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Effective Sterilized Foreign Exchange Intervention? Evidence from a Rule-Based Policy*

Guido M. Kuersteiner† David C. Phillips‡ Mauricio Villamizar-Villegas§

Abstract

We investigate the effectiveness of sterilized foreign exchange interventions by exploiting a discontinuous policy rule used by the Central Bank of Colombia (CBoC). We use a unique data set from CBoC comprised of tick by tick intervention and order book data, daily capital in- and outflow data, and balance sheet information of financial institutions. We apply regression discontinuity methods to identify the surprise component of rule based exchange rate interventions of the CBoC and use this variation to measure how interventions affect exchange rates and capital flows. At horizons of a few days, our empirical findings support sterilized exchange rate intervention effectiveness via a portfolio channel. The exchange rate effects we see are short-lived. At horizons of a month or longer, capital flows originating from foreign investors restore the exchange rate back to its original level. Our findings also show that the effects of sterilized interventions are amplified by capital controls. A methodological contribution of the paper is to extend regression discontinuity designs to a time series environment and to show how these techniques can be used to identify and estimate non-linear impulse response functions.

Key Words: Rule-Based Foreign Exchange Interventions, Portfolio Balance, Central Bank Policy, Regression Discontinuity, Non-linear Impulse Response.

JEL Codes: E58, F31, C22

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1 Introduction

Many countries, particularly in the developing world, aim for exchange rate stability as a macroeconomic goal. While most have adopted fixed exchange rate regimes, others have tried to limit short run fluctuations and smooth excessive trends in order to attract investment opportunities and avoid currency crises. Central banks in these countries often directly intervene in the foreign exchange market by purchasing or selling foreign currency. Calvo and Reinhart (2002) coined the term 'fear of floating' for such policies.

However, the monetary trilemma going back to Mundell (1963) and Fleming (1962), given a general equilibrium foundation in an influential paper by Backus and Kehoe (1989), indicates that arbitrage by international investors generally rules out adopting a managed exchange rate while having autonomous monetary policy and allowing for free capital flows. Policymakers can only regain control of the exchange rate if they abandon monetary policy or enact capital controls. Rey (2013) even argued in favor of a dilemma rather than a trilemma due to the presence of strong international factors driving asset prices for countries with floating currencies. On the other hand, alternative theories suggest that exchange rate management may be effective in the presence of free capital flows and independent monetary policy. The portfolio balance channel proposed by Henderson and Rogoff (1981), Kouri (1981), Branson and Henderson (1985)and more recently by Magud, Reinhart and Rogoff (2011), Blanchard, Adler and Carvalho Filho (2015), and Gabaix and Maggiori (2015) emphasizes investor preference about the mix of foreign and domestic assets in their portfolio. Likewise, Hassan, Mertens, and Zhang (2015) argue that central bank strategies, which reduce foreign exchange volatility, can affect the real economy through international portfolio decisions. Alternatively, non-equilibrium effects such as "order flow" were considered by Evans and Lyons (2002a) as determinants of exchange rates in the short run.

Establishing whether peripheral countries face a policy dilemma, trilemma or if in fact portfolio balance aspects provide enough of a wedge to afford sufficient degrees of freedom for monetary policies is an important empirical question that determines the best policy response to domestic and foreign shocks. A recent empirical literature considers the effectiveness of monetary policy under various exchange rate regimes. Frankel, Schmukler and Serven (2004) and Shambaugh (2004) focus on the sensitivity of domestic interest rates to foreign interest rate shocks. Shambaugh (2004) finds a significant difference in how economies with pegged versus floating exchange rates the respond to changes in the interest rates of the base country. Hausmann, Panizza and Stein (2001) document departures from flexible exchange rates even for countries that are officially letting their currencies float. Blanchard, Adler and Carvalho Filho (2015) directly investigate the effectiveness of foreign exchange interventions to fight currency appreciation in the face of capital inflows.

This paper takes a fresh look at two fundamental questions, namely the lack of central bank independence under free capital flows with floating exchange rates and the question of the effectiveness of capital controls. The challenge for empirical evidence on the effects of macroeconomic policies is to find credible exogenous variation in these policies. In this paper, we use specific details of the way foreign exchange interventions were implemented by the Central Bank of Colombia (CBoC henceforth). In 2002 the CBoC started a policy of sterilized exchange rate interventions aimed at stemming exchange rate volatility without pursuing a particular target for the level of the exchange rate.[1] The policy regime of a country with a generally floating currency and rule-based sporadic FX interventions is ideally suited to investigate the empirical questions at hand. In addition, we have access to a detailed dataset that offers a unique view into the inner workings of Colombian financial markets. We rely on daily administrative, as well as tick-by-tick order book data detailing rule-based foreign exchange interventions. Rule based interventions provide a sharp trigger at which certain interventions are carried out by the central bank. Uncertainty amongst market participants the day before trading opens about whether the trigger is met or just missed leads to random deviations of central bank actions from market expectations. We exploit this variation to identify the effects of foreign exchange interventions on macroeconomic aggregates. Rule based interventions have the additional advantage that the rule by which interventions are triggered is known to the public. Thus, the specification issues that arise in model based approaches to identification, where explicit or implicit policy rules need to be empirically estimated, do not arise in our approach. Uncertainty in the market thus only relates to the question of whether the rule was triggered, not what the rule is.

High frequency data was used to study the effectiveness of FXI by Dominguez (2003) who uses tick by tick DEM-USD quotes and Reuters information on Fed interventions in a simple regression design relating FX returns to intervention dummies. Fatum and Hutchinson (2003) is another example of an event study paper focusing on the DEM-USD market and interventions by the Fed and the Bundesbank. The authors note that event studies on the one hand exploit "sporadic and intense periods of official interventions" while also noting inherent endogeneity problems of their methodology. The regression discontinuity approach pursued in this paper shares with event studies the fact that variation from discontinuously triggered action by the central bank is exploited. What distinguishes it from event studies is that a localized analysis, to be made precise below, separates this variation from other continuously varying influences affecting exchange rates.

During our sample period from 2002 to 2012 Colombia went through two episodes of capital controls (see Magud et.al. 2011). Most of the empirical literature on capital controls employs some form of regression approach to identify the effects of controls on macroeconomic outcomes. Kaplan and Rodrik (2002), who base their inference on a difference in difference strategy that is valid under somewhat weaker conditions, are one notable exception. The approach we pursue in this paper differs in that we

[1] The fact that the CBoC did not defend a particular target zone is important to rule out exchange rate behavior such as in Krugman (1991).

estimate causal effects of sterilized interventions during episodes when capital control were in effect and when they were not. The comparison of the effects under both regimes then allows us to assess their effectiveness. The latter is similar to a difference in difference method. However, causal effects of exchange rate interventions are identified in both regimes, something that would not be possible in a conventional panel setting without the typical regression control assumptions.

We find that foreign exchange market interventions by the CBoC had asymmetric effects on the spot exchange rate. Central bank purchases of dollars via the issuance of put options leads to an approximately 0.8 percent depreciation of the peso on the day the options are issued, and this effect persists for 2-3 weeks.[2] The interventions we observe are equal to about 0.5 percent of the volume of monthly foreign exchange trades in Colombia. We thus interpret the effects we observe as large relative to the size of the intervention. On the other hand, dollar sales via call options show a less consistent effect on the spot exchange rate. The short run response to dollar sales is a 0.3 percent depreciation of the peso which is of opposite sign than what is expected. After about 5 days the response to call issuance is an appreciation of the peso, as expected, but is somewhat less significant than what we observe for puts.

We then investigate the channels through which foreign exchange interventions affect the exchange rate. To avoid problems with small samples and to more generally capture episodes when arbitrage was hindered either by capital control measures or thin forward markets, we proxy capital control episodes by periods when covered interest parity conditions were violated. We find exchange rate effects both when arbitrage conditions were met and when they did not hold. This rules out explanations of FXI effects that are solely based on restrictions on capital flows. Similarly, we rule out microstructure effects by analyzing order flow data. Our analysis of daily balance sheet data of Colombian financial institutions shows that relative holdings of foreign assets fall in response to a dollar purchase by the CBoC. However, these portfolio shifts are hedged with forward contracts in line with the short term effects of interventions. A decomposition of capital flows into domestic and foreign investors shows that capital flows respond significantly but only after a delay, are mostly attributed to foreign investors, and are consistent with current account dynamics bringing the exchange rate back to its pre-intervention level. Our findings are broadly consistent with the Gamma model of Gabaix and Maggiori (2015) which emphasizes exchange rate responses as a result of risk aversion by financial intermediaries and capital flows working to restore exchange rates back to equilibrium levels.

A literature on rule-based foreign exchange market intervention does exist, but generally focuses on straightforward descriptive results or event studies. To our knowledge, Guatemala, from 2005 to 2010, is the only other country to have systematically used rule-based issuance of exchange rate options

[2] Throughout the document we refer to an appreciating (depreciating) exchange rate whenever the dollar (peso) gains value. Alternatively, an appreciating (depreciating) currency means that the currency is gaining (losing) value.

as a method of central bank intervention.[3] As for the Colombian case, the only study that directly considered this policy is Mandeng (2003) who finds, through an event study approach, that rule-based interventions were only moderately successful and the effects generally short-lived. However, Mandeng's study consists of only 3 events (i.e. 3 auction observations), given that interventions were first triggered in July 2002. Other studies that have focused on the Colombian experience such as Uribe and Toro (2005), Kamil (2008), Ricon and Toro (2010), Echavarria, Vasquez and Villamizar (2010), and Villamizar (2015) have primarily focused on estimating the effects of discretionary interventions and have only provided a descriptive reading of the rule-based mechanism and its effects.

Our study also relates to the small but growing literature that applies quasi-experimental methods to macroeconomic questions. While well developed in microeconomics, field experiments and quasi-experimental methods like the regression discontinuity design we employ here have seen limited application to macroeconomic questions. This may partially be the result of the inherent difficulty of finding institutional arrangements at the level of national economies where these methods can be applied. However, some promising exploration has been conducted including the use of instrumental variables to measure the fiscal multiplier by Ramey (2011) and the estimation of the effectiveness of monetary policy using "policy shocks" in Romer and Romer (2004), Angrist and Kuersteiner (2004, 2011), and Angrist, Jorda and Kuersteiner (2014). A methodological contribution of this paper is to show how regression discontinuity methods can be used to identify and estimate non-linear impulse response functions without the need for complicated non-parametric or simulation based methods.[4]

2 Data and Institutional Environment

In October 1999, the CBoC adopted an inflation-targeting regime with a floating exchange rate. Prior to this date, pre-announced exchange rate bands were established dating back to 1994. In November 1999, one month after allowing the exchange rate to float, the CBoC adopted a rule-based intervention mechanism exclusively aimed at stemming exchange rate volatility. This mechanism, while initially designed to purchase foreign currency whenever volatility was high, became fully symmetrical (and operational) in 2002 by also triggering sales of foreign currency.

Two other mechanisms of foreign exchange intervention were established soon afterwards which, as opposed to the rule-based mechanism, granted the board of directors full discretion over when and how to intervene. Specifically, they consisted of: 1) option contracts aimed at accumulating/reducing international reserves (put in place in 1999), and 2) direct interventions in the spot market aimed at

[3] See Castillo (2010). In the case of Mexico, for instance, options were issued to build up reserves during 1996-2001, but auctions were held in pre-established dates (last business day of every month).

[4] See Galant and Tauchen (1993) for a general treatment of non-linear impulse response functions and Evans and Lyons (2002b, p.1043) for a method proposed specifically in the context of foreign exchange.

avoiding excessive movements in output and the exchange rate (put in place in 2004).[5] The CBoC also maintained monetary policy directed at the interest rate. However, these interventions were discretionary in nature and uncorrelated with triggering of the rule-based intervention we examine.

2.1 Rule-based interventions

Rule-based interventions were triggered whenever the nominal exchange rate, defined as pesos per dollar (COP/USD) henceforth, exceeded a specific threshold. For the most part, this threshold was 4% above or below the exchange rate's 20 day moving average. Table 1 shows that the rule was temporarily modified in December 2005 and October 2008 to be triggered whenever the exchange rate was 2% and 5% above or below its moving average, respectively. Interventions were temporarily stopped during Jun 2008 - Oct 2008 and during Oct 2009 - Oct 2011 when the board of directors of the CBoC decided that it was better to avoid sales of foreign currency in the midst of an appreciating currency. The CBoC thus intervened with discretion in these last two periods, by only purchasing foreign currency. The mechanism was permanently stopped in February 2012.

The mechanics of rule-based interventions were as follows: at the close of any business day, market participants gained information on whether the exchange rate would trigger the rule. The trigger depends on the average exchange rate for the entire day, including all trades through the end of trading at 1:00 pm. Hence, traders are not able to distinguish between days for which the rule is triggered and those for which it barely misses, until markets have closed for the day. If the rule is triggered, options are issued the following day (normally between 8:30am-9:00am) using Dutch auctions. Participants could include up to 5 bids without exceeding the total amount set by the CBoC.[6] Options expired exactly one calendar month after the day of the auction and could be exercised on a given day only if conditions that triggered the rule initially were also in effect that day (i.e. the exchange rate was still below or above its 20-day moving average by the established amount). During this one month period, exchange rate fluctuations outside the relevant band would not trigger a new auction but instead would allow market participants to exercise. If all options had been exercised, then the Central Bank could conduct a new auction.

During Dec 24 2001 - Feb 3 2012, the rule was triggered 231 times (38 auctions) and options were exercised in 75 cases. Purchases (through put options) totaled $2,373 million USD and sales (through call options) totaled $2,330 million USD. Average sales ($68.5 million USD) were higher than average purchases ($57.9 million USD) but purchases were conducted more frequently. Rule-based interventions were highly concentrated in the period of 2006-2008, partly because of higher exchange rate volatility but

[5](Uribe and Toro 2005) argue that these interventions had to be consistent with meeting inflationary targets and strengthening the country's international liquidity position.

[6]The offered amount was generally set at 180 million USD, with some exceptions set at 200 million USD. The strike price corresponded to the average exchange rate of the day before options were exercised.

mostly because the threshold that triggered the rule was set at 2% above or below its last 20 day moving average (see Table 1).

2.2 Data

Our data comes from two different sources. One source is *SET-ICAP FX S.A.*, a financial institution in charge of administrating all foreign exchange transactions that take place in the Colombian stock market. Data from this source include tick-by-tick foreign exchange transactions. We observe 3.5 million transactions from December 24, 2001 until February 3, 2012. The average transaction trades 670,000 USD at 2,080 COP/USD. The CBoC calculates a daily exchange rate (*Tasa Representativa de Mercado*, or TRM) as an average of individual transactions weighted by volume that takes place on the previous trading day.[7] Hence, when we refer to a particular day's exchange rate, we refer to the TRM_{t+1}. For shorter time periods, we similarly calculate a representative rate using a weighted average. The exchange trading data also includes the origin (bid/ask) of each trade, which we use to compute order flow.

