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

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Abstract

This paper investigates the effectiveness of sterilized foreign exchange interventions by exploiting a discontinuous policy rule used by the Central Bank of Colombia. We use a unique data set comprised of tick by tick intervention and order book data, daily capital in- and outflows, and balance sheet information of financial institutions. We apply regression discontinuity methods to identify the surprise component of rule-based interventions and use this variation to measure how they affect exchange rates and capital flows. Our findings indicate that interventions had significant effects on the exchange rate, albeit short-lived (2-3 weeks). Moreover, capital controls amplify the effect of intervention, though some effect remains even in the presence of free capital flows. 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 local non-linear impulse response functions. A clearly defined policy rule and high frequency data are crucial in exploiting local variation around the policy cutoff.

Key Words: Rule-Based Intervention, Portfolio Balance, Foreign Exchange 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.[1]

Alternative theories suggest that exchange rate management may be effective even in the face 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. Similarly, Hassan, Mertens, and Zhang (2015) argue that central bank strategies that reduce foreign exchange volatility can affect the real economy through international portfolio decisions. Alternatively, non-equilibrium effects such as "order flow" are considered by Evans and Lyons (2002a) as determinants of exchange rates in the short run. Establishing whether peripheral countries face a policy 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.[2]

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 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.[3] The policy regime of a small open economy

[1] More recently, Obstfeld (2015) argues that, even with flexible exchange rates, monetary policy is constrained by global financial conditions, i.e. by a "financial policy trilemma." Alternatively, Rey (2013) argues 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. Hence, monetary policies are independent if and only if the capital account is managed.

[2] Du, Tepper, and Verdelhan (2017) support these positions empirically by arguing that deviations from the covered interest rate parity appear in the data.

[3] The fact that the CBoC did not defend a particular target zone is important to rule out exchange rate behavior such as

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 high frequency 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. The CBoC used a cutoff rule with a sharp trigger to determine when certain interventions would be carried out. 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 exchange rates, interest rates and bank balance sheets at horizons of between one and sixty working days. 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. The availability of high frequency data is critical to our approach because it allows us to measure foreign exchange markets within minutes of rule based interventions. Localized variation around the cutoff is at the heart of our identification strategy and differentiates our study from other work using event studies and work based on high frequency data.

We find that foreign exchange interventions by the CBoC had significant, albeit short-lived, 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.[4] 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 the opposite sign from what is expected. We attribute this initial effect to the CBoC's tendency to offset rule-based dollar sales with discretionary purchases. Excluding episodes in which the central bank simultaneously conducted purchases and sales of foreign currency eliminates this effect. After about 5 days, the peso appreciates in response to sales, as expected, but this effect 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

in Krugman (1991).

[4]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.

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 result rules out an explanation in which intervention can only be effective because of 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 suggests 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. Capital flows seem to respond but only after a delay, with most changes attributable to foreign investors. While not definitive, these findings are consistent with current account dynamics bringing the exchange rate back to its pre-intervention level. These results also line up 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 methodological contribution of this paper is to show how regression discontinuity design (RDD) methods known from the cross-sectional literature can be applied to a time series setting.[5] Discontinuous policy rules can be used to identify local average impulse response functions in environments where outcomes are continuous in the state variables absent intervention. While there are similarities with the microeconometric treatment literature in terms of the techniques we use, it is important to stress that the parameters we identify and estimate have a very distinct time series flavor to them. The reason for this is that the 'stable unit treatment value assumption' (SUTVA) of Rubin (1974), which assumes that treatment of one unit has no causal effect on other units, does not hold in a time series setting. Policies enacted in one period can and do influence the probability of further action or inaction in subsequent periods. Any structural VAR (SVAR) impulse analysis implicitly accounts for this dependence and likewise cannot generally isolate current period policy effects from subsequent policy actions. This lack of separation results not from particular statistical methods but rather from dynamic equilibrium responses and policy actions that endogenously depend on state variables. Our method thus exhibits the same limitations as any conventional impulse response analysis: the results are limited to the actual policy enacted during the observation period of the sample, and the estimated responses account both for the immediate effect of a policy shock on current and future outcomes as well as an indirect channel where the current policy shock may trigger further policy action in subsequent periods. Specifically, in the Colombian context we cannot separate the long-run effects of a given intervention from how that intervention affects future intervention. Related to these points, the equilibria are specific to the implemented policy rules and may change under different policy scenarios. Neither VAR analyses nor our approach provide insights into policy responses under alternative policy settings.

