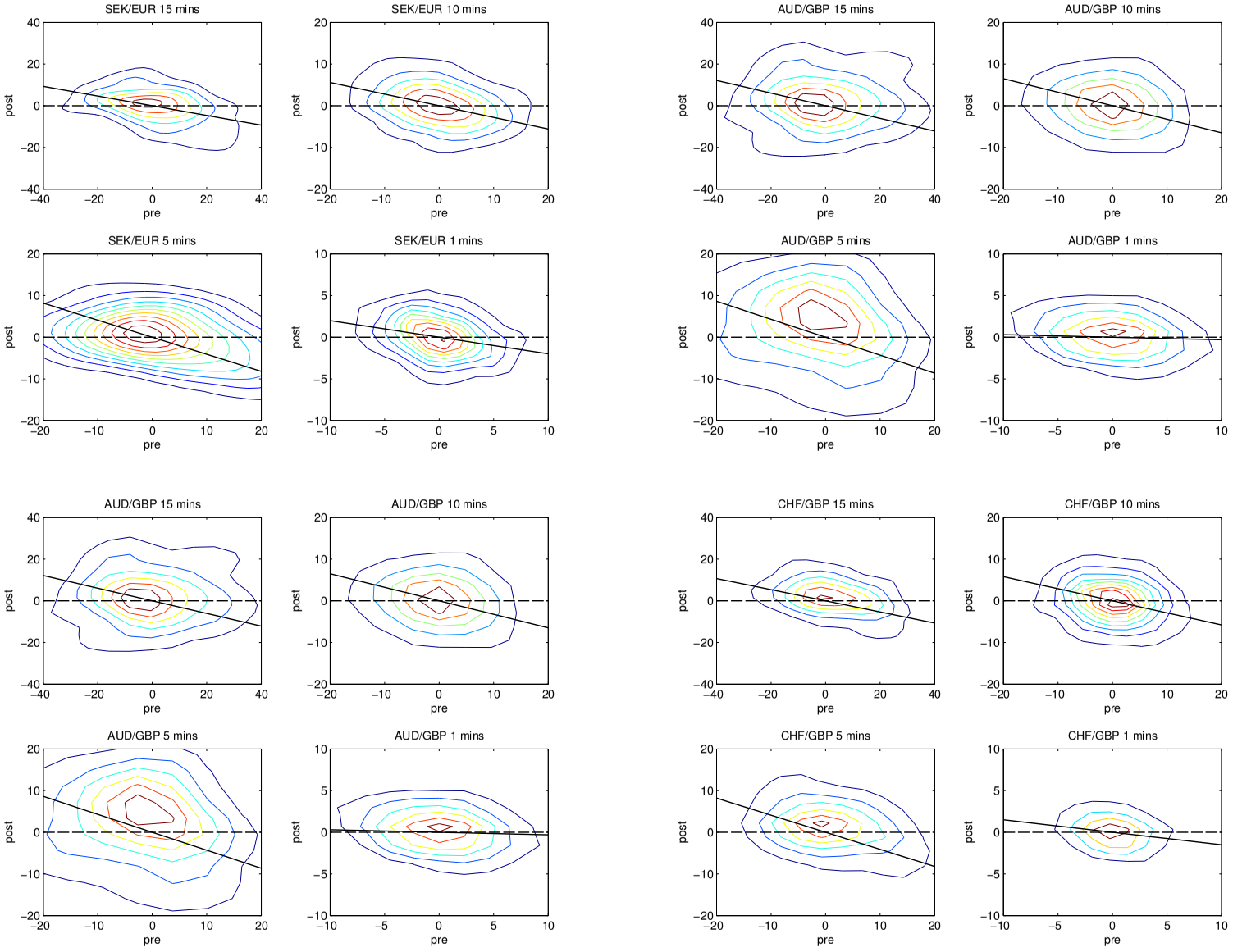
Notes: Densities of price changes (in basis points) away from Fix (black) intra-month pre-Fix (blue) and end-of-month pre-Fix (red).