The second data source is the CBoC, specifically the Market Operations and Development Department (*Departamento de Operaciones y Desarrollo de Mercados -Mesa de Dinero*) and the International Affairs Department (*Departamento de Cambios Internacionales*). Part of the data comprise the timing and amount of every auction held by the CBoC from December 2001 up until February 2012 (2,433 observations). It contains the specific dates when each option was exercised, the resulting premiums, and the total amount bid by market participants. Additional (daily) variables include: (i) the intended policy rate (analogous to the US Federal Funds rate), (ii) discretionary foreign exchange intervention mechanisms, (iii) the inter-bank rate, (iv) international reserves, (v) sterilization operations by the CBoC -repurchasing agreements and sales and purchases of sovereign bonds, (vi) exchange rate forwards, (vii) inflows and outflows -foreign and domestic investment on portfolio flowing in and out of the country, and (viii) foreign holdings of all commercial banks -net assets denominated in both domestic and foreign currency. Appendix C provides a more detailed description of each variable. Further, Tables 2 and 3 summarize these data, broken down by different periods and by episodes in which the rule was barely missed and barely triggered, respectively.

2.3 Capital Controls

Between December 2004 and June 2006, the CBoC introduced controls on outflows, requiring all foreign investments to remain in the country for at least one year. A year later, between May 7, 2007 and October 8, 2008 capital controls on inflows were enacted, mostly due to a strong currency appreciation

[7]The TRM is calculated each day after markets close and becomes the reference rate for market participants during the next business day.

and a surge in inflows (Rincon and Toro (2010)). In our sample, these time periods include approximately 30% of all rule-based interventions. Controls on inflows required foreign investors to deposit 40% of portfolio and debt investments at the CBoC during a six month period without interest payments (i.e. an unremunerated reserve requirement). The CBoC also imposed a limit of 500% on the net position of foreign exchange derivatives relative to total capital (Magud, Reinhart and Rogoff (2011)).

3 Methodology

3.1 Local Estimation of Non-Linear Impulse Responses

We assume that macroeconomic variables contained in a vector $\chi_t \in \mathbb{R}^d$ follow a stationary Markov process. Higher order dynamics of elements in χ_t can be accommodated by sufficiently augmenting the statespace of the system. The vector χ_t contains the exchange rate e_t, the domestic interest rate r_t, information on outstanding currency options and other macroeconomic variables. Our goal is to measure the effect of foreign exchange interventions on elements of χ_t at future dates in time. We denote outcome variables generically with y_t, noting that y_t can be any one of the elements in χ_t. The reduced form of y_{t+j} describes how y_{t+j} depends on state variables χ_t, foreign exchange interventions D_t and other exogenous variation. We assume that the reduced form of y_{t+j}, conditional on time t information, is well defined and denote it by

$$y_{t+j} = F_{t,j}\left(D_t, \chi_t\right).$$

We note that $F_{t,j}$ is a random function of χ_t and D_t. The function $F_{t,j}$ is random because y_{t+j} depends not only on χ_t and D_t but also on future shocks. However, we suppress that dependence in our notation because the exact form of it plays no role in our analysis. The marginal distribution of $F_{t,j}$, conditional on χ_t and D_t only depends on j but not on t because of the assumption of stationarity.[8]

Let the binary policy indicator D_t follow a fixed rule $D_t = 1\left\{X_t > c\right\}$ where the running variable X_t is a continuous, non-random function of χ_t such that $g\left(\chi_t\right) = X_t$ and c is a known threshold. In this paper, D_t is an indicator of whether the CBoC issues currency options on a particular day and the running variable X_t is the measure the CBoC uses to determine whether it is issuing options. The function g and constant c represent the fixed policy rule adopted by the CBoC.

To emphasize the dependence of D_t on χ_t we sometimes write $D_t = D\left(\chi_t\right)$. Now consider a perturbation $\varepsilon\left(\delta\right) : [0, \infty) \to \mathbb{R}^d$ of the initial condition χ_t in a direction such that the running variable X_t changes by an amount δ. Formally, we require $\varepsilon\left(\delta\right)$ to be such that $g\left(\chi_t + \varepsilon\left(\delta\right)\right) - g\left(\chi_t\right) = \delta$ with $\delta > 0$. This

[8] Note that the function $F_{t,j}$ does depend on t because at each point in time t, the system is affected by different realizations of the shocks. If the model is driven by a specific sequence of shocks $v_{t+1}, ..., v_{t+j}$ one could write more explicitly $F_{t,j}\left(D_t, \chi_t\right) = F^j\left(v_{t+j}, ..., v_{t+1}, D_t, \chi_t\right)$.

somewhat complicated formulation is needed because χ_t may have many elements whose perturbations do not change the running variable. Since we are interested in variation that affects D_t we are only interested in perturbations of χ_t that can actually trigger such changes.[9] For δ fixed and $\varepsilon = \varepsilon(\delta)$ the impulse response of y_{t+j} then is defined as

$$\theta_j(\varepsilon, \chi_t) = F_{t,j}(D(\chi_t + \varepsilon), \chi_t + \varepsilon) - F_{t,j}(D_t, \chi_t).$$

Clearly, variation in χ_t in general is not suitable to identify the effects of the policy D_t. The discontinuous nature of the policy rule helps in this regard: unless χ_t is near a critical point where $X_t = c$, D_t remains unchanged along the path $\varepsilon(\delta)$ as $\delta \downarrow 0$. It is also the case that $\theta_j(\varepsilon, \chi_t)$ will be zero at the limit as $\delta \downarrow 0$ if $F_{t,j}(.)$ is continuous in its arguments and if χ_t is not near a critical point $X_t = c$. Our analysis therefore focuses on the critical points $X_t = c$ where D_t changes discontinuously along the path $\varepsilon(\delta)$.

If (D_t, χ_t) were a linear process such as an identified structural VAR, the impulse response $\theta_j(\varepsilon, \chi_t)$ would be easy to compute, be linear in ε, not depend on χ_t, and be non-random. More generally, $\theta_j(\varepsilon, \chi_t)$ is a non-linear and random function of both ε and χ_t. It is common in the literature on non-linear impulse response functions (c.f. Gallant, Rossi and Tauchen, 1993) to focus on the average response $E[\theta_j(\varepsilon, \chi_t)]$. Unfortunately, statistical inference about the average response is difficult because in the absence of a fully parametric model, $F_{t,j}(.)$ or its conditional distribution are unknown and hard to estimate.

We make progress on this inference problem by utilizing the regression discontinuity design known in the cross-sectional literature, see for example Thistelthwaite and Campbell (1960), Hahn, Todd and Van der Klaauw (2001, henceforth HTV) and Porter (2003). We are interested in the impulse response of y_{t+j} to changes in the policy D_t. This response is given by

$$\theta_j^D(\chi_t) = F_{t,j}(1, \chi_t) - F_{t,j}(0, \chi_t).$$

Note that $\theta_j^D(\chi_t)$ is well defined even though it ignores the functional dependence between χ_t and D_t. Our setting also accommodates the scenario where D_t does not separately affect the outcome y_{t+j} in which case $\theta_j^D(\chi_t) \equiv 0$. The response $\theta_j^D(\chi_t)$ answers the question of what would happen to y_{t+j} if we could change D_t from 0 to 1 while holding all other state variables fixed. Identifying this type of variation in observational data typically requires an identifying assumption that allows one to identify variation in

[9] A simple example arises when $\boldsymbol{\chi}_t$ is univariate, i.e. $\chi_t = X_t$ such that $g(\chi_t) = \chi_t$. Then, $\varepsilon(\delta) = \delta$.A slightly more elaborate example is a bivariate case where $\chi_t = (y_t, x_t)$ and $g(\chi_t) = y_t/x_t$. Then, $\varepsilon(\delta) = (\delta x_t, 0)$ is a path perturbing y_t and $\varepsilon(\delta) = \left(0, \delta x_t^2/(y_t + \delta x_t)\right)$ is a path perturbing x_t.The second example shows that in general $\varepsilon(\delta)$ depends both on χ_t and g and that there are usually many different perturbations of χ_t that lead to the same change in X_t. We later impose the condition that $\varepsilon(\delta)$ is continuous in δ and $\varepsilon(0) = 0$.The latter requirement limits considerations of perturbations that are local to χ_t. The assumption that a path $\varepsilon(\delta)$ with these properties exists implies that there are local deviations in χ_t that are able to trigger the policy rule.

D_t that is unrelated to χ_t. In other words, enough structure needs to be imposed on the model so that a policy shock to D_t can be identified. Regression discontinuity uses a different identification strategy.

To better understand the difference between our method and more conventional regression analysis it is useful to write the observed outcome y_{t+j} as

$$y_{t+j} = F_{t,j}\left(0, \chi_t\right) + \theta_j^D\left(\chi_t\right) D_t.$$

If $F_{t,j}\left(0, \chi_t\right)$ were linear in χ_t and θ_j^D was a constant parameter we could use regression methods to identify the parameter θ_j^D by simply regressing y_{t+j} on D_t and χ_t. In addition to linearity, regression requires that D_t is randomly assigned conditional on χ_t. This situation is commonly referred to as 'selection on observables'. Without a linear model and only a selection on observables assumption, the propensity score methods of Angrist, Jorda and Kuersteiner (2013) could be used. Here, we rely on neither of these assumptions. Instead, we use assumptions about the continuity of conditional expectations and localized inference in line with the regression discontinuity literature. We impose the following condition.

Assumption 1 *For $D \in \{0,1\}$, D fixed, the function $E\left[F_{t,j}\left(D, \chi_t\right) | X_t = x\right]$ is a.s. continuous in x at c.*

The assumption of continuity imposed in Assumption 1 is typical for the RD literature (c.f. HTV). It is generally not sufficient to identify $E\left[\theta_j^D\left(\chi_t\right)\right]$. Rather, regression discontinuity analysis is localized at the point of discontinuity. As a result we can identify the average impulse response conditional on $X_t = c$, namely[10]

$$\lim_{\delta \downarrow 0} E\left[y_{t+j} | X_t = c + \delta\right] - \lim_{\delta \downarrow 0} E\left[y_{t+j} | X_t = c - \delta\right] = \lim_{\delta \downarrow 0} E\left[\theta_j\left(\varepsilon\left(\delta\right), \chi_t\right) | X_t = c\right] = E\left[\theta_j^D\left(\chi_t\right) | X_t = c\right]. \tag{1}$$

The relationship in (1) shows two things: how a local average of y_{t+j} around $X_t = c$ can be used to identify the average impulse response $E\left[\theta_j^D\left(\chi_t\right) | X_t = c\right]$ and that variation in χ_t local to $X_t = c$ is required to identify the parameter of interest. As we will see below, in our application X_t is an indicator that is specific to the policy rule for foreign exchange interventions employed by the CBoC. What is required then, are instances where X_t is just below and just above the point c. Loosely speaking, averages of the outcome y_{t+j} in these two subsets then identifies the policy effect.

More specifically, limits of the conditional expectation of y_{t+j} in (1) must be estimated using localized inference. We estimate these limits using the local linear regressions developed by Fan (1992). This method consists of linear regressions evaluated within a window surrounding the cutoff point using weighted least squares to give more weight to observations that are closer to the cutoff. Imbens and

[10]A formal result is given in Appendix A.

Lemieux (2008) pointed out that local regressions improve over simple comparison of means around the discontinuity point as well as over standard kernel regressions by reducing bias. Formally, we estimate the vector of impulse response coefficients $\theta = (\theta_1, ..., \theta_J)'$ by solving the problem

$$\left(\hat{a}, \hat{b}, \hat{\gamma}, \hat{\theta}\right) = \underset{a,b,\gamma,\theta}{\arg\min} \sum_{j=1}^{J} \sum_{t=2}^{T-J} \left(y_{t+j} - a_j - b_j \left(X_t - c\right) - \theta_j D_t - \gamma_j \left(X_t - c\right) D_t\right)^2 K\left(\frac{X_t - c}{h}\right)$$

where $K(\cdot)$ is a kernel function that assigns weights and h is a bandwidth defining the sample via the size of the window around the cutoff c. Our parameter of interest is $\hat{\theta}_j$ which measures the jump in outcomes at the policy rule cutoff. As detailed in Appendix A, we use a triangular kernel and optimal bandwidth similar to Imbens and Kalyanaraman (2012) and we conduct inference as defined in Appendix A.

3.2 Colombia's Rule-Based Intervention

The CBoC carried out rule-based currency interventions that are at the heart of our identification strategy. In particular, the intervention was triggered whenever the exchange rate, e_t, appreciated or depreciated (vis-a-vis its last 20-day moving average, $\bar{e}_t$) at a rate faster than a cutoff r_t, typically set at 4%. Figure 1 depicts the rule-based intervention program of the CBoC. The upper graph shows when the CBoC held auctions (red lines) and when exchange rate options were exercised (black lines), leading to purchases and sales of US dollars by the CBoC. New auctions and exercising existing options could only occur when the policy rule was triggered. The lower pane demonstrates this fact by displaying the policy rule, $X_t = \left(\frac{1}{r_t}\frac{e_t - \bar{e}_t}{\bar{e}_t}\right)$, which was triggered whenever its absolute value exceeded unity. As can be observed, the CBoC only auctioned and allowed redemption of options whenever the rule was triggered, mostly during 2006-2008.

There were two necessary conditions for the CBoC to issue foreign exchange options. One condition was for the rule to be triggered. The other was that there could not be outstanding options from a previous auction. This latter condition could be satisfied if all previous options had been exercised or if one month had passed since the most recent auction, causing all outstanding options to expire.

The two conditions defining the CBoC's policy rule naturally fit into a sharp regression discontinuity design where the policy D_t is enacted if the running variable X_t crosses a specific threshold c. Formally, if we define OS_t (OP_t) as a dummy variable switched on whenever call (put) options from a previous auction remain outstanding at date t, then we can define our two running variables $X_{S,t}$ and $X_{P,t}$ as:

$$X_{S,t} = \frac{1}{r_t}\frac{e_t - \bar{e}_t}{\bar{e}_t}(1 - OS_t), \;\; X_{P,t} = \frac{1}{r_t}\frac{e_t - \bar{e}_t}{\bar{e}_t}(1 - OP_t).$$

The policy dummies ($D_{S,t}$, $D_{P,t}$) describe the time at which the CBoC issued new *call* and *put* options, respectively:

$$D_{S,t} = \mathbf{1}\{X_{S,t} > 1\},\ D_{P,t} = \mathbf{1}\{X_{P,t} < -1\}.$$

Policy dummies accurately characterize the policy because the CBoC intervened by issuing 180 million USD of options in nearly every instance. The right panel of Figure 2 displays this cutoff rule for auctioning call options. When the spot rate changes by less than the cutoff rate, making $X_{S,t} < 1$, the CBoC does not auction any call options in the foreign exchange market. Above the cutoff, though, the central bank does conduct auctions. The left panel of Figure 2 shows a similar discontinuity at the -1 cutoff for put options. The large jump in policy decisions at the cutoffs represent the sharp changes that we will use to identify the effect of foreign exchange market intervention.