[5] 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.

However, our method provides several advantages over standard VAR analysis. We require fewer assumptions about the structure of the economy, identification comes from clearly specified policy variation, and our estimates are both non-linear and non-parametric. A limitation of our method is that we only identify impulse responses conditional on the state variables being close to the policy trigger.

2 Empirical Literature

We contribute to the large literature on the effectiveness of foreign exchange intervention (FXI henceforth) by exploiting a new empirical approach. A large portion of the literature examines the effectiveness of FXI with cross-country panel techniques (c.f. Adler et al. 2015; Daude et al. 2016). More similar to the current paper, Dominguez (2003) uses high frequency data to study the effectiveness of FXI, exploiting 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 in Section 4, separates this variation from other continuously varying influences affecting exchange rates. Even though traders know the policy rule, they are unable to predict with certainty whether the intervention will be triggered or not. Thus, we study movements in market rates localized near the trigger point of the policy.

A literature on rule-based foreign exchange market intervention does exist but generally focuses on straightforward descriptive results or event studies, in part because information on the rule is not always made public. One example is the Canadian case, which enacted rule-based interventions during 1975-1988 and in 1995. More recently, Guatemala used rule-based FXI during 2005-2010. In Mexico during 1996-2001, options were issued on pre-established dates, albeit with a rule-based exercising condition. We note that the FX mechanism in our investigation consists of a public and purely deterministic rule that depends on previous values of the exchange rate. Our analysis thus departs from regimes with pegs, crawling pegs, exchange rate bands, etc., as well as from discretionary or constant intervention, such as the case of Chile, Czech Republic, or Brazil.[6]

As for the Colombian case, the only study that directly considers this policy is Mandeng (2003) who finds, through an event study approach, that rule-based interventions were only moderately successful

[6] Countries transitioning toward a flexible exchange rate regime (e.g. East Asia countries during the 1990s) generally adopted exchange rate bands which were later widened or adjusted.

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 center on the Colombian case, but which consider other intervention mechanisms, include Uribe and Toro (2005), Kamil (2008), Ricon and Toro (2010), Echavarria et al. (2010), Echavarria et al. (2013), and Villamizar (2015). These studies all focus on *discretionary* operations and only provide a descriptive reading of the rule-based mechanism (which is central to our investigation). The methodology presented in these other works is based on a selection-on-observables approach, where a policy rule is estimated. In this paper, the discontinuity provided by the triggering rule creates a localized quasi-experiment, in which we identify the effect of intervention by comparing days where the cut-off for triggering the rule was barely met or barely missed. We argue that the variation near the cut-off is as good as randomly generated and thus providing the basis for identification.

More broadly, 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 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 FXI to fight currency appreciation in the face of capital inflows.[7]

We also investigate capital controls. 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 estimate causal effects of sterilized interventions during episodes when capital controls 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.

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

[7]Useful compilations of empirical works are found in Sarno and Taylor (2001), Neely (2005), Menkhoff (2010, 2013), and Villamizar and Perez (2017).

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 (Ramey 2011) and the estimation of monetary policy shocks (Romer and Romer 2004; Bernanke and Kuttner 2005; and Angrist, Jorda and Kuersteiner 2016).

3 Data and Institutional Environment

In October 1999, the CBoC adopted an inflation-targeting regime with a floating exchange rate.[8] Nonetheless, following this new regime and during most of the 2000s, the CBoC conducted frequent and large-scale foreign exchange intervention without targeting a particular value. In fact, most of these policies were aimed at avoiding excessive trends in the exchange rate and to strengthen the country's international liquidity position (see Uribe and Toro 2005).