Figure A.21: Bivariate Pre- and Post- Fix Rate Change Density



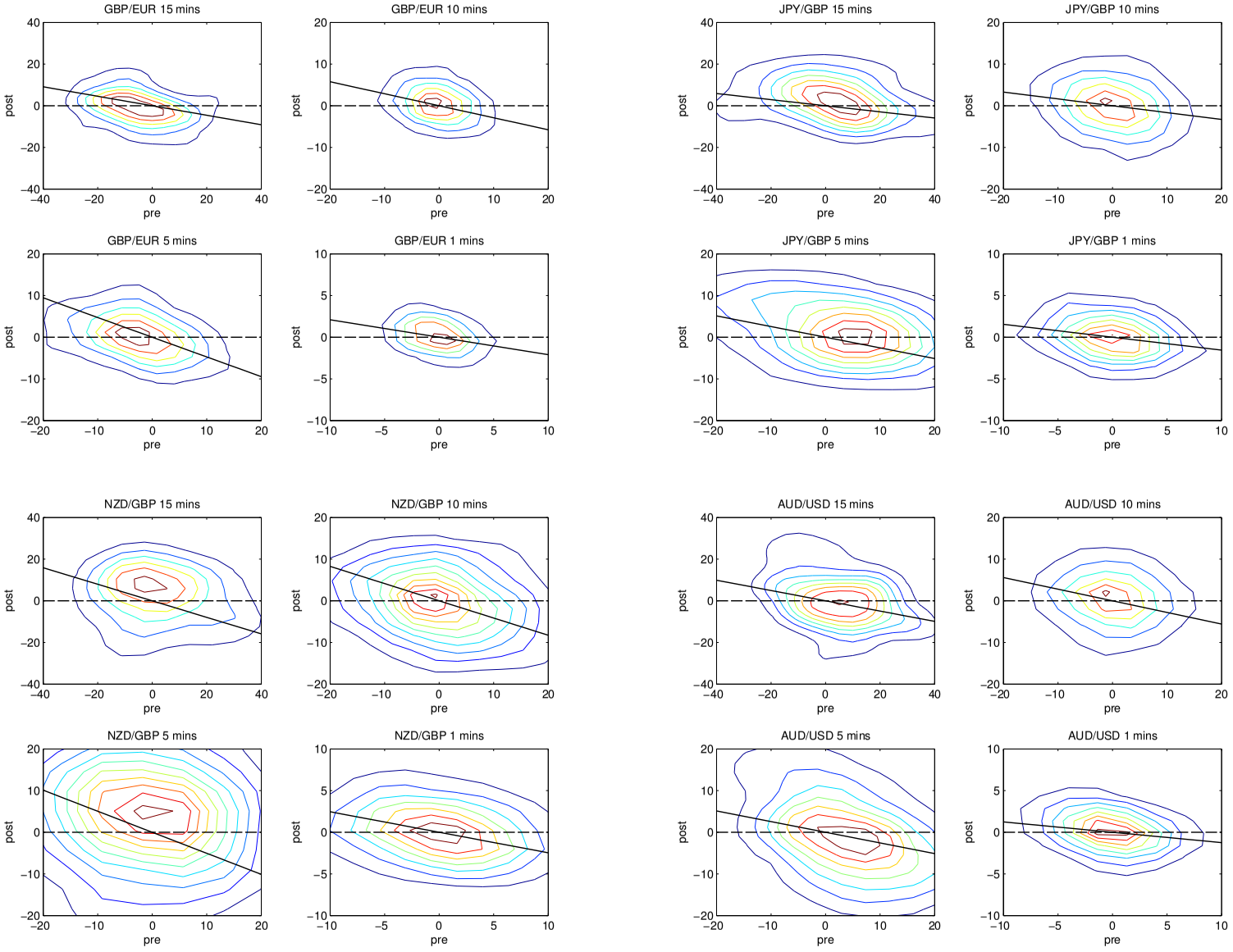
Notes: Each plot shows the contours of the estimated bivariate density for pre- and post-fix price changes (in basis points) over horizons of 1 to 15 minutes. The solid line in each plot is the estimated projection of the post-fix price change in the pre-fix change. All estimates are based on end-of-month data.