Tables 4 and 5 quantify these changes more precisely. The first line of Table 4 shows how exchange rate depreciation triggers CBoC intervention. Each cell in the table shows the results of a local linear regression-based regression discontinuity estimate. As shown in the first column, if the rule is barely triggered (just below the cutoff level), the CBoC on average issues 46 million USD of put options. However, auctions only occur on days without outstanding options. If we change the running variable to $X_{S,t}$ to focus only on days in which no existing options were outstanding, we find that triggering the rule leads to the issue of 116 million USD of put options. If we focus on days with outstanding options using the running variable, the rule triggers no new auction. Similarly, Table 5 shows that when the exchange rate appreciates, the rule triggers the issuance of call options concentrated on days when no outstanding options remain with an average increase of 122 million USD of options on those days.[11]

The next row of Tables 4 and 5 quantifies what portion of the options was immediately exercised. Figure 3 displays this effect graphically. Immediately exercised options can be interpreted as a direct sale/purchase of dollars by the central bank. Triggers in both directions led to many options being immediately exercised; however, call options are more likely to be exercised immediately. Crossing the cutoff rule leads to 72 million USD of call options being exercised compared to 20 million USD of put options. The left and right panels of Figure 4 trace when options are exercised out to two weeks after the initial auctions. Of those options which market participants eventually exercise, most are exercised on the same day as the auction. Thus, issuing call options bears more similarity to straightforward sales of foreign exchange by CBoC while issuing put options leads to less direct FX purchases, instead leaving a larger number of options outstanding.

Once issued, market participants may exercise the options at some point over the next 30 days. The options can only be exercised, though, on days when the appreciation/depreciation threshold was met. Thus, they could be exercised either immediately after being purchased or on future days when the policy

[11]Triggering the rule does cause two instances where CBoC issues call options despite the existence of outstanding call options, hence the non-zero effect at the top of the middle column in Table 5. It is not clear whether this is an error in the data or non-compliance with the policy rule. However, this happens only twice in our sample.

rule was still triggered. The effect of those exercised on the same day will be included in our estimates of issuing options. Exercising of options on other days can be embodied in an alternative regression discontinuity design. Market participants can exercise their options on days other than the auction if a) the rule is triggered and b) there are outstanding options remaining. This yields the following two new running variables ($\tilde{X}_{S,t}$ and $\tilde{X}_{P,t}$):

$$\tilde{X}_{S,t} = \frac{1}{r_t}\frac{e_t - \bar{e}_t}{\bar{e}_t} OS_t, \;\; \tilde{X}_{P,t} = \frac{1}{r_t}\frac{e_t - \bar{e}_t}{\bar{e}_t} OP_t.$$

We can then characterize the assignment to exercise *call* and *put* auctions ($\tilde{D}_{S,t}$, $\tilde{D}_{P,t}$), as follows:

$$\tilde{D}_{S,t} = \mathit{1}\{\tilde{X}_{S,t} > \; 1\}, \;\; \tilde{D}_{P,t} = \mathit{1}\{\tilde{X}_{P,t} < -1\}.$$

Thus, we can also use a regression discontinuity framework to measure the effects of allowing participants to exercise options. Namely, while triggering the policy rule on days with outstanding options generally does not lead to new options being issued, it does allow market participants to exercise existing options. Estimates using this running variable are shown in the middle column of Tables 4 and 5. Specifically, the middle row and middle column of Table 4 shows that investors exercise 24 million USD of put options on days when the downward rule is triggered, and the middle row and middle column of Table 5 shows that investors exercise 33 million USD of call options on days when the upward rule is triggered.

3.3 Testing RDD Assumptions

All regression discontinuity designs rely on the assumption that the potential outcome functions are continuous at the cutoff point. Perhaps more intuitively, this requires that agents not be able to precisely manipulate the running variable to predict FX interventions. In our context, the running variable that determines intervention is itself a function of the lagged exchange rate. This would initially suggest an endogeneity bias when comparing mean future exchanges rates, especially if exchange rates are autocorrelated. However, the fundamental RDD assumption will be met and unbiased inference will result from RDD estimation provided that exchange rates are locally determined by random factors that cannot be predicted or controlled by market participants. And even though exchange rates seem to respond to economic fundamentals as shown in Echavarria and Villamizar (2016) and the actions of market participants as in Evans and Lyons (2001), we simply require that these actors are not able to precisely manipulate the exchange rate to exceed the cutoffs that trigger new auctions (or the ability to exercise previously purchased options).

While identifying assumptions cannot be fully tested, RDD does have testable implications. Following McCrary(2008), we test whether the densities of the running variables exhibit a discontinuity at the cutoff. In principle, a discontinuity would suggest that agents are able to manipulate the exchange rate (i.e. pushing it "over the edge") resulting in a disproportionate number of days in which auctions are barely triggered versus barely not triggered. The test estimates the density separately on either side of the cutoff and provides a Wald estimate in which the null hypothesis is the non-existence of a discontinuity at the cutoff (i.e. discontinuity equals zero).

Results are displayed in Figure 5 for the full sample. The dark line displays the estimated density of the absolute value of the running variable. We estimate the density separately on either side of the cutoff at (the absolute value of) 1. As can be seen, the cutoff does not generate a clear discontinuity. We test for manipulation in the running variable formally using McCrary's test. We combine both cutoffs, creating a more powerful test by looking for manipulation in the absolute value of the running variable around a +1 cutoff. We find no evidence of manipulation with a p-value of 0.80. Thus, we do not reject the null. Our results are consistent with exchange rates that are allocated randomly around the cutoff and with no manipulation by market participants.

A second falsification test for the regression discontinuity assumptions, proposed by Lee (2008), relies on the fact that if the values of the running variable in the neighborhood of the cutoff are as good as randomly assigned, then the values of baseline covariates should not differ for observations just above and below the cutoff. In the language of experimental design covariates, even including lagged outcomes, should be balanced between treatment and control.

Figure 6 examines lagged spot rates to see if these appear to respond to policy interventions which have not yet been triggered. In particular, we examine the difference between the log of the average exchange rate at the start of the day before the auction and the log exchange rate two days before the auction. Spot rates vary smoothly across the cutoffs for both types of auctions, consistent with the RDD assumptions that such conditional expectations are continuous in the absence of policy intervention. Table 6 quantifies these changes. As can be seen in the first row for put options and the second row for call options, we find no statistically significant relationship between lagged exchange rate changes and triggering the policy rule, both in the whole sample or focused only on days with or without outstanding options.

Given the time series nature of our data, we generalize this idea to test whether treatment and lags of multiple variables are correlated, conditional on the running variable. For simplicity, we consider a parametric linear regression of the policy indicator $D_{i,t}$ on a polynomial of $(X_{i,t-1} - c_i)$ and a vector Z of variables that would likely predict both policy and exchange rate movements (i.e. would cause bias) outside of our RDD setup. In particular, we include lagged values of the exchange rate changes, the inter-bank interest rate, and two variables measuring expected appreciation built into forward contracts. We measure implied daily appreciation of a forward contract as $\left(\left(f_{j,t}^{t+k}/e_t\right)^{1/k} - 1\right)$ where $f_{j,t}^{t+k}$ denotes the pesos per dollar forward exchange rate for contract j traded on date t, to be exercised on date $t + k$. We calculate average appreciation separately for contracts traded versus exercised on the given date, weighting by the volume of each contract.

In our context, if the RDD setup is a valid quasi-experiment, then predetermined variables should not be able to predict treatment conditional on a smooth function of the running variable. For the case of lagged exchange rates for instance, if days on which purchase auctions were barely triggered happened to coincide less frequently with downward trending exchange rates than days on which auctions were not triggered (barely missing the cutoff), this could generate a false positive treatment effect. However, in this case we would also expect to find that treatment days have lower lagged exchange rates. Our regression based test is designed to detect these departures from our assumptions.

Table 7 shows the impact of predetermined variables on the issuance of auctions and the possibility of exercising options ($D_{S,t}$, $D_{P,t}$, $\tilde{D}_{S,t}$, $\tilde{D}_{P,t}$). All estimations included a polynomial function of the running variable of degree 4 as well as 1 and 2 day lags of the four predictors. The top two rows of the bottom pane present a χ^2 test examining whether the coefficients on all of the lagged $Z's$ are zero. The first two columns correspond to our main quasi-experiments of interest (triggering of new call and put auctions). Results show that in both cases, we cannot reject the null (H_0 : all coefficients equal zero). The final two columns report similar results for exercising options. Altogether, the results show that there is no noticeable baseline difference between days on which new auctions are triggered and those on which they are not.

4 Effects on the Spot Exchange Rate

4.1 1-Day Effects

We implement the regression discontinuity strategy and find evidence that central bank intervention in the foreign exchange market affects the spot rate asymmetrically. Figure 7 displays how the exchange rate reacts immediately following issuance of options to buy and sell foreign exchange. Recall that market participants observe the previous day's average exchange rate and the triggering of the auction rule at the end of trading. Thus, we examine the difference in the log spot exchange rate between start of trading (8 AM) on the day of the auction and the average for the previous day (TRM). This log difference can be interpreted roughly as the percent change in the exchange rate. The left panel of Figure 7 shows the effect of crossing the -1 cutoff, which triggers an auction issuing put options and ultimately the central bank purchasing dollars. The exchange rate tends to appreciate more when the auction is barely triggered (below the cutoff) relative to just missing the threshold (above the cutoff). As expected, the exchange rate (COP/USD) increases indicating that the peso loses value when the CBoC purchases dollars.

Table 4 quantifies this effect using local linear regressions. The third row of the table shows the effect on the following day's average log exchange rate relative to the present day's log exchange rate. The CBoC issues new put options when the rule is triggered on days when no existing options are outstanding. Thus, issuing put options increases the average spot rate for the day by 0.8 percent, an effect which is statistically significant at the 1 percent level. The right panel of Figure 7 tests for a similar effect of auctioning call options which leads to sale of dollars by the CBoC. If selling dollars had an effect it would appreciate the peso. However, we observe no such effect. The percent appreciation in the exchange rate varies smoothly around the +1 cutoff which triggers selling dollars. As shown in Table 5, this effect is small and precisely measured. The exchange rate actually increases by 0.3 percent on days when the rule triggers the CBoC to issue call options. The 95 percent confidence interval for this effect only includes declines of the exchange rate of at most -0.1 percent. Altogether, we find that central bank intervention has asymmetric immediate effects with dollar purchases having the expected effect and dollar sales having no observable effect.

We now extend our analysis to the entire day following the triggering of foreign exchange intervention. Figure 8 shows the impulse response function of difference in the log exchange rate moving from the beginning of trading (8:00 AM) on the day prior to the auction until close of trading (1:00 PM) on the day of the auction (i.e. day before and after auction). Panel (a) displays results for auctioning put options. The 0.7 percent increase in the spot rate at 8:00 AM on the same day as the auction matches previous results from the same regression discontinuity empirical strategy using local linear regression. It indicates that the spot rate jumps by 0.7 percent as we move from days when auctions where barely missed to barely triggered (i.e. from left to right). This effect is statistically significant at the 1-percent level. The impulse response function then shows that this effect lasts for the entire day following the auction, rising slightly to a roughly 1 percent appreciation of the spot rate that remains statistically significant at the 5-percent level. Panel (b) shows results for issuing call options. The effect of CBoC dollar sales initially is statistically insignificant, although eventually significant, smaller than the effect of dollar purchases, and if anything positive, contrary what we would predict. The asymmetry of the effects of intervention persists throughout the first day following issuance of options.

We can conduct a similar analysis on whether allowing market participants to exercise options affect the spot exchange rate. Recall that the ability of market participants to exercise options on days other than issue date depends on the same cutoff rule, allowing us to implement a similar RD strategy. Panels (c) and (d) of Figure 8 shows our results. For both call and put options, market participants exercising the options has no noticeable effect on the spot exchange rate. This matches quantitative results based on daily average exchange rates reported in Tables 4 and 5. While issuing options may affect the exchange rate, we do not measure an effect of exercising options.

If our empirical strategy correctly measures the effect of central bank intervention, then an auction should not have an effect on the previous day's spot rate. Because we are measuring the difference between the log exchange rate for a given quarter hour and the log of the average exchange rate the day before the auction, the previous day's effects trivially average to zero. More importantly, though, the measured hourly effects of future intervention do not trend. The difference between the log exchange rate for a particular hour on the day prior to the auction and the average for the whole day does not increase throughout the day. Instead, for puts the effect of the auction appears sharply at the end of the trading day when the day's average exchange rate has been set and market participants become aware of whether the rule governing central bank intervention has been triggered.

4.2 Expectations and Measured Treatment Effects

We can separate the effect of central bank intervention into how it affects days on which intervention is triggered versus days when it is barely not triggered. In the standard regression discontinuity framework, days when intervention does not occur are a control group assumed to be unaffected. However, in a rational expectations framework, the spot rate may begin to incorporate the positive probability of intervention prior to final revelation whether the rule is triggered. When the trading day ends at 1 pm and the CBoC reveals information related to intervention, 'treatment' and 'control' days may both be affected in opposite directions as the probability of intervention jumps to 1 or 0. We investigate this possibility in Figure 9. The figure considers the -1 border for triggering put options. It splits out the discontinuous jump in exchange rate appreciation across that border into appreciation on the "barely triggered' side of the border (red, solid line) and the "barely not triggered' side of the border (green, dashed line). The revelation of information at the end of trading affects both types of days. The spot rate increases following a barely triggered CBoC intervention as expected, and this effect accounts for most of our measured effect of intervention. But the spot rate also drops slightly when the market barely avoids intervention, suggesting that the spot rate through the end of the prior day at least partially priced in the possibility of intervention. This does not affect the validity of our empirical strategy as the end of trading still leads to a discontinuous jump in the spot rate, indicating that market participants cannot fully anticipate intervention. Also, our main estimates still have the interpretation of the effect of moving the probability of intervention from zero to one.

4.3 60-Day Effects

Finally, we can measure the effect of intervention over a longer time period. As shown in Figure 2, triggering the policy rule leads to immediate issuance of put and call options by which the CBoC buys and sells dollars, respectively, relative to days when the rule is barely not triggered. However, because the CBoC intervenes based on a cutoff rule relative to a moving average and exchange rates can trend, days on which the rule is barely not triggered tend to be followed by intervention a few days in the future. Figure 10 demonstrates this fact by displaying 60-day impulse response functions for cumulative amount of put and call options issued since the intervention. Both figures exhibit spikes immediately after the rule is triggered, indicating that the central bank intervenes immediately when the rule is triggered relative to when it is not. However, the control days catch up over time. The first column of Table 8 quantifies this effect with each row showing the effect of triggering the rule after a certain number of days. For puts, triggering the rule leads to an immediate issuance of 115.6 million USD of options, relative to the control group, but within 10 days the control group has closed this gap. Similarly, when the rule is triggered for issuing calls, the control group closes the gap within 30 days. The reason for such catch-up is that treated days cannot experience subsequent auctions for 30 days, but control days can. Within 15-30 days of the original date, subsequent auctions have been triggered for previously untreated time periods such that cumulative intervention by CBoC does not differ significantly for originally treated versus untreated time periods. Ultimately, this means that we measure the effect of CBoC intervening sooner compared to later.