In total, four intervention mechanisms were established: (i) discretionary FX options aimed at accumulating/reducing international reserves (put in place in 1999), (ii) rule-based FX options aimed at stemming exchange rate volatility (put in place in 2002), (iii) spot-market interventions (put in place in 2004), and (iv) pre-announced and constant FX auctions (put in place in 2008). While our study focuses exclusively on mechanism (ii), we do analyze the potential for correlation and interference with the other FX mechanisms.

3.1 Rule-based interventions

Rule-based interventions were triggered whenever the nominal exchange rate, defined as pesos per dollar (COP/USD) henceforth, exceeded a specific value vis-a-vis its past moving average. For the most part, this cutoff was 4% above or below the exchange rate's 20 day moving average. The rule was modified to have a cutoff of 2% from December 19, 2005 to June 24, 2008 and 5% from October 7, 2008 to October 27, 2009.[9] Interventions were temporarily stopped during June 26, 2008 to October 6, 2008 and October 28, 2009 to October 30, 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 (see Uribe 2016.) For the purpose of this investigation, we treat these periods as having an arbitrarily high cutoff (100%), so as to never bind, while including the entire sample period. The mechanism was permanently stopped on February 6, 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

[8]Prior to 1999, pre-announced exchange rate bands were established, dating back to 1994.

[9]Results are qualitatively similar, though noisier, if we examine only the period with the original cutoff of 4% (see Figure G.1 in the supplemental appendix).

pm. Hence, traders are not able to distinguish between days for which the rule is barely 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 a uniform clearing-price format of Dutch auctions. Participants could include up to 5 bids without exceeding the total amount set by the CBoC.[10] 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 Jan 2002 - Feb 2012, the exchange rate exceeded the cutoff 231 times. If options from a previous auction were outstanding, then market participants could exercise existing options. If no options were outstanding, it triggered a new auction. A total of 38 auctions were triggered by these 231 events, and options were exercised in 75 cases. For the other triggered days, option-holders chose not to exercise options. 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 mostly because the threshold that triggered the rule was set at 2% above or below its last 20 day moving average.

3.2 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.[11] 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.[12] 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

[10]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.

[11]Note that our sample period starts in December 2001 in order to have enough observations to model the triggering rule in January 2002.

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

Affairs Department (*Departamento de Cambios Internacionales*). Part of the data comprise the timing and amount of every auction held by the CBoC from January 2002 up until February 2012. Information includes every bid (amount and premium) presented by each participant, as well as the resulting 'clearing price' premium. We also observe the timing and amount of when options were exercised. 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 D provides a more detailed description of each variable. Further, Table G.1 in the supplemental appendix summarize these data, broken down by episodes in which the rule was barely missed and barely triggered.

4 Methodology

4.1 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 for there not to exist outstanding options from a previous auction. The 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. Namely, given that we incorporate the cut-off (r_t) within the policy rule (X_t), the thresholds become $+1$ for the issuance of call options and -1 for put options. 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:[13]

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

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

$$D_{S,t} = \mathbf{1}\{X_{S,t} \geq 1\},\ D_{P,t} = \mathbf{1}\{X_{P,t} \leq -1\}. \tag{1}$$

Policy dummies accurately characterize the policy because nearly all CBoC interventions involve issuing 180 million USD of options.[14] Panel (b) 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. Panel (a) 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 use to identify the effect of foreign exchange market intervention.

Table 1 quantifies these changes more precisely. The first row of Table 1 shows how exchange rate depreciation triggers CBoC put options. Each cell in the table shows the results of a local linear regression. 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 issuance of 116 million USD in put options. If we focus on days with outstanding options using the running variable, the rule triggers no new auction. Similarly, the lower part of Table 1 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.[15]

Rows 2 (puts) and 7 (calls) of Table 1 quantify the share of options that were immediately exercised. Panels (c-d) of Figure 2 display 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

[13] This formulation sets the running variable to zero when options are outstanding. We use narrow enough bandwidths that this choice does not substantively affect the estimates. Results are very similar if we instead limit the sample to days with no options outstanding.