Figure A.22: Bivariate Pre- and Post- Fix Rate Change Density



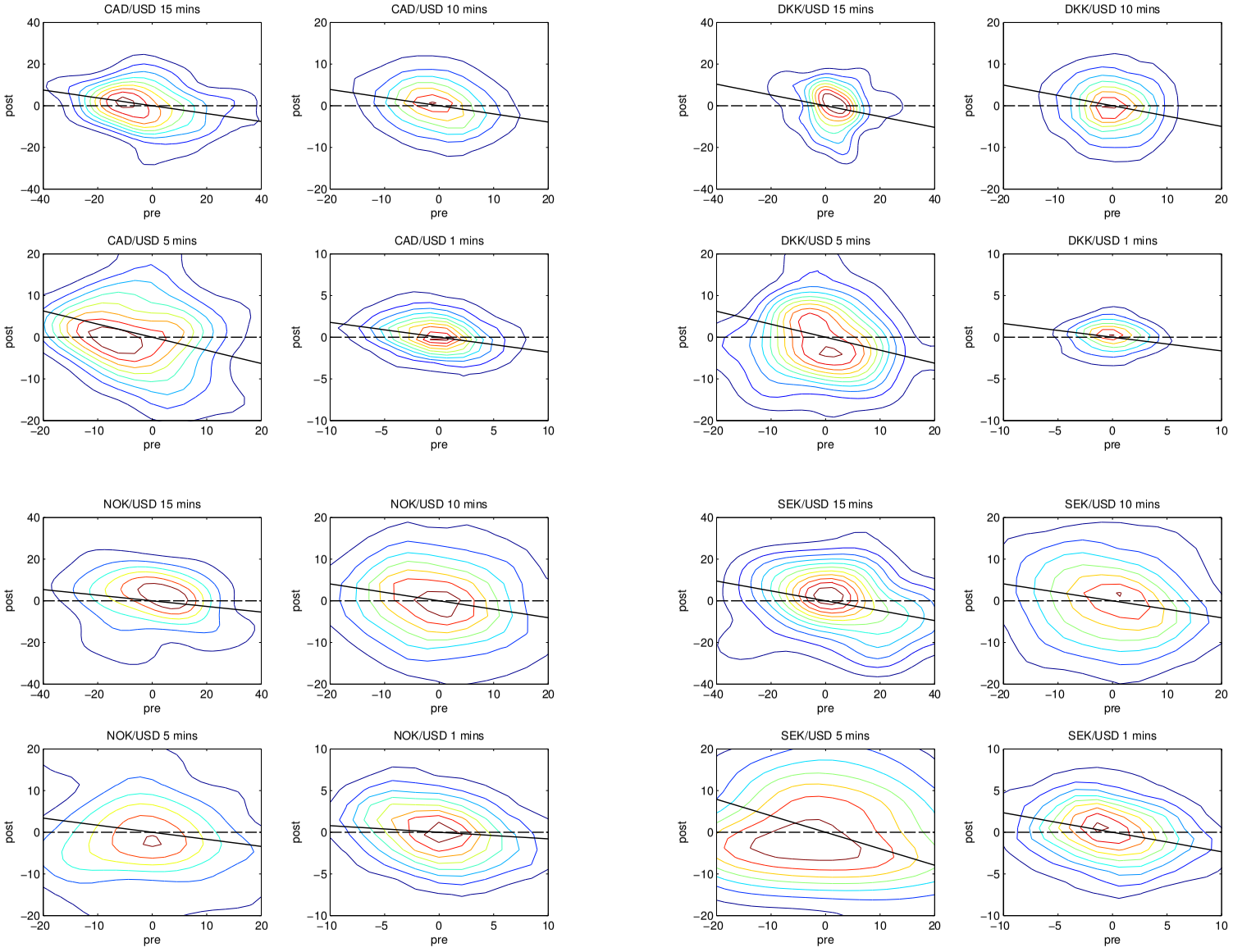
Notes: Each plot shows the contours of the estimated bivariate density for pre- and post-fix rate changes (in basis points) over horizons of 1 to 15 minutes. The solid line in each plot is the estimated projection of the post-fix rate change in the pre-fix change. All estimates are based on end-of-month data.