In Figure 11 we extend our time horizon for the main results, showing impulse response functions for exchange rate appreciation out to 60 days. The left panel of Figure 11 shows results for issuing put options. After issuance of put options, exchange rate appreciation relative to the day before the auction peaks at about 2 percent one week after the intervention. The exchange rate then returns to its pre-auction level by 2-3 weeks after the auction. The right panel of Figure 11 shows similar results for issuing call options. While the measured effect of intervention becomes negative and briefly pointwise statistically significant about 10 days after intervention, these effects are noisily measured. Overall, we find evidence that issuing put options increases the pesos per dollar exchange rate for a period of 2-3 weeks. The evidence for issuing call options is a bit less clear. We do measure a decline in the exchange rate between 5 and 40 days after the intervention, but the response is measured less precisely than for the put options. In addition, we observe an initial response lasting a couple days that goes in the opposite direction, although again this response is small in magnitude and barely significant, in line with our earlier results for the one day effect. As before, Table 8 quantifies these effects more precisely.

The effects that we measure suggest that central bank intervention can move exchange rates in noticeable and significant magnitudes. We observe a roughly 1 percent increase in the spot exchange rate in response to, on average, issuance of 116 million USD of put options. Since these effects last for a couple weeks and the CBoC's rule regarding no intervention with outstanding options often limits intervention to once per month, it is useful to consider the magnitude of the measured effects out to one month. The effects shown for purchases in Figure 11 over the 30 days following the auction average to a 0.8 percent increase in the spot rate. Over our sample period, foreign exchange trades have an average volume of 715 million USD per day. Thus, over a 30-day period the CBoC's intervention of 116 million USD of put options represents a purchase of up to 0.5 percent of the monthly volume of foreign exchange trade. This implies that the elasticity of the spot rate to the size of the intervention relative to monthly foreign exchange market volume is about 1.5. We interpret this magnitude as implying that interventions of reasonable magnitude can have noticeable effects on the foreign exchange rate.

4.4 Effects on Forward Rates

We can use forward exchange rates to test whether market participants rationally anticipate the short-run effects on the spot rate that we measure. We have daily data on the forward rate agreed upon in forward contracts of various maturities traded on the day of central bank intervention (see Appendix C). We implement our regression discontinuity strategy using forward rates as the outcome variable and running a separate model for each maturity length. Figure 12 shows these results for issuance of put and call options respectively. The left panel of Figure 12 demonstrates that issuing put options not only increased the spot rate but also increased forward rates by a similar magnitude on contracts with maturities of 3, 30, and 90 days with no effect on maturities of 180 days. However, as shown in the right panel of Figure 12, issuing call options appears to have no statistically significant effect on forward rates.

Thus, intervention by CBoC appears to have changed investors' expectations regarding the peso/dollar exchange rate but only for the near term and with strongest effects when issuing put options. This result extends our analysis in two key ways. First, clearer effects of CBoC intervention on the forward rate for puts matches our results for the spot rate. Any potential asymmetry in the effectiveness of FXI in moving the spot rate carries through to the forward rate. Second, the forward rate results suggest that market participants rationally anticipate that central bank intervention will be effective but only temporarily. Some models allow for effective sterilized FXI if investors display bounded rationality. FXI may move spot rates through an 'expectations channel' by shifting investor expectations about future exchange rate movements without changing interest rates. Instead, our results for forward rates suggest agents with rational expectations.

4.5 Sterilization

We confirm that interventions by the CBoC represent sterilized interventions that do not affect interest rates. The third column of Table 8 shows responses of the Colombian interbank rate to FX interventions after 1, 10, 20, 30, and 60 days. Impulse Response Functions reported in the Auxiliary Technical Appendix show that the response is not statistically significant for either put and call auctions. For put auctions we observe some downward trending interest rate, perhaps suggesting some undershooting of the domestic sterilization effort. However, this effect is less pronounced in the short run and becomes larger in magnitude with time. If incomplete sterilization were present in our data, we would expect effects on the spot rate to grow with time, which is the opposite of what we observe. For the purposes of our results, issuance of put options appears to be sterilized. The response of the interbank rate to call auctions is generally small and not statistically significant, suggesting that sterilization was also effective in this scenario.

Additional exercises in the Auxiliary Technical Appendix show responses of the different ways that the CBoC sterilizes its operations. Specifically, the central bank can expand its monetary base by either issuing repurchasing agreements (REPOS) as shown in Panes (a) and (b), or by buying domestic sovereign bonds as shown in Panes (c) and (d). The opposite holds for a monetary contraction. In sum, these operations respond to both foreign exchange intervention and government transfers made to the CBoC, in order to leave the monetary base unchanged (i.e. to minimize the distance between the policy rate and the interbank rate). As seen in the Auxiliary Appendix, the issuance of call options were mostly sterilized by REPOS. This result is consistent with the fact that call options were mostly exercised on the same day as the auction.

CBoC's discretionary interventions were not timed to coincide with rule-based intervention either. The fourth column of Table 8 measures whether the CBoC used discretionary mechanisms of intervention (mostly purchases of dollars) more or less after the rule-based intervention was triggered. In panel A, the CBoC shows no trend in discretionary interventions after rule-based purchases than otherwise. The coefficients are not statistically significant, and of inconsistent sign, and smaller in magnitude than the rule-based intervention (i.e. less than 115.6 million USD). Similarly, panel B shows that discretionary intervention does not coincide or counteract rule-based sales of dollars. The immediate response of discretionary intervention is marginally statistically significant but very small (190 thousand USD) and longer-term responses are statistically insignificant and of inconsistent sign. CBoC does not appear to use alternative discretionary foreign exchange intervention to complement or counteract rule-based intervention. Hence, the empirical results solely reflect the effects of the rule-based intervention.

5 Mechanisms of Foreign Exchange Market Intervention

5.1 Capital Controls and Covered Interest Rate Parity

In this section we investigate possible channels through which interventions in Colombia may work their way into the economy. We start with capital controls. If one country enacts capital controls, covered interest parity (CIP) no longer holds. For instance, if as in Colombia, the home country enacts a proportional tax on capital inflows, incumbent and new capital face different arbitrage conditions which provides space for sterilized FXI to move the exchange rate. Thus, during a period in which CIP is violated by restrictions on capital flows, sterilized foreign exchange intervention may be more effective because arbitrage is hindered. Farhi and Werning (2014) show in a New Keynesian model with nominal rigidities that capital controls play a role in optimal policy responses to sudden stops and capital inflow surges even in a flexible exchange rate environment. Other theoretical work arguing in favor of a role for capital controls in monetary policy include Devreux and Yetman (2014), Korinek and Sandri (2014) and Magud, Reinhart and Rogoff (2011), who also review the empirical literature. Recent empirical work investigating the effectiveness of capital controls using cross-country panel data includes Kaplan and Rodrik (2002), Ostry, Qureshi, Ghosh and Chamon (2011) and You, Kim and Ren (2014). This literature generally finds that capital controls are effective, and in the case of You et. al. that capital controls enhance the effectiveness of monetary policy. De Gregorio, Edwards and Valdes (2000) use univariate time series and VAR methods to investigate the effects of capital controls on capital flows in Chile and find a change in the composition of flows and a small effect on the exchange rate. Rincon and Toro (2011) analyze daily Colombian data using a GARCH model and find that a combination of capital controls and central bank interventions was effective in depreciating the currency without increasing volatility. Forbes and Warnock (2012) use data on gross- rather than net capital flows to investigate the relationship between the probability of sudden stops/surges and global factors. They find little relation between capital controls and flows.[12] Montiel and Reinhart (1999) consider a panel of emerging economies and find effects of sterilized interventions on short term capital flows. Capital controls on the other hand have an effect on the composition of flows, but not on the volume. Eichengreen and Rose (2014) and Fernandez, Rebucci and Uribe (2015) find no evidence of countercyclical capital control policies, but rather find that capital controls tend to be in place for extended periods of time. The latter fact poses problems for the empirical evaluation of capital controls because of a lack of variation in controls.

During our sample period, capital controls and other frictions were relevant. For instance, by financial regulation, banks had to have a positive foreign exposure (defined as net assets denominated in foreign currency relative to total capital) that did not exceeded 50% (see Garcia et al. 2015). Most of these measures were implemented to control for speculative attacks on the currency.

To alleviate data problems we use an empirical distinction between periods when CIP holds and does not hold rather than relying on conventional definitions of capital control episodes. This allows us to isolate periods when capital does not flow freely. Figure 13 graphs the spot peso/dollar exchange rate over our sample period against the spot rate implied by Colombian interest rates, US interest rates, and forward contracts for the peso/dollar exchange rate. Clearly, CIP holds at least approximately throughout our sample period with the actual spot rate closely following the value implied by CIP. However, CIP holds more in some periods than others. The right panel of Figure 13 uses interest rate, spot exchange rate, and forward exchange rate to compare the gross return to a 1 USD investment in US bonds versus

[12]See also Engle (2015) for a brief survey.

Colombian bonds (covered by a forward contract). CIP implies that these should be equal at all times; however, three distinct periods appear. In the middle of our sample from mid-2003 through mid-2008, CIP appears to hold. The returns to investing in Colombia and the US are quite similar. However, the two returns diverge at the beginning and end of our sample. At the beginning of our sample, a thin forward market for foreign exchange likely made it difficult in practice to cover exchange rate risk and the two returns diverged. At the end of our sample, restrictions on the movement of capital likely led to violations of CIP.

Having formed this division, we can then test for whether foreign exchange intervention by the CBoC was effective at all when CIP holds and if it becomes more effective when arbitrage was hampered by violations of CIP. Our split between periods when CIP holds and does not hold differs somewhat from that recorded in the existing literature, e.g. Magud et.al (2011) who focus on one major, explicitly defined capital control mechanism in Colombia. We instead focus on whether CIP holds for two reasons. First, practically, the time period defined by Magud et.al (2011) creates a very short capital controls period, which generates small sample problems empirically. Second, more importantly, whether CIP holds is itself the important distinction with regard to capital controls because, as argued by Backus and Kehoe (1989), CIP holding rules out a large number of mechanisms for the effectiveness of sterilized FXI. In a world where many small frictions prevent the flow of capital, whether CIP holds is a good summary of whether agents can arbitrage.

Interventions remain effective even when CIP holds closely but have greater effects when it does not. Figure 14 shows the one-day effects of purchasing dollars via issuing put options for the July 2003 – June 2008 period when CIP held and the pre-July 2003 and post-June 2008 periods when it did not. Figures 14 (a) and (c) display interventions with put auctions that led to spot rate appreciation of approximately 2 percent before July 2003 and after June 2008, which is larger than the measured effect during the middle period when CIP held. However, FXI through put options remains effective even when CIP holds. Table 9 quantifies the similarity of FXI effects between periods when CIP does and does not hold. Both time periods exhibit large, immediate appreciation of the exchange rate that fades quickly. Figures 14 (b) and (d) and the second panel of Table 9 show analogous results for the CBoC selling dollars via call options. Interestingly, the call intervention shows the expected negative sign during the non-CIP period, though this effect is statistically insignificant. Altogether, we find evidence that foreign exchange intervention affected the exchange rate to a larger extent in the intended direction when the covered interest rate parity condition was violated by thin forward markets or restrictions on international investment but that FXI effects remain even when arbitrage holds.

5.2 Order Flow

The literature on order flow emphasizes that the relative prevalence of bids and asks predicts short-run exchange rate movements better than traditional fundamentals. In such situations, central banks may retain some ability to manage exchange rates in the short run. Lyons (2001) and Evans and Lyons (2002a) pioneered work on using order flows. Evans and Lyons (2002b) propose a simulation based estimator of the non-linear impulse response function of an order flow shock on FX prices. Scalia (2008), building on Evans and Lyons (2002b), considers a model where central bank FX interventions change the effects of order flow on price while Girardin and Lyons (2008) investigate the effects of FX interventions on order flows. Here we similarly investigate whether FX interventions have any effect on order flows.

If short run imbalances between bids and asks were behind the exchange rate responses we observe then we should see a response of order flows to rule based policy interventions. We measure order flow as the relative frequency of bids and asks for currency. Our data on individual spot rate trades includes whether the trade originates as a bid, ask, or otherwise.[13] For any hour we can thus compute order flow as the difference in volume of bids and asks. Figure 15 shows the results of applying our regression discontinuity strategy using order flow as the outcome. Figure 15(a) shows the results for issuing put options and 15(b) for issuing call options. Neither analysis shows any signs that central bank intervention affects order flow. The estimated coefficients show no clear pattern and are generally statistically insignificant.

5.3 Capital Flows and Asset Balances

We turn our attention to portfolios held by domestic financial institutions. For the portfolio balance channel to be effective, sterilized foreign exchange intervention must change the composition of domestic and foreign assets held by financial institutions. In particular, sale of dollars (via call options) by the CBoC would decrease the monetary base of pesos. To sterilize the intervention, the CBoC buys peso-denominated bonds, restoring the monetary base to its previous level. However, this should decrease the amount of domestic bonds in circulation and thus increase the ratio of dollar-denominated to peso-denominated bonds on banks' balance sheets. Likewise, we would predict that a purchase of dollars via put options would decrease the ratio of dollar-denominated to peso-denominated bonds in circulation.

We use a daily panel of asset reports by the 5 largest Colombian banks to the CBoC to test whether the CBoC's rule-based intervention affected the ratio of dollar-denominated to peso-dominated assets. We first measure the ratio of net dollar-denominated assets, including loans and portfolio investment but ignoring forward contracts, to peso-denominated government bonds at these banks. These detailed data provide a unique view of the forces at work after a central bank intervention. The first column of Table

[13] We consider bids and asks, which comprise 79.4% of total trades we observe. The remainder, which we ignore for our order flow analysis, consists mostly of 'over the counter -OTC' bilateral trades.

10 shows the response of this asset ratio to issuing put and call options. First, consider puts. In panel A, we find suggestive evidence that domestic banks' relative holdings of foreign assets temporarily fall in response to CBoC's dollar purchases, as expected. This effect reaches its peak after about 3 weeks, and in the long run these banks re-balance their portfolios as the effect of intervention moves back to zero. The second column shows results for a similar asset ratio that now includes forward contracts for dollars as dollar-denominated assets. As is evident, central bank intervention does not affect asset ratios when including forward contracts. The coefficients are much smaller and consistently statistically insignificant. This result suggests that Colombian financial institutions only re-balance their assets in the short term. Central bank intervention leads them to quickly shed dollar-denominated loans and/or portfolio investments, but they simultaneously buy forward contracts for dollars, facilitating a shift back into dollar-denominated assets in the future. This evidence fits well with our prior result that rates in the forward market for pesos anticipate a temporary depreciation in response to CBoC issuing puts. The same columns of panel B shows the effects of issuing call options. We do not see strong evidence that CBoC selling dollars leads to an expected increase in the ratio of dollar to peso denominated assets in this case. This fits with our prior weaker results for call options.