[14] We find similar results when including controls (e.g. cutoff rate, lag exchange rates, forwards, and interest rates) as shown in Figure G.2, and when using the amount issued relative to total volume, as shown in Figure G.3 in the supplemental appendix.

[15] Triggering the rule does cause two instances where CBoC issues call options despite the existence of outstanding call options, hence the non-zero effect in the top middle cell of the call section of Table 1. 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.

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. Thus, issuing call options bears more similarity to straightforward sales of foreign exchange by the CBoC while issuing put options leads to less direct FX purchases, instead leaving a larger number of options outstanding.[16]

Once issued, market participants may exercise the options at some point over the next 20 working 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 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:

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

Thus, we can also measure the effects of allowing participants to exercise options. Estimates using this running variable are shown in the middle column of Table 1. Rows 2 (for puts) and 7 (for calls) show that investors exercise 24 million USD of put options on days when the downward rule is triggered, and 33 million USD of call options on days when the upward rule is triggered.

4.2 Local Identification

We identify the effects of sterilized foreign exchange interventions by the CBoC using local variation just before market outcomes determine whether the fixed intervention rule is triggered or not. Our localized identification strategy differs from event studies which compare average outcomes after the occurrence of certain events to average outcomes without those events. Event studies can address reverse causality by pairing high frequency data with the precise timing of policy changes. However, they require events to be independent of underlying macroeconomic fundamentals. This independence assumption can be weakened by conditioning on observed covariates, but any variable unobserved by the econometrician

[16] The left and right panels of Figure G.4 in the supplemental appendix 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.

must be assumed to be independent. Such unobservables may affect both the exchange rate and the likelihood of intervention when, for example, central bankers exercise discretion about when to intervene based on information from many sources. Our identification strategy, on the other hand, exploits how market movements near the trigger and the end of the trading day generate a discontinuous change in policy. Unlike with event studies, our empirical method discards trading days far from the cutoff when intervention will predictably occur because in those cases there may be an endogenous link between the level of the exchange rate and interventions the central bank undertakes. Instead, we compare trading days on either side of a sharp cutoff in the central bank's policy rule. Focusing attention locally around this cutoff justifies the assumption that observable and unobservable macroeconomic fundamentals do not vary with the policy.

We use the simple regression framework of Lee (2008) to formalize the essence of our method and its underlying assumptions. A more technical interpretation of our estimates as local impulse response functions is given in the appendix where we consider general non-linear models for the outcome variable. Thus, for expositional purposes, consider the following simple linear regression model

$$y_{t+j} = \alpha + \theta_j D_{S,t} + \varepsilon_{t,j} \tag{2}$$

where y_{t+j} is an outcome variable of interest observed j periods ahead and $\varepsilon_{t,j}$ is an unobserved factor affecting the outcome. The causal effect of the policy dummy $D_{S,t}$ on the outcome y_{t+j} is captured by the parameter θ_j. An example for the outcome variable is the j-period change in the exchange rate $y_{t+j} = e_{t+j} - e_t$. A simple regression estimate of θ_j obtained by regressing outcomes on the intervention dummy leads to the OLS estimator $\hat{\theta}_j$ being close to $E\left[y_{t+j}|D_{S,t} = 1\right] - E\left[y_{t+j}|D_{S,t} = 0\right]$ in large samples, i.e. the difference in mean exchange rate changes with and without the intervention by the CBoC. There is little reason to believe that this difference in mean outcomes represents the policy effect θ_j of the CBoC intervening in the foreign exchange market. The reason is that the intervention $D_{S,t}$ as defined in (1) depends directly on the exchange rate which by itself can be correlated with other macro factors affecting future movements in exchange rates. In Model (2) above these factors are subsumed in the error term $\varepsilon_{t,j}$ and thus lead to a correlation between $D_{S,t}$ and $\varepsilon_{t,j}$. In a regression setting one could try to control for these factors by adding additional covariates to (2). However, this is often not fully credible because some factors affecting current exchange rates may be unobservable and correlated with future changes.