Figure A.23: Bivariate Pre- and Post- Fix Rate Change Density



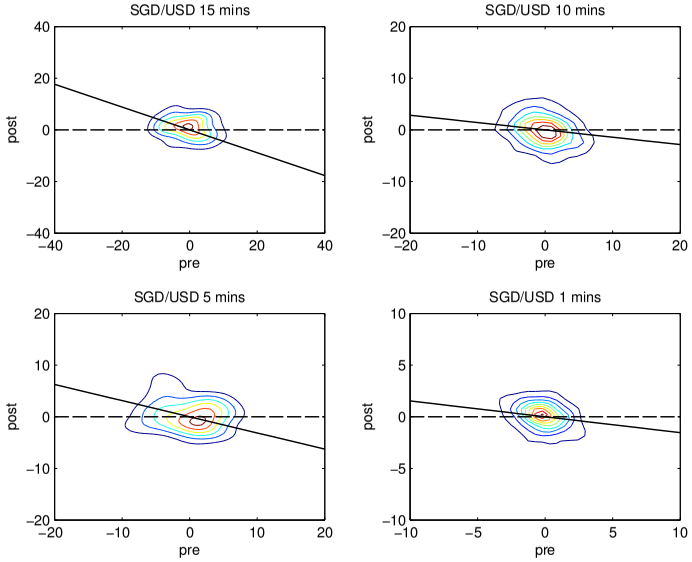
Notes: Each plot shows the contours of the estimated bivariate density for pre- and post-fix rate changes (in basis points) over horizons of 1 to 15 minutes. The solid line in each plot is the estimated projection of the post-fix rate change in the pre-fix change. All estimates are based on end-of-month data.

Figure A.24: Bivariate Pre- and Post- Fix Rate Change Density



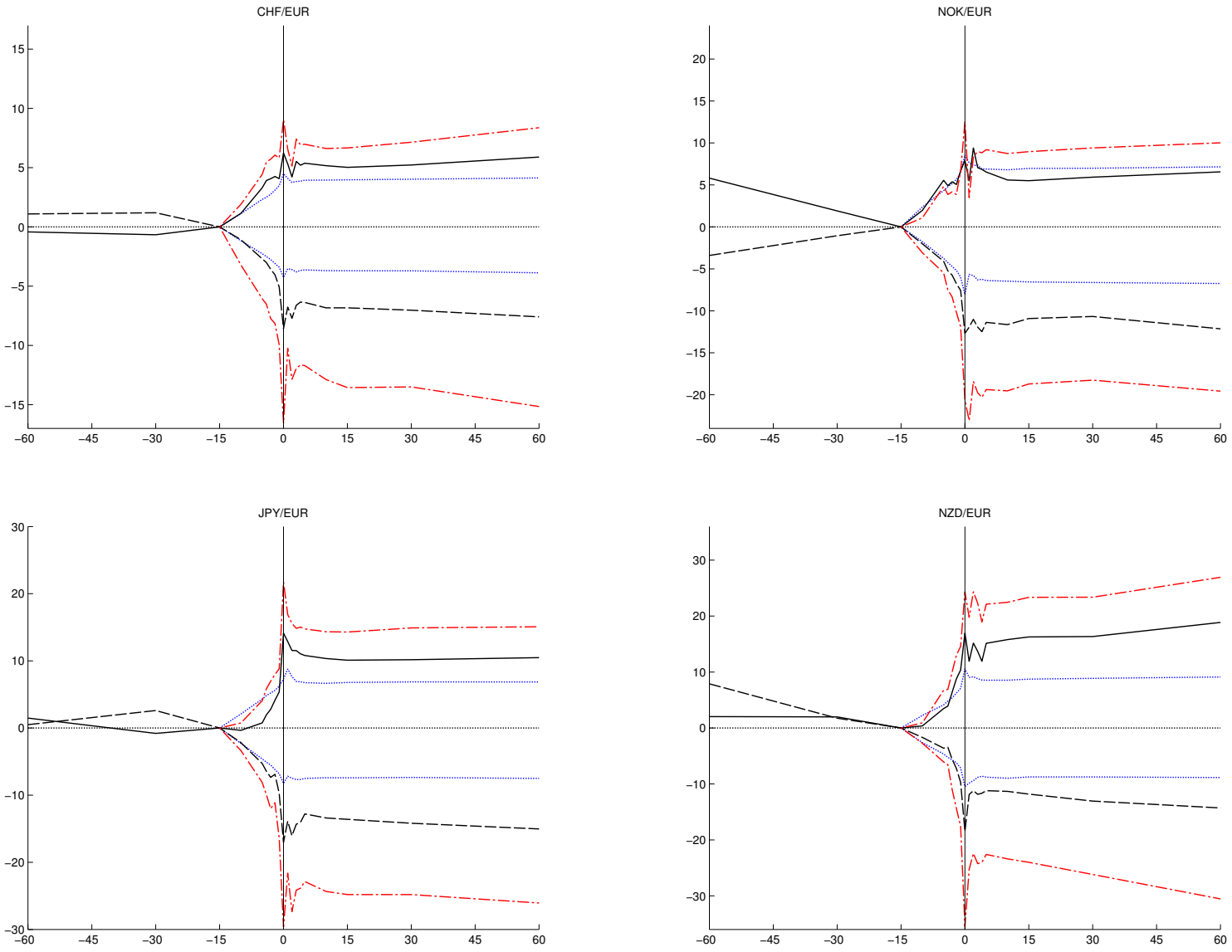
Notes: Each plot shows the contours of the estimated bivariate density for pre- and post-fix rate changes (in basis points) over horizons of 1 to 15 minutes. The solid line in each plot is the estimated projection of the post-fix rate change in the pre-fix change. All estimates are based on end-of-month data.