We next turn our attention to capital in and outflows in response to sterilized foreign exchange interventions. When the CBoC purchases dollars through issuing put options, we expect two possible channels for adjustments. One is through put options that would lead to an increase in international reserves. A second channel is through the current account. As documented earlier, issuance of put options appreciates the exchange rate over a 60 day window. This depreciation of the peso implies a current account surplus that results in capital outflows.[14] For call options issuance we expect the same pattern with reversed signs.

We have access to daily capital flow data both in terms of net flows of foreign investors investing in Colombia as well as domestic investors investing in foreign assets. Forbes and Warnock (2012) emphasize the importance of considering both inflows and outflows separately when it comes to determining the factors that affect capital flows. They also discuss a large literature that is divided into a camp emphasizing external (push) forces driving capital flows and another camp focusing on domestic (pull) factors. In this paper, we identify variation in capital flows that is associated with domestic exchange rate policy. However, this does not mean that domestic factors are the only determinants of capital flows.

We first consider capital flows originating from domestic investors. The third column of Table 10 measures the effect of FXI on net flows for domestic investors. Capital flows from domestic investors do not respond significantly to the CBoC issuing either call or put options.

However, foreign investors respond with significant capital flows, at least eventually. The final column

[14] see for example Magud et.al. (2011) p.20.

of Table 10 shows effects on net capital flows from foreign investors. For put options we see a particularly interesting trend. Foreign flows respond to CBoC intervention very little at first, about 5 million USD in the first 10 days. After this point, foreign capital flows accelerate leading to large capital outflows of 100 million USD after 60 days.

The responses we find confirm predictions of portfolio balance models, including the Gamma model advocated by Gabaix and Maggiori (2015). The 'risk bearing capacity' of financial intermediaries determines the elasticity of their demand of foreign assets. As risk aversion vanishes their model converges to the frictionless case where asset ratios do not respond to central bank purchases or sales of domestic assets. We see a temporary response in domestic bank asset ratios that fades over time. The response of domestic banks is consistent with risk aversion in light of the Gamma model: holding a sub-optimal ratio of dollar to peso denominated assets requires a market adjustment via temporary depreciation of the peso. On the other hand, we also observe a slow outflow of foreign investment that persists in the long run. Such flows suggest the existence of large, risk-neutral global investors. These actors cannot fully arbitrage away exchange rate depreciation in the short run due to financial market frictions, but within weeks they initiate capital outflows that restore the spot exchange rate to equilibrium. Thus, we find results consistent with a portfolio balance channel that allow sterilized FXI to move the exchange rate, but only temporarily.

6 Conclusion

Exchange rate interventions remain important tools of central banks aimed at stabilizing the domestic economy and shielding it from global shocks. Yet, standard theory suggests that such interventions are not effective and recent evidence suggests that there exist strong global factors that limit central bank independence. We use a unique policy environment in Colombia to shed new light on foreign exchange interventions from an empirical perspective. During our sample period, the Colombian central bank generally allowed the peso to float freely while at the same time engaging in rule based sporadic interventions mostly aimed at curtailing exchange rate volatility. Rule based interventions make it possible to identify policy variation with regression discontinuity methods so far not utilized in macro data. In addition we have access to data that allow us to track tick-by-tick exchange rate movements as well as daily administrative data on bank balance sheets and capital flows. These data not only provide measures of the effects of interventions at various levels of resolution but also enable us to dissect the channels through which interventions affect exchange rates.

We find short run effects of foreign exchange interventions at horizons of one hour up to one month after the intervention. There is some evidence of asymmetric effects with dollar purchases by the CBoC having a somewhat stronger effect. In our data, Colombian financial institutions respond to central bank interventions with portfolio adjustments that are consistent with a 'limited risk bearing capacity' as defined by Gabaix and Maggiori (2015). Risk aversion of financial intermediaries reduces their demand elasticity for foreign assets, requiring an exchange rate move to restore financial market equilibrium. Consistent with the Gamma model of Gabaix and Maggiori (2015) we find that the demand elasticity of financial institutions is further reduced with capital controls in effect. Capital flows originating from abroad subsequent to an exchange rate move are suggestive of large risk neutral global investors bringing the exchange rate back to its pre-intervention level over the span of roughly a month after the intervention.

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A Model and Assumptions

Let χ_t be a strictly stationary stochastic process defined on a probability space $(\Omega, \mathcal{F}, P)$ and taking values in $\mathbb{R}^d$. Let $\mathcal{F}_l^k = \sigma(\chi_t : l \leq t \leq k)$ be the sigma field generated by $\{\chi_t\}_{t=l}^k$. The strong mixing coefficient α_m is defined as

$$\alpha_m = \sup_{A \in \mathcal{F}_{-\infty}^0, B \in \mathcal{F}_m^\infty} |P(A \cap B) - P(A)P(B)|.$$

The process χ_t is called strongly mixing (Doukhan, 1994) if $\alpha_m \to 0$ as $m \to \infty$.

The parameter of interest is the expectation of the impulse response $\theta_j^D(\chi_t)$ conditional on $X_t = c$, given by

$$\theta_j(c) = E\left[\theta_j^D(\chi_t) | X_t = c\right].$$

The parameter $\theta_j(c)$ is well defined by Assumption 1 and can be estimated by local linear regression (LLR) as advocated in HTV. LLR goes back to Fan (1992) and was studied in the context of regression discontinuity designs in HTV and Porter (2003). Masry and Fan (1997) establish asymptotic properties as well as bandwidth selection rules for LLR with dependent data.

Imbens and Lemieux (2008) note that the combined method of HTV can be represented in a numerically equivalent regression using appropriate dummies and interaction terms. The advantage of their formulation in our context is that it automatically produces joint inference that accounts for the (temporal) dependence in our data. An additional complication that arises in our case is the fact that we may also be interested in the joint distribution of estimators of all $\theta_j(c)$ for $j = 0, ..., J$. Neither the RD design nor the inclusion of multiple outcomes does directly correspond to the model considered in Masry and Fan (1997). The necessary extensions are given here. Thus, let $a = (a_1, ..., a_J)'$, $b = (b_1, ..., b_J)$, $\gamma = (\gamma_1, ..., \gamma_J)'$ and $\theta = (\theta_1(c), ..., \theta_J(c))'$. Extending Imbens and Lemieux (2008) define the estimator $\hat{\theta}$ of the parameter θ as the solution to

$$\left(\hat{a}, \hat{b}, \hat{\gamma}, \hat{\theta}\right) = \underset{a,b,\gamma,\theta}{\arg\min} \sum_{j=1}^{J} \sum_{t=1}^{T-J} \left(y_{t+j} - a_j - b_j(X_t - c) - \theta_j D_t - \gamma_j (X_t - c) D_t\right)^2 K\left(\frac{X_t - c}{h}\right)$$

where $K(.) \geq 0$ is a kernel function and h is a bandwidth parameter, both to be specified in more detail below. Let $\Pi = (a, b, \theta, \gamma)$, be a $J \times 4$ matrix of parameters, $Y_t = (y_{t+1}, ..., y_{t+J})'$ and $Z_t = (1, (X_t - c), D_t, (X_t - c) D_t)'$. Now define the data-matrices $Y = (Y_1, ...Y_{T-J})'$, $Z = (Z_1, ...Z_{T-J})'$ and $W = \text{diag}(K((X_1 - c)/h), ..., K((X_{T-J} - c)/h))$. Then, similar to Masry and Fan (1997, p.167), the estimator can be written in closed form as

$$\text{vec}\,\hat{\Pi}' = \left(I_J \otimes (Z'WZ)^{-1} Z'W\right) \text{vec}\, Y$$

where I_J is the $J \times J$ dimensional identity matrix. The expression for $\hat{\Pi}$ is formally the same as for weighted least squares in a system of seemingly unrelated regressions (SUR) and indicates that $\hat{\theta}_j$ for a particular horizon j can be obtained by an individual weighted least squares regression for that horizon with the weights given by the kernel function. However, for joint inference on θ the joint distribution of these estimators needs to be derived. The following assumptions correspond to assumptions made in Masry and Fan (1997).

Assumption 2 *(i)Let $f(x)$ be the marginal distribution of X_t. Assume that $f(x)$ is continuous and bounded.*
(ii) $|f_l(u,v) - f(u)f(v)| \leq M < \infty$ for all $l > 0$ where $f_l(u,v)$ is the joint density of X_0 and X_l.
(iii) The process χ_t is strong mixing with $\sum_{m=1}^{\infty} m^a \alpha_m^{1-2/\delta} < \infty$ for some $\delta > 2$ and $a > 1 - 2/\delta$.
(iv) The kernel function $K(.)$ is a bounded density function satisfying $u^{4\delta+2}K(u) \to 0$ as $|u| \to \infty$.

Assumption 3 *(i) The kernel $K(.)$ is bounded with bounded support $[-1,1]$.*
(ii) Assume that $f_l(u,v) \leq M_1$ and $E\left[y_1^2 + y_j^2 | X_0 = u, X_l = v\right] \leq M_2 < \infty$ for all l and u,v in a neighborhood of c.
(iii) Let $\Sigma(x) = \text{Var}(Y_t|X_t = x)$ and assume that $\Sigma(x)$ is positive definite and bounded for all x. For $\delta > 2$ as in Assumption 2, $E\left[|y_1|^\delta |X = u\right] \leq M_3 < \infty$ for all u in a neighborhood of c.
(iv) assume $h_T \to 0$ and $Th_T \to \infty$. (we often used the notation h instead of h_T). Assume that there is a sequence $s_T > 0$ such that $s_T \to \infty$ and $s_T = o\left((Th_T)^{1/2}\right)$ such that $(T/h_T)^{1/2} \alpha_{s_T} \to 0$ as $T \to \infty$.

An additional set of technical assumptions specific to the RD estimator are similar to assumptions made in HTV.

Assumption 4 *Let $m_j(x) = E[y_{t+j}|X_t = x]$, $m_j^+(x_0) = \lim_{x \to x_0^+} E[y_{t+j}|X_t = x]$ and*

$$m_j^-(x_0) = \lim_{x \to x_0^-} E[y_{t+j}|X_t = x].$$

For $x > c$, assume that $m_j^+(x)$ is twice continuously differentiable with uniformly bounded derivatives $m_j^{'+}(x), m_j^{''+}(x)$ on $(c, c+M]$. Similarly, for $x < c$, $m_j^-(x)$ is twice continuously differentiable with uniformly bounded derivatives $m_j^{'-}(x), m_j^{''-}(x)$ on $(c-M, c)$ for some M. Let $\Sigma^+(x_0) = \lim_{x \to x_0^+} \text{Var}(Y_t|X_t = x)$, $\Sigma^-(x_0) = \lim_{x \to x_0^-} \text{Var}(Y_t|X_t = x)$ and assume that $\Sigma^+(x_0), \Sigma^-(x_0)$ are positive definite for $x_0 = c$.

B Results

This section summarizes the results for the identification of the impulse response function and the asymptotic distribution of individual impulse response parameters. The latter is useful for optimal bandwidth selection which leads to similar results as in Masry and Fan (1997) and Imbens and Kalyanaraman (2012). Additional results regarding the joint limiting distribution of vec $\hat{\Pi}'$ are given in a supplemental appendix. We start with a result on the identification of the impulse response function.

Theorem 5 *Assume that there is a non-random function $g : \mathbb{R}^d \to \mathbb{R}$ of χ_t such that $g(\chi_t) = X_t$ and c is a known threshold. Let $D_t = 1\{X_t > c\}$. If Assumption 1 holds, it follows that*

$$\theta_j(c) = \lim_{x \to c^+} E[y_{t+j} | X_t = x] - \lim_{x \to c^-} E[y_{t+j} | X_t = x]$$

Assume that there exists at least one continuous path $\varepsilon(\delta) : [0, \infty) \to \mathbb{R}^d$ such that $g(\chi_t + \varepsilon(\delta)) - g(\chi_t) = \delta$ for all $\delta \geq 0$ and $\varepsilon(0) = 0$. Assume that $E[F_{t,j}(D_t, \chi_t) | \chi_t = x]$ is continuous in x a.s., $|E[F_{t,j}(D_t, \chi_t) | \chi_t]| \leq B(\chi_t)$ and $E[B(\chi_t) | X_t = c] < \infty$ a.s. Let $\theta_j(\varepsilon, \chi_t) = F_{t,j}(D_t(\chi_t + \varepsilon), \chi_t + \varepsilon) - F_{t,j}(D_t(\chi_t), \chi_t)$. Then it follows that

$$\theta_j(c) = \lim_{\delta \downarrow 0} E[\theta_j(\varepsilon(\delta), \chi_t) | X_t = c].$$

Remark 1 *Note that the local conditional independence assumption used in HTV, Theorem 2 is not required here because we only consider sharp regression discontinuity designs.*

We introduce the following notation which is needed to describe the asymptotic distributions. Let $\mu_{lk} = \int_{-\infty}^{\infty} 1\{u > 0\}^k u^l K(u)\, du$ and define the matrix

$$\Gamma = \begin{bmatrix} \mu_{00} & \mu_{10} & \mu_{01} & \mu_{11} \\ \mu_{10} & \mu_{20} & \mu_{11} & \mu_{21} \\ \mu_{01} & \mu_{11} & \mu_{01} & \mu_{11} \\ \mu_{11} & \mu_{21} & \mu_{11} & \mu_{21} \end{bmatrix}.$$

Let $v_l^+ = \int_0^{\infty} u^l K^2(u)\, du$ and $v_l^- = \int_{-\infty}^0 u^l K^2(u)\, du$ and define the matrices

$$V^+ = \begin{bmatrix} v_0^+ & v_1^+ \\ v_1^+ & v_2^+ \end{bmatrix},\ V^- = \begin{bmatrix} v_0^- & v_1^- \\ v_1^- & v_2^- \end{bmatrix},$$

and

$$\Omega^{+}=\left[\begin{array}{cc} V^{+} & V^{+} \\ V^{+} & V^{+} \end{array}\right],\ \Omega^{-}=\left[\begin{array}{cc} V^{-} & 0 \\ 0 & 0 \end{array}\right]$$

Also define

$$\Lambda_{lk}^{-}=1\{k=0\}\int_{-\infty}^{0}u^{l+2}K(u)\,du$$

and

$$\Lambda_{lk}^{+}=\int_{0}^{\infty}u^{l+2}K(u)\,du$$

and let $\Lambda^{-}=\left(\Lambda_{00}^{-},\Lambda_{10}^{-},\Lambda_{01}^{-},\Lambda_{11}^{-}\right)'$ and similarly for $\Lambda^{+}=\left(\Lambda_{00}^{+},\Lambda_{10}^{+},\Lambda_{01}^{+},\Lambda_{11}^{+}\right)'$ as well as $m''^{-}(c)=\left(m_0''^{-}(c),....,m_J''^{-}(c)\right)'$ and similarly for $m''^{+}(c)$. Let b^{+} be the third element of $\Gamma^{-1}\Lambda^{+}$, b^{-} the third element of $\Gamma^{-1}\Lambda^{-}$, ω^{+} the third diagonal element of $\Gamma^{-1}\Omega^{+}\Gamma'^{-1}$ and ω^{-} the third diagonal element of $\Gamma^{-1}\Omega^{-}\Gamma'^{-1}$.To consider the limiting distribution of an individual impulse coefficient $\hat{\theta}_j$ for the response at horizon j let $\sigma_{+j}^{2}(c)$ be the corresponding diagonal element of $\Sigma^{+}(c)$ and $\sigma_{-j}^{2}(c)$ the corresponding diagonal element of $\Sigma^{-}(c)$. We obtain the following result.[15]

Theorem 6 *Assume that Assumptions 1-4 hold and that $h=O\left(T^{-1/5}\right)$. Then,*

$$\sqrt{Th}\left(\hat{\theta}_j-\theta_j-\frac{h^2}{2}\left(m_j''^{-}(c)\,b^{-}+m_j''^{+}(c)\,b^{+}\right)\right)\rightarrow_d N\left(0,f(c)^{-1}\left(\sigma_{+j}^{2}(c)\,\omega^{+}+\sigma_{-j}^{2}(c)\,\omega^{-}\right)\right)$$

as $T\rightarrow\infty$.

The result in Theorem 6 can be used to obtain optimal bandwidth rules analogous to the ones obtained by Masry and Fan (1997) and Imbens and Kalyanaraman (2012). For a given horizon j the optimal bandwidth rule is given by

$$h_{opt,j}=\left(\frac{\sigma_{+j}^{2}(c)\,\omega^{+}+\sigma_{-j}^{2}(c)\,\omega^{-}}{f(c)\left(m_j''^{-}(c)\,b^{-}+m_j''^{+}(c)\,b^{+}\right)^2}\right)^{1/5}T^{-1/5}$$

Note that we are not assuming $b^{-}=-b^{+}$. However, with a symetric kernel it follows that $b^{-}=-b^{+}$ and $\omega^{+}=\omega^{-}$. The bandwidth formula then futher simplifies to

$$h_{opt,j}=\left(\frac{\omega^{+}}{(b^{+})^2}\right)^{1/5}\left(\frac{\sigma_{+j}^{2}(c)+\sigma_{-j}^{2}(c)}{f(c)\left(m_j''^{-}(c)-m_j''^{+}(c)\right)^2}\right)^{1/5}T^{-1/5}$$

[15] Results for the joint distribution of all parameters as well as optimal bandwidth rules for averages of responses are available in a supplementary appendix.

which corresponds to the plug in formula of Imbens and Kalyanaraman (2012). For example, for the Bartlett kernel $K(u) = (1 - |u|)\,1\{|u| \leq 1\}$ it can be shown that $\omega^+ = \omega^- = 24/5$ and $b^- = -b^+ = 1/10$ which leads to $\left(\omega^+ / (b^+)^2\right)^{1/5} = 2\,(15)^{1/5} \approx 3.4375$. This is the same as the constant obtained in Imbens and Kalyanaraman (2012).

C Data

1. Exchange rate: tick-by-tick (3.5 million) foreign exchange transactions from SET-ICAP FX S.A. (financial broking services entity). Data include order flow and closing price for each trade.

2. Central bank intervention data: Daily data from the Market Operations and Development Department (*Departamento de Operaciones y Desarrollo de Mercados -Mesa de Dinero*). Data include: (i) Rule-based intervention (option premiums, amount bid, and dates in which options were triggered, issued and exercised), and (ii) Discretionary intervention (orders in the spot market and option information -same as rule-based intervention, for discretionary mechanisms).

3. Capital flows: Daily data from the International Affairs Department (*Departamento de Cambios Internacionales*). Data include: (i) foreign investment on domestic portfolio (inflows and outflows), and (ii) domestic investment on foreign portfolio (inflows and outflows).

4. Central bank Sterilization Operations: Daily data from the International Affairs Department (*Departamento de Cambios Internacionales*). Data include: (i) Repurchasing agreements issued by the central bank to expand the monetary base, and (ii) Domestic sovereign bond operations (Colombian treasuries entitled *TES*).

5. Financial Sector balances: Daily data from the Market Operations and Development Department (*Departamento de Operaciones y Desarrollo de Mercados -Mesa de Dinero*). Data include: (i) foreign holdings of the financial sector as well as of the five largest commercial banks (net assets and equity denominated in domestic and foreign currency), and (ii) exchange rate forwards (date and amounts when forwards were issued and exercised).

6. Other central bank data: Public daily data that includes: (i) the central bank policy rate, (ii) the inter-bank rate, and (iii) international reserves.[16]

[16] See the following website: http://www.banrep.gov.co/es/-estadisticas.

D Tables

Table 1: Timing and Description of Rule-Based Interventions

Time Frame	Description of when rule was triggered
Dec 24, 2001 - Dec 16, 2005	Whenever the exchange rate was 4% above/below its last 20 day MA
Dec 19, 2005 - Jun 24, 2008	Whenever the exchange rate was 2% above/below its last 20 day MA
Jun 25, 2008 - Oct 06, 2008	Intervention mechanism was temporarily stopped
Oct 07, 2008 - Oct 28, 2009	Whenever the exchange rate was 5% above/below its last 20 day MA
Oct 29, 2009 - Oct 28, 2011	Intervention mechanism was temporarily stopped
Oct 31, 2011 - Feb 03, 2012	Whenever the exchange rate was 4% above/below its last 20 day MA
Feb 06, 2012 - Onwards	Intervention mechanism was permanently stopped

SOURCE: Central Bank of Colombia. MA stands for Moving Average.

Table 2: Descriptive Statistics

Variable	Full Sample Mean	Full Sample St.Dev	Full Sample Obs	CIP Mean	CIP St.Dev	No CIP Mean	No CIP St.Dev
Central Bank Sterilization Operations							
Repurchasing Agreements[a]	2956	2534	1950	2851	1977	3085	3077
COL Treasuries[a]	-2.3	45.4	1950	-4.3	52.8	0.01	34.1
Financial Sector Balances							
COL Treasuries of 5 largest banks[a]	13588	4030	1799	11315	2395	17963	2714
US/COL net assets (PP) of 5 largest banks[b]	0.02	0.02	1794	0.02	0.01	0.01	0.01
US/COL net assets (PPC) of 5 largest banks[b]	0.13	0.10	1799	0.13	0.10	0.13	0.08
USD net assets (PPC) of 5 largest banks[c]	532	390	1799	443	377	703	355
USD net assets (PPC) of financial sector[c]	879	533	1799	768	534	1093	463
USD net assets/capital (PPC) of 5 largest banks	0.13	0.06	1799	0.14	0.05	0.11	0.06
USD net assets/capital (PPC) of financial sector	0.09	0.04	1799	0.10	0.03	0.08	0.04
Capital Flows							
Portfolio Inflows (Domestic Investors)[c]	28.7	36.7	2433	37.1	38.2	20.5	33.1
Portfolio Outflows (Domestic Investors)[c]	30.1	38.4	2433	37.5	40.1	23.1	35.4
Net Portfolio Flows (Domestic Investors)[c]	-1.54	27.7	2433	-0.42	31.7	-2.62	23.06
Portfolio Inflows (Foreign Investors)[c]	2.9	9.8	2433	2.5	7.5	3.2	11.6
Portfolio Outflows (Foreign Investors)[c]	1.7	6.9	2433	1.4	6.2	1.9	7.3
Net Portfolio Flows (Foreign Investors)[c]	1.2	11.5	2433	1.05	9.7	1.3	12.9
Macroeconomic Variables							
Policy Rate (%)	6.4	2.03	2432	7.4	1.2	4.4	2.2
Interbank rate (%)	6.4	2.02	2432	7.3	1.2	5.3	2.1
International Reserves[c]	17975	6688	2347	14966	3659	2180	7623
Exchange rate (COP/USD) Amount Traded[c]	0.67	1.31	$3.5\text{x}10^6$	0.69	1.18	0.66	1.36
Exchange rate (COP/USD) Closing Price	2080	295.3	$3.5\text{x}10^6$	2264	299.8	1998	253.4
Exchange rate (COP/USD) 6-month Forwards	2203	357.5	1103	2385	269.7	2078	356.8
Rule-Based FX Intervention (Auctions)							
Frequency of Call Options Triggered (%)	4.63	21.01	2433	5.20	22.21	4.05	19.72
Frequency of Call Options Issued (%)	0.70	8.33	2433	0.75	8.66	0.65	8.01
Frequency of Call Options Exercised (%)	1.40	11.74	2433	1.50	12.20	1.29	11.29
Frequency of Put Options Triggered (%)	5.95	23.66	2433	9.97	29.97	1.81	13.33
Frequency of Put Options Issued (%)	0.86	9.25	2433	1.34	11.51	0.40	6.34
Frequency of Put Options Exercised (%)	1.69	12.87	2433	2.77	16.41	0.65	8.01

Authors' Calculations. Sample period corresponds to Dec 2001-Feb 2012. CIP -Covered Interest rate Parity- corresponds to Jul 2003-Jun 2008 (49% of sample). (^{a}) denote variables in billions (10^9) of pesos -COP. (^{b}) denote ratios of USD-to-COP denominated assets, expressed in COP. (^{c}) denote variables in millions of dollars -USD. PP (*Posicion Propia*) and PPC (*Posicion Propia de Contado*) include and exclude positions in derivatives, respectively.

Table 3: Descriptive Statistics: ± 20% below or above threshold for daily variables

	Put missed		Put triggered		Call missed		Call triggered	
Variable	Mean	St.Dev	Mean	St.Dev	Mean	St.Dev	Mean	St.Dev
Central Bank Sterilization Operations								
Repurchasing Agreements[a]	2962	2851	4050	2486	1517	1918	2503	1933
COL Treasuries[a]	-10.4	46.27	1.31	30.79	3.19	10.68	5.75	30.43
Financial Sector Balances								
COL Treasuries of 5 largest banks[a]	13874	3072	14870	2599	14457	2701	14694	1927
US/COL net assets (PP) of 5 largest banks[b]	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02
US/COL net assets (PPC) of 5 largest banks[b]	0.17	0.10	0.21	0.11	0.20	0.13	0.21	0.12
USD net assets (PPC) of 5 largest banks[c]	718	490	903	458	693	398	738	357
USD net assets (PPC) of financial sector[c]	1133	620	1332	611	1099	545	1170	467
USD net assets/capital (PPC) of 5 largest banks	0.13	0.07	0.16	0.06	0.14	0.06	0.16	0.05
USD net assets/capital (PPC) of financial sector	0.11	0.04	0.12	0.04	0.11	0.04	0.13	0.04
Capital Flows								
Portfolio Inflows (Domestic Investors)[c]	40.51	30.72	61.60	45.69	38.15	46.79	39.64	43.64
Portfolio Outflows (Domestic Investors)[c]	37.79	35.57	58.16	36.63	37.46	40.87	53.85	45.79
Net Portfolio Flows (Domestic Investors)[c]	2.72	30.15	3.45	41.48	0.70	30.68	-14.21	26.36
Portfolio Inflows (Foreign Investors)[c]	3.73	7.54	5.60	14.51	0.77	1.57	1.08	2.45
Portfolio Outflows (Foreign Investors)[c]	3.22	10.21	3.14	11.05	2.08	90.31	8.87	20.79
Net Portfolio Flows (Foreign Investors)[c]	0.51	13.39	2.47	18.98	-1.30	9.17	-7.79	20.13
Macroeconomic Variables								
Policy rate (%)	7.26	1.88	7.88	1.81	6.77	1.93	7.74	1.85
Interbank rate (%)	7.20	1.82	7.81	1.75	6.73	1.91	7.71	1.84
International Reserves[c]	19325	3882	20344	3351	15730	5436	17810	5134
Exchange rate (COP/USD) Amount Traded[c,d]	837	310	980	400	655	250	719	293
Exchange rate (COP/USD) Closing Price	2083	235	2074	188	2444	264	2431	203
Exchange rate (COP/USD) 6-month Forwards	2109	218	2144	167	2506	245	2491	173
Rule-Based FX Intervention (Auctions)								
Frequency of Call Options Triggered (%)	0	0	0	0	0	0	100	0
Frequency of Call Options Issued (%)	0	0	0	0	0	0	24	43
Frequency of Call Options Exercised (%)	0	0	0	0	0	0	62	49
Frequency of Put Options Triggered (%)	0	0	100	0	0	0	0	0
Frequency of Put Options Issued (%)	0	0	20	40	0	0	0	0
Frequency of Put Options Exercised (%)	0	0	38	49	0	0	0	0

Authors' Calculations. Sample period corresponds to Dec 2001-Feb 2012. ([a]) denote variables in billions (10^9) of pesos -COP. ([b]) denote ratios of USD-to-COP denominated assets, expressed in COP. ([c]) denote variables in millions of dollars -USD. ([d]) corresponds to aggregated daily data collapsed from tic-to-tic transactions. PP (*Posicion Propia*) and PPC (*Posicion Propia de Contado*) include and exclude positions in derivatives, respectively.

Table 4: Same Day Effects of Intervention (Puts)

Outcome	Full Sample	Outstanding Options	No Outstanding Options
Quantity of Put Options	46***	–	116***
Auctioned (million USD)	(13)	(–)	(23)
Quantity of Exercised Options	24***	24***	20*
(million USD)	(7)	(8)	(11)
Log Exchange Rate 1-day Lead	0.004**	-0.001	0.008***
(COP/USD)	(0.002)	(0.002)	(0.003)

The sample is a time series of days for the time period when rule-based foreign exchange interventions were in place in Colombia. The time period includes all days from December 24, 2001 to February 3, 2012 excluding October 29, 2009 to February 26, 2010 when the rule-based mechanism was temporarily suspended. Options refer to options to buy or sell dollars at CBoC. Exchange rates are measured as the difference between the log average daily exchange rate the day of the intervention and the day before the intervention. Each listed coefficient results from a separate regression discontinuity model implemented using local linear regression on daily data with optimal bandwidth from Imbens and Kalyanaraman (2012). Heteroskedasticity-robust standard errors are in parentheses.

Table 5: Same Day Effects of Intervention (Calls)

Outcome	Full Sample	Outstanding Options	No Outstanding Options
Quantity of Call Options	39***	9	122***
Auctioned (million USD)	(11)	(7)	(31)
Quantity of Exercised Options	42***	33***	72***
(million USD)	(10)	(12)	(20)
Log Exchange Rate 1-day Lead	0.001	-0.001	0.003*
(COP/USD)	(0.002)	(0.003)	(0.002)

The sample is a time series of days for the time period when rule-based foreign exchange interventions were in place in Colombia. The time period includes all days from December 24, 2001 to February 3, 2012 excluding October 29, 2009 to February 26, 2010 when the rule-based mechanism was temporarily suspended. Options refer to options to buy or sell dollars at CBoC. Exchange rates are measured as the difference between the log average daily exchange rate the day of the intervention and the day before the intervention. Each listed coefficient results from a separate regression discontinuity model implemented using local linear regression on daily data with optimal bandwidth from Imbens and Kalyanaraman (2012). Heteroskedasticity-robust standard errors are in parentheses.