Figure A.25: Bivariate Pre- and Post- Fix Rate Change Density



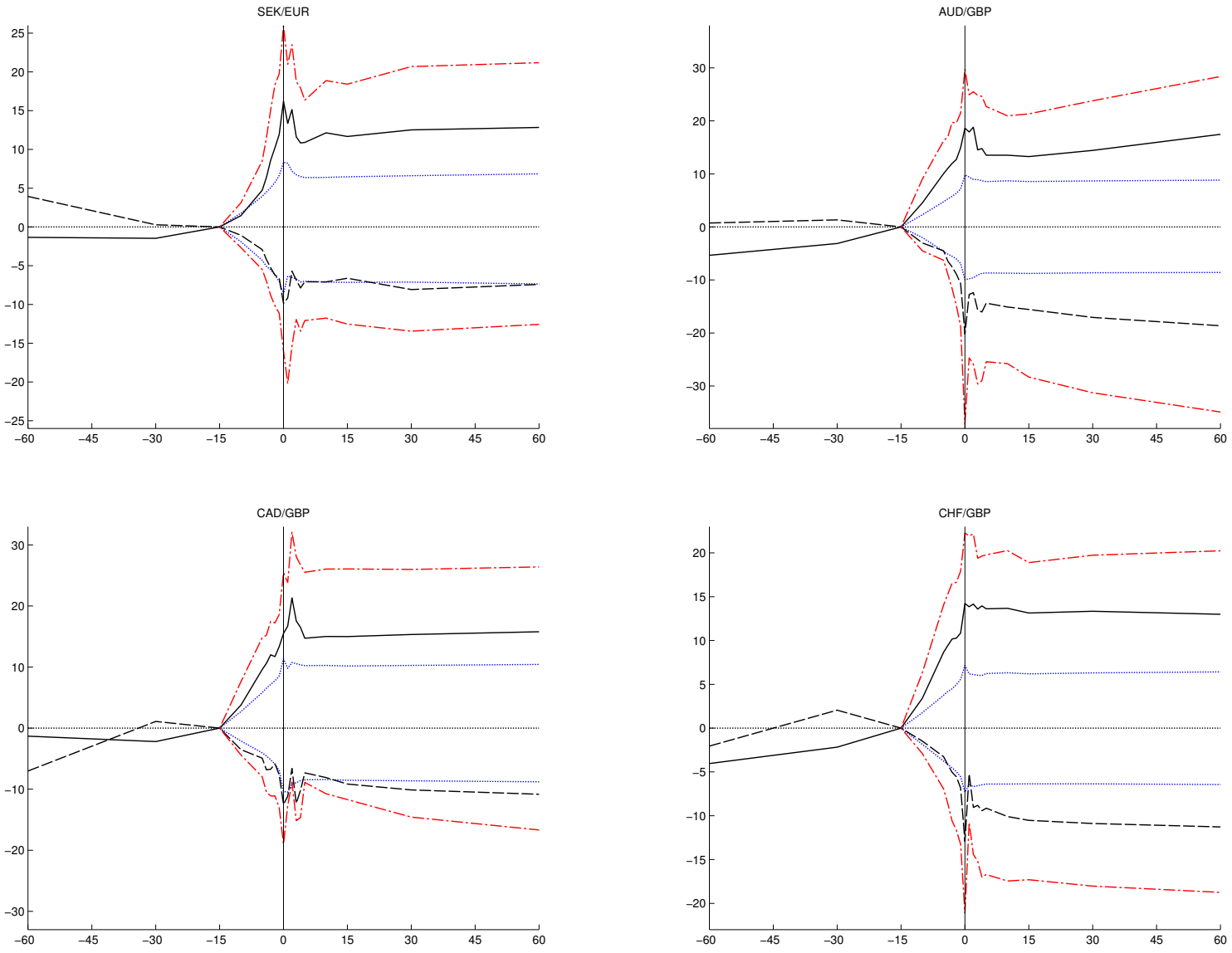
Notes: Each plot shows the contours of the estimated bivariate density for pre- and post-fix rate changes (in basis points) over horizons of 1 to 15 minutes. The solid line in each plot is the estimated projection of the post-fix rate change in the pre-fix change. All estimates are based on end-of-month data.