Table 6: Effects on the 1-Day Lag of the Spot Exchange Rate

Type of Options	Full Sample	Outstanding Options	No Outstanding Options
Puts	0.001	0.002	0.001
(million USD)	(0.001)	(0.002)	(0.002)
Calls	0.001	0.002	0.001
(million USD)	(0.001)	(0.002)	(0.002)

The sample is a time series of days for the time period when rule-based foreign exchange interventions were in place in Colombia. The time period includes all days from December 24, 2001 to February 3, 2012 excluding October 29, 2009 to February 26, 2010 when the rule-based mechanism was temporarily suspended. Options refer to options to buy or sell dollars at CBoC. Lagged exchange rates are measured as the difference between the log average daily exchange rate the day before the intervention and two days before the intervention. Each listed coefficient results from a separate regression discontinuity model implemented using local linear regression on daily data with optimal bandwidth from Imbens and Kalyanaraman (2012). Heteroskedasticity-robust standard errors are in parentheses.

Table 7: Test of Locally Balanced Covariates (OLS)

	(1)	(2)	(3)	(4)
	Call Issuance	Put Issuance	Call Exercising	Put Exercising
Quartic Polynomial in Running Variable	Yes	Yes	Yes	Yes
Lags of Exchange Rate Changes	Yes	Yes	Yes	Yes
Lags of Negotiated FX Forwards	Yes	Yes	Yes	Yes
Lags of Exercised FX Forwards	Yes	Yes	Yes	Yes
Lags of Inter Bank Rate	Yes	Yes	Yes	Yes
Chi Squared	11.2	5.88	13.2	11.4
p-value	0.19	0.66	0.11	0.18
R-Squared	0.55	0.64	0.78	0.79
N	2350	2350	2350	2350

The sample is a time series of days for the time period when rule-based foreign exchange interventions were in place in Colombia. The time period includes all days from December 24, 2001 to February 3, 2012 excluding October 29, 2009 to February 26, 2010 when the rule-based mechanism was temporarily suspended. Each column runs a linear regression on daily data with a treatment dummy for the listed action on a quartic polynomial in the running variable as well as two daily lags of the listed observable variables. χ^2 and its associated p-value provide a joint test of the null that all variables other than the running variable have zero coefficients. This test uses heteroskedasticity and autocorrelation-robust standard errors.

Table 8: Short and Medium Run Effects of FXI: Interventions and Spot Exchange Rate

	Options Issued	Log Exchange Rate	Interbank Rate	Discretionary FXI
A. Puts				
1 Day	115.6***	0.0085***	0.0030	38.5
	(23.3)	(0.0033)	(0.025)	(44.5)
10 Days	3.12	0.017*	-0.098	-2.64
	(26.3)	(0.0094)	(0.090)	(73.5)
20 Days	-20.8	0.0013	-0.12	51.7
	(32.9)	(0.0091)	(0.11)	(118.3)
30 Days	-8.03	-0.0021	-0.13	27.0
	(50.8)	(0.013)	(0.19)	(118.4)
60 Days	-54.3	0.0086	-0.44	18.7
	(69.9)	(0.024)	(0.29)	(220.8)
B. Calls				
1 Day	122.2***	0.0031*	-0.0060	0.19*
	(31.4)	(0.0017)	(0.033)	(0.10)
10 Days	86.4**	-0.031***	-0.095	3.70
	(42.7)	(0.0081)	(0.073)	(5.16)
20 Days	71.3*	-0.018	0.068	32.6
	(41.9)	(0.015)	(0.11)	(20.8)
30 Days	26.2	-0.033	0.016	34.5
	(49.5)	(0.024)	(0.15)	(21.9)
60 Days	-56.9	-0.017	-0.037	-56.6
	(80.6)	(0.021)	(0.25)	(51.3)

The sample is a time series of days for the time period when rule-based foreign exchange interventions were in place in Colombia. The time period includes all days from December 24, 2001 to February 3, 2012 excluding October 29, 2009 to February 26, 2010 when the rule-based mechanism was temporarily suspended. Each listed coefficient results from a separate regression discontinuity model implemented using local linear regression on daily data with optimal bandwidth from Imbens and Kalyanaraman (2012). The first panel measures the effect of issuing put options (purchases of dollars by CBoC) and the second panel measures calls (sales). Rows denote outcomes X days since the intervention. Options measure the cumulative quantity of options issued, in millions of USD, by CBOC since the original intervention was triggered. Discretionary FXI measures the same outcome for discretionary rather than rule-based interventions by CBoC. Exchange rates and the interbank interest rate are measured as changes relative to the day before the original intervention. Heteroskedasticity-robust standard errors are in parentheses. ***, **, and * denotes statistical significance at the 1, 5, and 10 percent level respectively.

Table 9: Heterogeneous Effects of FXI by whether CIP Holds

	CIP Holds Log Exchange Rate	CIP Does Not Hold Log Exchange Rate	CIP Holds Foreign Flows	CIP Does Not Hold Foreign Flows
A. Puts				
1 Day	0.0071**	0.019**	6.35	-15.2
	(0.0036)	(0.0091)	(6.42)	(22.0)
10 Days	0.010	0.012	-27.0	6.34
	(0.013)	(0.022)	(26.8)	(25.8)
20 Days	-0.0037	-0.010	-55.3	-30.5
	(0.013)	(0.016)	(36.2)	(42.6)
30 Days	0.0024	-0.0032	-84.5*	-55.7
	(0.014)	(0.040)	(47.4)	(42.3)
60 Days	0.042	-0.025	-191.0**	-65.2**
	(0.029)	(0.053)	(76.6)	(33.3)
B. Calls				
1 Day	0.0030	-0.0011	0.33	0.014
	(0.0020)	(0.0023)	(2.15)	(0.74)
10 Days	-0.042***	-0.034***	49.1**	3.93
	(0.012)	(0.0088)	(24.6)	(4.96)
20 Days	-0.024	-0.030	107.8***	26.9
	(0.016)	(0.026)	(38.4)	(19.8)
30 Days	-0.035*	-0.044	110.5**	28.0
	(0.021)	(0.039)	(50.5)	(22.1)
60 Days	0.0093	-0.015	97.8	22.3
	(0.027)	(0.026)	(72.6)	(19.6)

The sample is a time series of days for the time period when rule-based foreign exchange interventions were in place in Colombia. The full time period includes all days from December 24, 2001 to February 3, 2012 excluding October 29, 2009 to February 26, 2010 when the rule-based mechanism was temporarily suspended. The period when CIP holds refers to the middle of the sample between July 1, 2003 and June 30, 2008, and the remainder of the period composes the period when CIP does not hold. Columns indicating each period are estimated only on that sub-sample. Each listed coefficient results from a separate regression discontinuity model implemented using local linear regression on daily data with optimal bandwidth from Imbens and Kalyanaraman (2012). The first panel measures the effect of issuing put options (purchases of dollars by CBoC) and the second panel measures calls (sales). Rows denote outcomes X days since the intervention. Exchange rates are measured as changes relative to the day before the original intervention. Foreign flows are net portfolio inflows initiated by foreign investors cumulatively measured since the original intervention, in millions of USD. Heteroskedasticity-robust standard errors are in parentheses. ***, **, and * denotes statistical significance at the 1, 5, and 10 percent level respectively.

Table 10: Short and Medium Run Effects of FXI: Capital Flows

	Dollar/Peso Assets	Dollar/Peso (w/ forwards)	Domestic Flows	Foreign Flows
A. Puts				
1 Day	0.0033	-0.0010	5.72	5.71
	(0.0045)	(0.0019)	(13.2)	(6.13)
10 Days	-0.021	0.0020	-7.68	5.56
	(0.018)	(0.0033)	(40.1)	(17.8)
20 Days	-0.033*	0.0040	-46.6	-18.2
	(0.018)	(0.0037)	(61.8)	(24.3)
30 Days	-0.012	0.0037	-13.8	-50.6
	(0.028)	(0.0038)	(89.3)	(34.9)
60 Days	-0.0062	0.0040	-75.7	-100.3*
	(0.035)	(0.0037)	(98.8)	(51.7)
B. Calls				
1 Day	-0.0049	-0.00047	5.90	0.58
	(0.0073)	(0.0018)	(6.72)	(1.34)
10 Days	-0.040	0.0013	38.3	27.2
	(0.028)	(0.0075)	(43.0)	(23.5)
20 Days	-0.048	-0.0057	52.6	62.3
	(0.031)	(0.0063)	(75.9)	(38.4)
30 Days	-0.019	-0.0073	73.4	62.2
	(0.065)	(0.0062)	(76.8)	(47.0)
60 Days	0.021	0.0013	58.8	43.2
	(0.050)	(0.0065)	(79.3)	(40.8)

The sample is a time series of days for the time period when rule-based foreign exchange interventions were in place in Colombia. The time period includes all days from December 24, 2001 to February 3, 2012 excluding October 29, 2009 to February 26, 2010 when the rule-based mechanism was temporarily suspended. Each listed coefficient results from a separate regression discontinuity model implemented using local linear regression on daily data with optimal bandwidth from Imbens and Kalyanaraman (2012). The first panel measures the effect of issuing put options (purchases of dollars by CBoC) and the second panel measures calls (sales). Rows denote outcomes X days since the intervention. The ratio of dollar-to-peso assets measures this asset ratio for the 5 largest banks in Colombia. The first column measures this ratio for all assets except derivatives, which are primarily forward contracts for foreign exchange, and the second column includes forwards. This ratio is measured as the difference between the value after X days and the value the day before intervention. Domestic and foreign are net portfolio inflows by domestic and foreign investors, respectively, cumulatively measured since the original intervention, in millions of USD. Heteroskedasticity-robust standard errors are in parentheses. ***, **, and * denotes statistical significance at the 1, 5, and 10 percent level respectively.

E Figures

Figure 1: Rule-Based Intervention Program 2001-2012

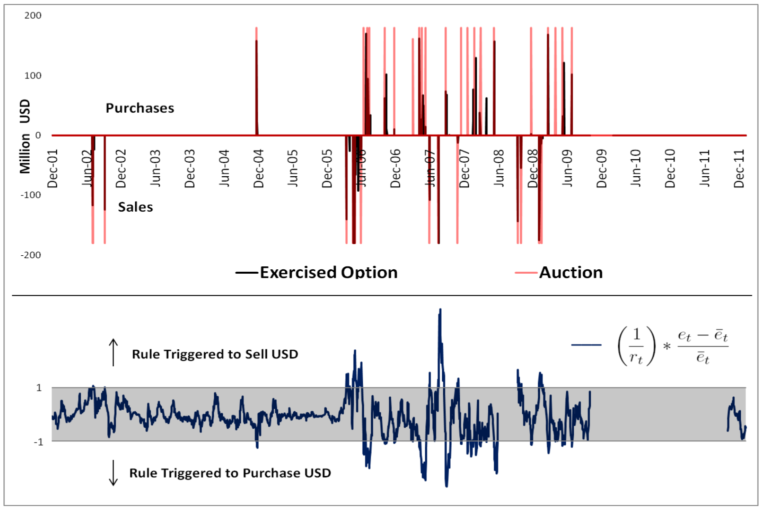
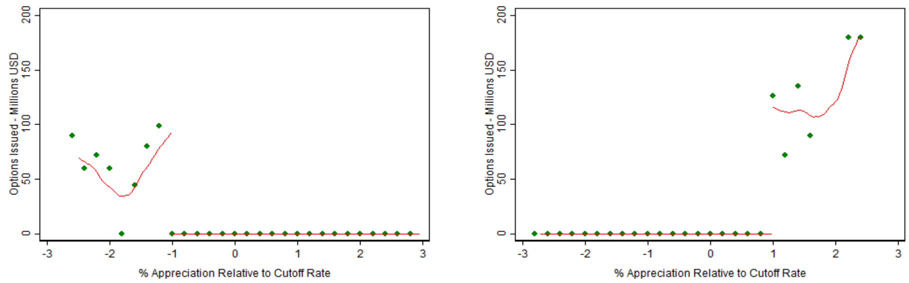


Figure 2: Cutoff Rule for Auctioning Options

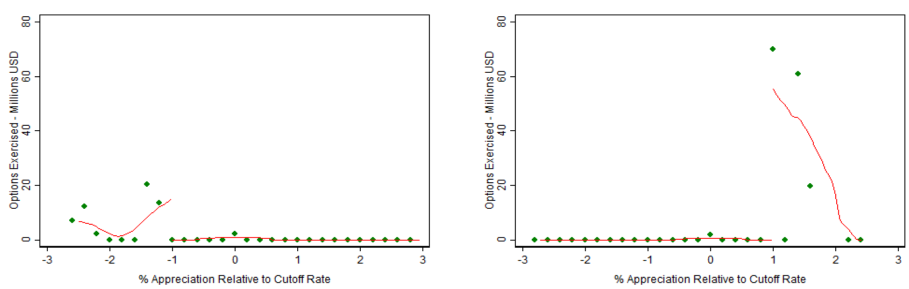
(a) Issuance of Put Options (b) Issuance of Call Options



Plotted points show averages of the dependent variable for 0.2 width bins. Fitted curves result from a local linear regression of options issued on the running variable with optimal bandwidth from Imbens and Kalyanaraman (2012).

Figure 3: Cutoff Rule for Exercising Options

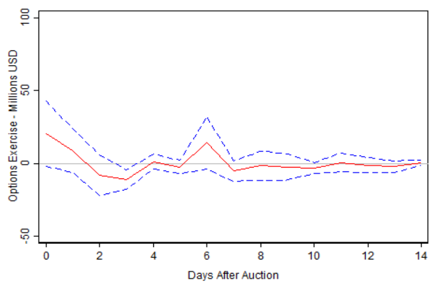
(a) Exercising of Put Options (b) Exercising of Call Options



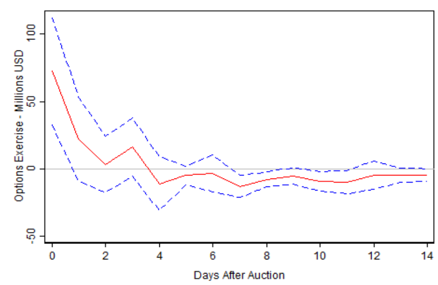
Plotted points show averages of the dependent variable for 0.2 width bins. Fitted curves result from a local linear regression of options exercised on the running variable with optimal bandwidth from Imbens and Kalyanaraman (2012).

Figure 4: Options Exercised: Two Weeks after Issuance

(a) Exercising of Put Options

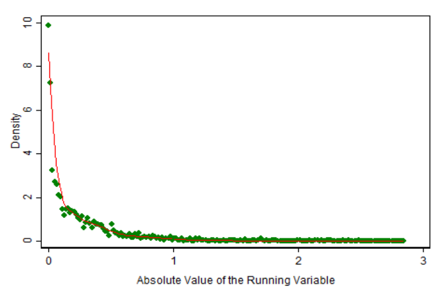


(b) Exercising of Call Options



Solid curve presents a series of regression discontinuity estimates implemented using local linear regression of options exercised X days since the auction on the running variable. Dashed curves display 95% confidence intervals of the estimates.