Figure A.26: Rate Paths Around the Fix



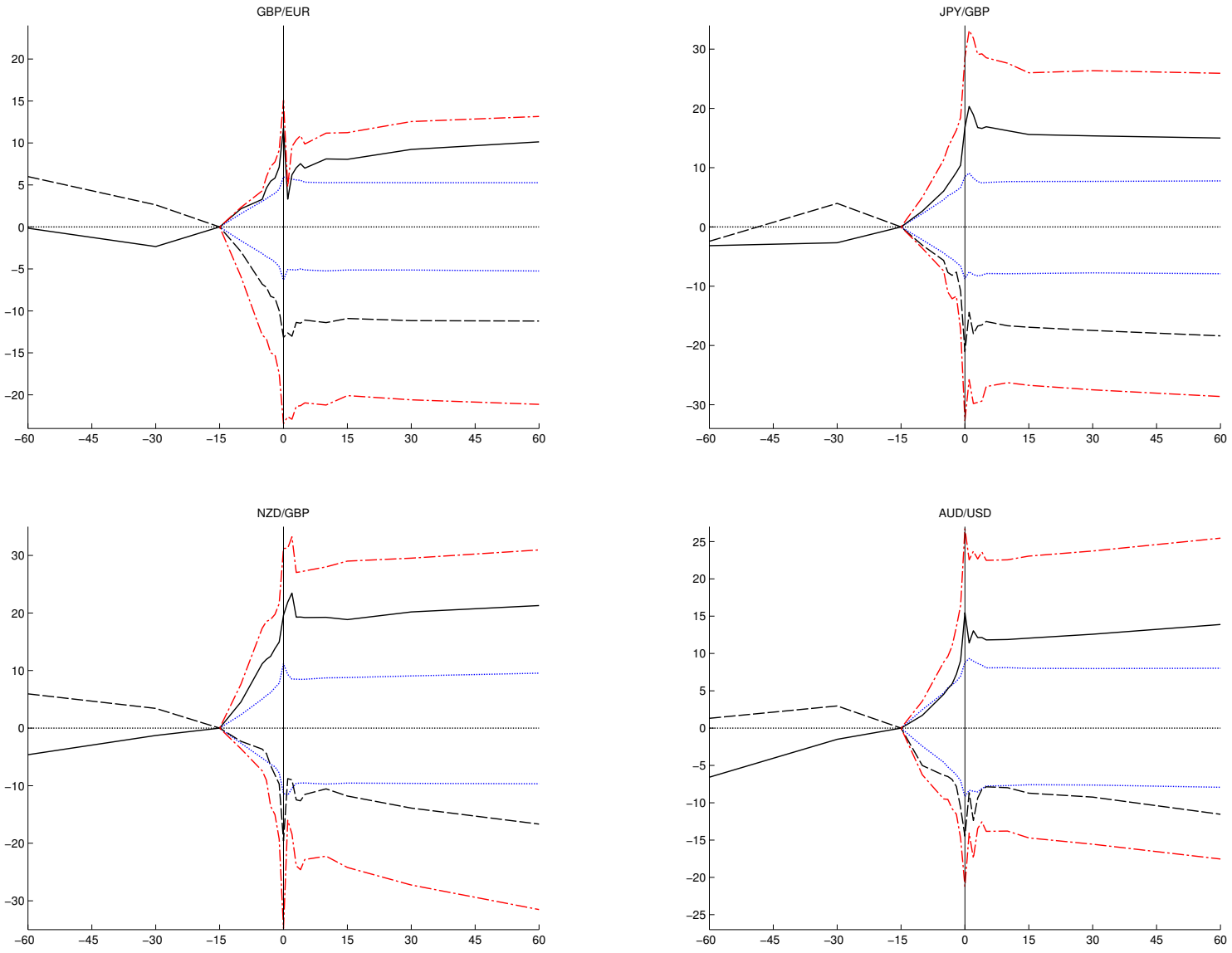
Notes: Average rate path in basis points around 3:45 pm level conditioned on: (i) positive pre-fix changes (over 15 mins) at end of month (solid black); (ii) negative pre-fix changes (over 15 mins) at end of month (dashed black); (iii) pre-fix changes above the 75th. percentile of end-of-month distribution (upper red dashed dot); (iv) pre-fix changes in the 25th. percentile of end-of-month distribution (lower red dashed dot); (v) positive and negative pre-fix changes on intra-month days (upper and lower blue dots).

Figure A.27: Rate Paths Around the Fix



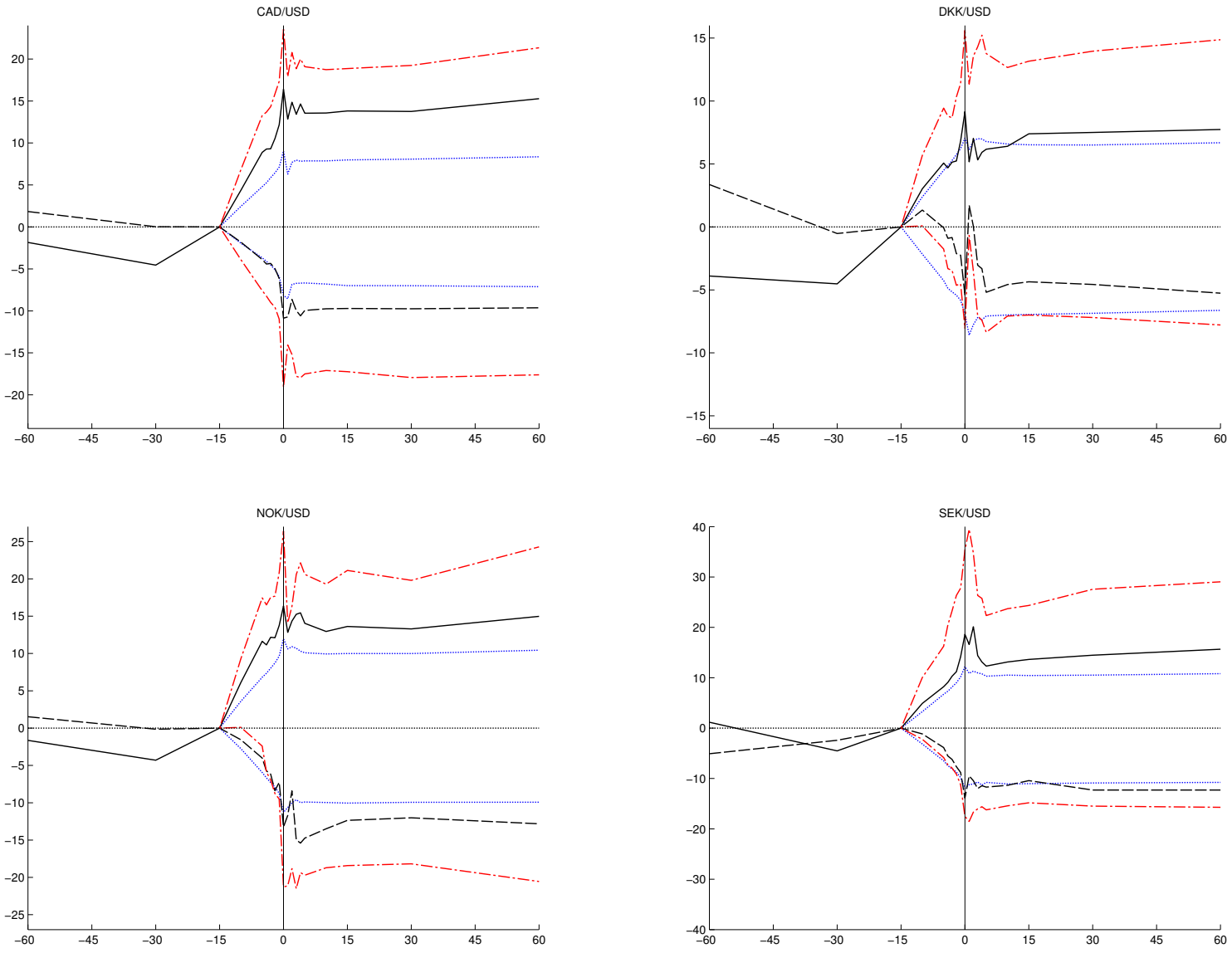
Notes: Average rate path in basis points around 3:45 pm level conditioned on: (i) positive pre-fix changes (over 15 mins) at end of month (solid black); (ii) negative pre-fix changes (over 15 mins) at end of month (dashed black); (iii) pre-fix changes above the 75th. percentile of end-of-month distribution (upper red dashed dot); (iv) pre-fix changes in the 25th. percentile of end-of-month distribution (lower red dashed dot); (v) positive and negative pre-fix changes on intra-month days (upper and lower blue dots).