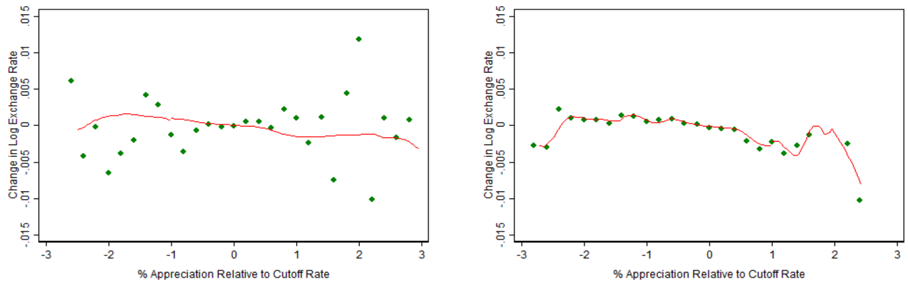
Figure 5: Test of Discontinuities in the Distribution of the Running Variable



Plotted points show the frequency of the absolute value of the running variable in bins of width 0.016, implemented as in McCrary (2008). The solid curve shows a local linear fit of the density of the absolute value of the running variable on the absolute value of the running variable for each side of the cutoff at 1.

Figure 6: Effect of Issuing Options on Lagged Exchange Rate Appreciation

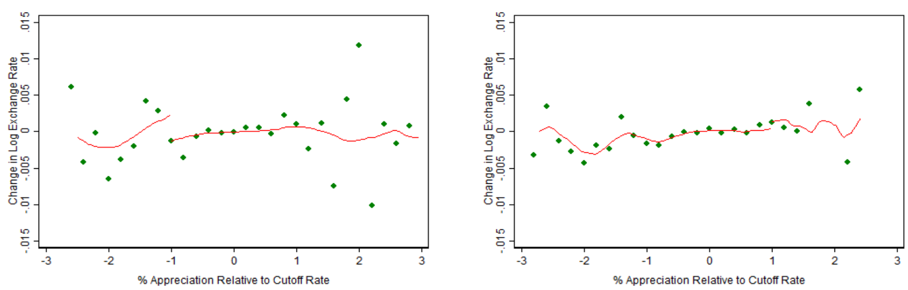
(a) Issuance of Put Options (b) Issuance of Call Options



The outcome is the difference between the log average spot rate from 8:00 a.m. to 8:15 a.m. on the day before issuance and the log average spot rate for the entire day two days before issuance. Plotted points show averages of the dependent variable for 0.2 width bins. Fitted curves result from a local linear regression of the outcome on the running variable with optimal bandwidth from Imbens and Kalyanaraman (2012).

Figure 7: Effect of Issuing Options on Exchange Rate Appreciation

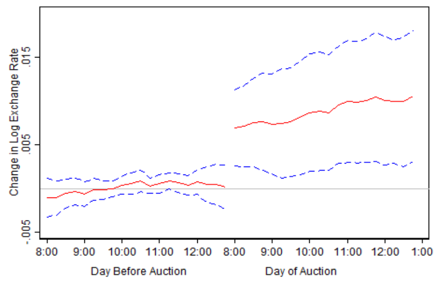
(a) Issuance of Put Options (b) Issuance of Call Options



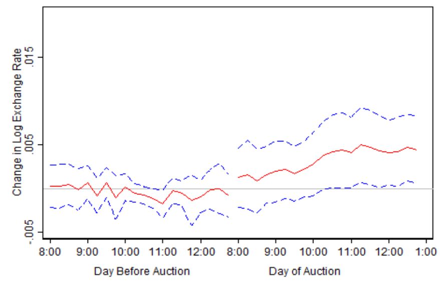
The outcome is the difference between the log average spot rate from 8:00 a.m. to 8:15 a.m. on the day of issuance and the log average spot rate on the entire day before issuance. Plotted points show averages of the dependent variable for 0.2 width bins. Fitted curves result from a local linear regression of the outcome on the running variable with optimal bandwidth from Imbens and Kalyanaraman (2012).

Figure 8: IRF of Log Exchange Rate: +/- 1 Day From Auctions

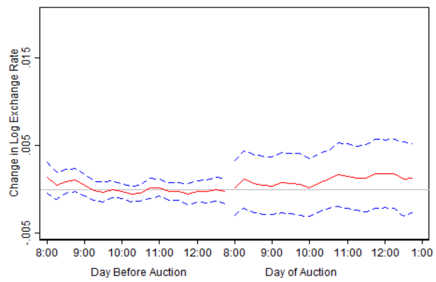
(a) Issuance of Put Options



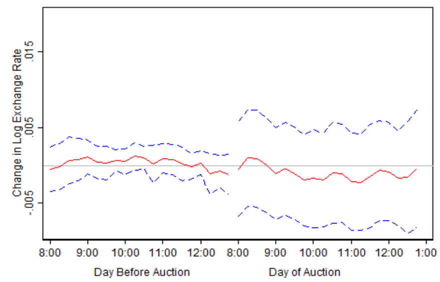
(b) Issuance of Call Options



(c) Exercising of Put Options



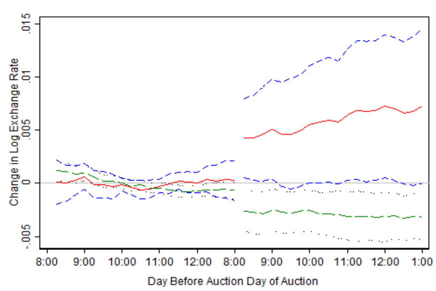
(d) Exercising of Call Options



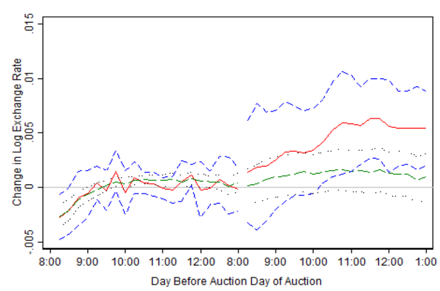
The spot rate is measured as the log of a volume-weighted average in 15-minute increments minus the log of the volume-weighted average for the day before the auction. The solid curve presents a series of regression discontinuity estimates implemented using local linear regression of the dependent variable on the running variable. The dashed curves display 95% confidence intervals of the estimates.

Figure 9: Separating Effects on Treated and Untreated Days

(a) Issuance of Put Options



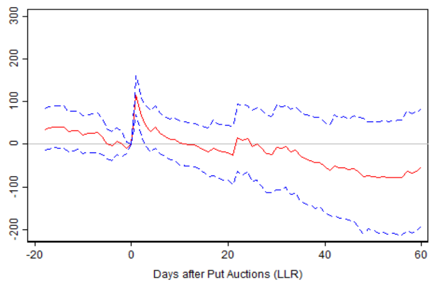
(b) Issuance of Call Options



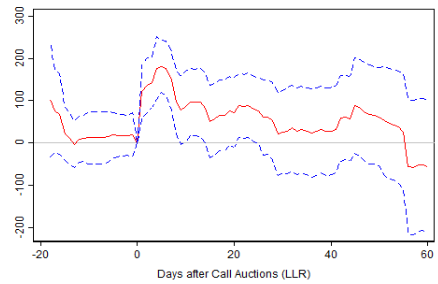
The spot rate is measured as the log of a volume-weighted average in 15-minute increments minus the log of the volume-weighted average for the day before the auction. The solid (red) and long-dash (green) curves present a series of local linear estimates of the dependent variable on the running variable for treatment and control groups, respectively. Short-dash (blue) and dotted (black) curves display 95% confidence intervals of the estimates.

Figure 10: IRF of Cumulative Options Issued: 60 days

(a) Issuance of Put Options



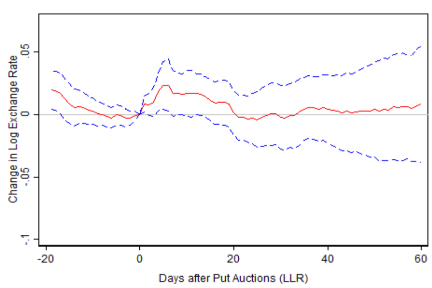
(b) Issuance of Call Options



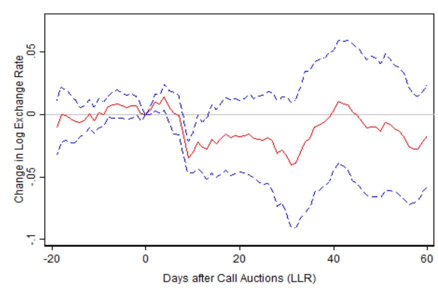
The dependent variable is the volume of options issued, in millions of dollars, between the date in question and the auction. The solid curve presents a series of regression discontinuity estimates implemented using local linear regression of the dependent variable on the running variable using daily data. Dashed curves display 95% confidence intervals of the estimates.

Figure 11: IRF of Log Exchange rate: 60 days

(a) Issuance of Put Options



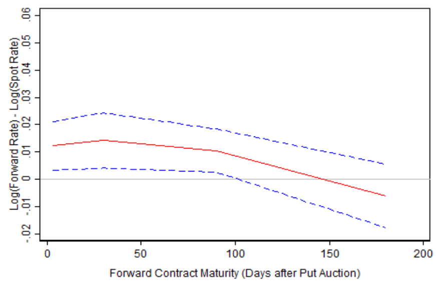
(b) Issuance of Call Options



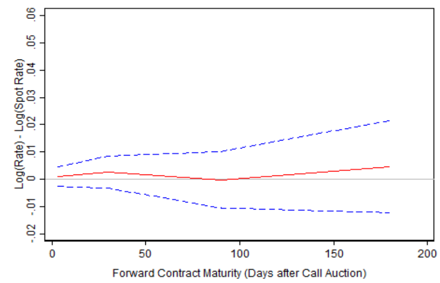
The dependent variable is the log daily average spot rate relative to the log average spot rate the day before the auction. The solid curve presents a series of regression discontinuity estimates implemented using local linear regression of the dependent variable on the running variable using daily data. Dashed curves display 95% confidence intervals of the estimates.

Figure 12: Effect on Forward Rates the Day of the Auction (Different Maturities)

(a) Put - Full Sample



(b) Call - Full sample

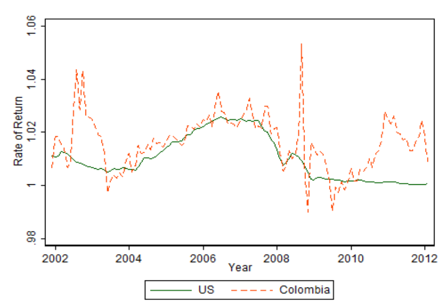


The dependent variable is the log average exchange rate implied by forward contracts the day after CBoC issues options relative to the log spot rate on the day before the CBoC issues options. The solid curve presents a series of regression discontinuity estimates implemented using local linear regression of the dependent variable on the running variable separately for samples of different maturities. Dashed curves display 95% confidence intervals of the estimates.

Figure 13: Covered Interest Rate Parity Condition

(a) CIP in Pesos

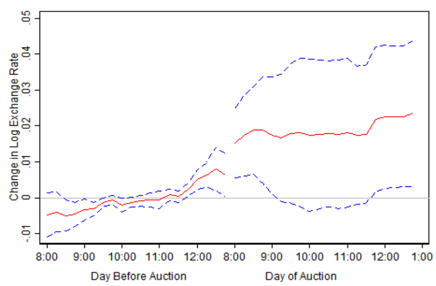
(b) Implied Interest Rate



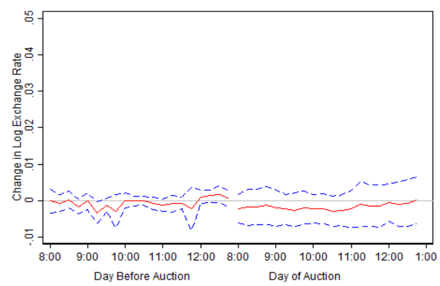
The left pane shows the actual spot rate and the spot rate that would satisfy CIP, given interest rates. The right pane shows the rate of return to a US investor of purchasing US bonds versus changing dollars into pesos at the spot rate, purchasing Colombian government bonds, and changing pesos into dollars at the forward rate. We calculate these using 6-month Colombian government bonds for the domestic interest rate, 12-month US government bonds (adjusted to 6 months) for the US interest rate, and volume-weighted average exchange rates from the spot and 6-month forward markets.

Figure 14: IRF of Log Exchange Rate depending on the CIP condition: +/- 1 Day

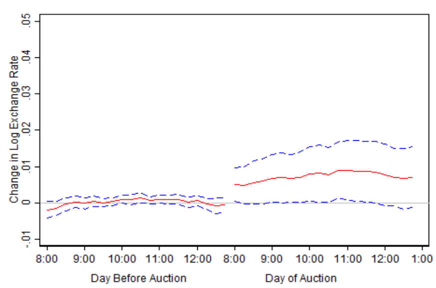
(a) Put Options: CIP Does Not Hold



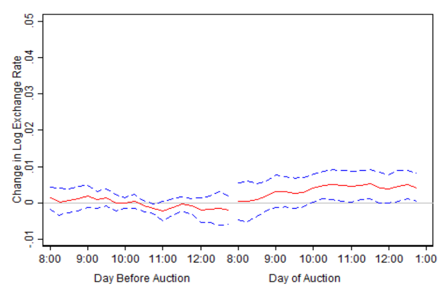
(b) Call Options: CIP Does Not Hold



(c) Put Options: CIP Holds



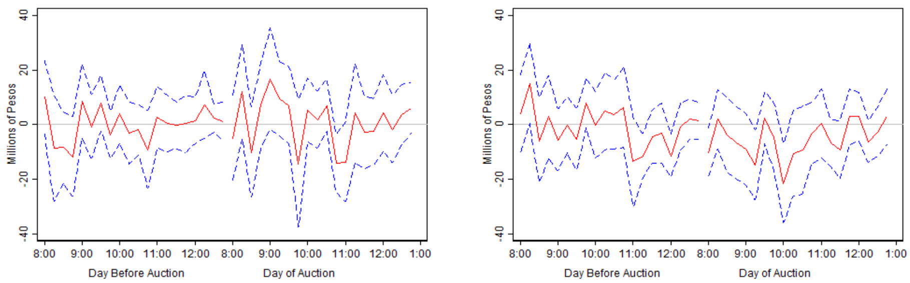
(d) Call Options: CIP Holds



The dependent variable is the log average spot rate in 15-minute increments relative to the log average spot rate the day before the auction. The solid curve presents a series of regression discontinuity estimates implemented using local linear regression of the dependent variable on the running variable. Dashed curves display 95% confidence intervals of the estimates. We define the time CIP holds as July 1, 2003 to June 30, 2008 and the time CIP does not hold as all dates before and after this time period.

Figure 15: Effect of Issuing Options on Order Flow

(a) Issuance of Put Options (b) Issuance of Call Options



Order flow measures the volume-weighted difference between orders originating as bids versus asks, measured in 15-minute increments relative to the average difference the day before the auction. The solid curve presents a series of regression discontinuity estimates implemented using local linear regression of the dependent variable on the running variable. Dashed curves display 95% confidence intervals of the estimates.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