Figure A.28: Rate Paths Around the Fix



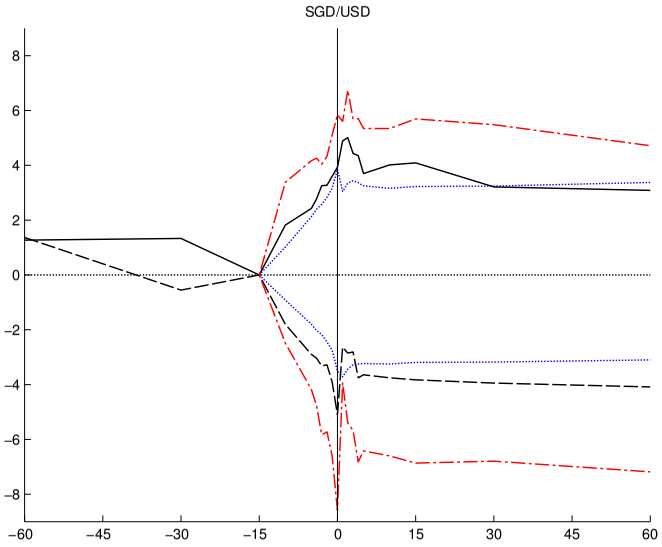
Notes: Average rate path in basis points around 3:45 pm level conditioned on: (i) positive pre-fix changes (over 15 mins) at end of month (solid black); (ii) negative pre-fix changes (over 15 mins) at end of month (dashed black); (iii) pre-fix changes above the 75th. percentile of end-of-month distribution (upper red dashed dot); (iv) pre-fix changes in the 25th. percentile of end-of-month distribution (lower red dashed dot); (v) positive and negative pre-fix changes on intra-month days (upper and lower blue dots).

Figure A.29: Rate Paths Around the Fix



Notes: Average rate path in basis points around 3:45 pm level conditioned on: (i) positive pre-fix changes (over 15 mins) at end of month (solid black); (ii) negative pre-fix changes (over 15 mins) at end of month (dashed black); (iii) pre-fix changes above the 75th. percentile of end-of-month distribution (upper red dashed dot); (iv) pre-fix changes in the 25th. percentile of end-of-month distribution (lower red dashed dot); (v) positive and negative pre-fix changes on intra-month days (upper and lower blue dots).

Figure A.30: Rate Paths Around the Fix



Notes: Average rate path in basis points around 3:45 pm level conditioned on: (i) positive pre-fix changes (over 15 mins) at end of month (solid black); (ii) negative pre-fix changes (over 15 mins) at end of month (dashed black); (iii) pre-fix changes above the 75th. percentile of end-of-month distribution (upper red dashed dot); (iv) pre-fix changes in the 25th. percentile of end-of-month distribution (lower red dashed dot); (v) positive and negative pre-fix changes on intra-month days (upper and lower blue dots).