Our approach relies on a different, likely weaker assumption that unobservable exchange rate fundamentals vary smoothly around the cutoff. If the conditional mean of unobservables, $E\left[\varepsilon_{t,j}|X_{S,t} = x\right]$ is continuous in the forcing variable locally at $x = 1$ then a local regression approach can identify the policy effect θ_j even when $X_{s,t}$ and $\varepsilon_{t,j}$, and therefore $D_{S,t}$ and $\varepsilon_{t,j}$, are correlated. The interpretation of the continuity assumption is similar to Lee (2008, p. 684). We are choosing t so that we are observing

$X_{S,t}$ right before the close of trading, when the policy $D_{S,t}$ is set. If $X_{S,t}$ is very close to the cut-off, any movement in $X_{S,t}$ at this point is as good as random noise. It has a small effect on the average $\varepsilon_{t,j}$ but moves $D_{S,t}$ in a discontinuous way from 0 to 1 or vice versa. Thus, the variation we are able to extract from the data when $X_{S,t}$ is local to the cut-off is as good as if we could randomly change $D_{S,t}$: it is not related to corresponding movements in $\varepsilon_{t,j}$. Economically, we are postulating that small movements in the exchange rate, just before the close of trading and when the forcing variable is close to the cut-off, are not related to fundamentals driving the exchange rate and cannot be influenced by traders trying to take advantage of positions the CBoC may take. Reverse causality is ruled out because even though traders know the policy rule, they are unable to predict with certainty whether the rule will be triggered or not. An episode where news arrival is significant enough to move $\varepsilon_{t,j}$ and $X_{S,t}$ so that the intervention is known in advance will not be local to the cutoff and thus be automatically excluded by our estimation method. The plausibility of these assumptions is evaluated empirically later in the paper.

A rigorous argument for the identification of the policy parameter θ_j in Model (2) is based on the fact that $\mathbf{1}\{x > 1\}$ is discontinuous in x such that the right limit $\lim_{x\downarrow 1} \mathbf{1}\{x > 1\} = 1$ while the left limit $\lim_{x\uparrow 1} \mathbf{1}\{x > 1\} = 0$. Note that $D_{S,t} = \mathbf{1}\{X_{S,t} > 1\}$ is a deterministic function of $X_{S,t}$ and thus fixed at $\mathbf{1}\{x > 1\}$ when $X_{S,t}$ is fixed at x. It follows that $E[y_{t+j}|X_{S,t} = x] = \alpha + \theta_j \mathbf{1}\{x > 1\} + E[\varepsilon_{t,j}|X_{S,t} = x]$ which implies

$$\begin{aligned} & \lim_{x\downarrow 1} E[y_{t+j}|X_{S,t} = x] - \lim_{x\uparrow 1} E[y_{t+j}|X_{S,t} = x] \\ = & \left(\alpha + \theta_j + \lim_{x\downarrow 1} E[\varepsilon_{t,j}|X_{S,t} = x]\right) - \left(\alpha + \lim_{x\uparrow 1} E[\varepsilon_{t,j}|X_{S,t} = x]\right) = \theta_j. \end{aligned} \tag{3}$$

The second equality holds because, by continuity of $E[\varepsilon_{t,j}|X_{S,t} = x]$, the right and left limits for the conditional means of the error terms are the same and thus cancel out.

The remaining task is to devise an estimator for the left hand side of (3). We estimate these limits using the local linear regressions developed by Fan (1992). Hahn, Todd and Van der Klaauw (2001) and Porter (2003) were the first to consider local linear regressions for inference in regression discontinuity designs. Local linear regression 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. High frequency data is critical in our endeavor because it allows us to measure market outcomes and policy actions right down to the minute when the policy decision is made and by doing so, eliminate variation in $D_{S,t}$ that may be correlated with fundamentals. Imbens and 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 policy effect θ_j by solving the problem

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

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 change in average outcomes between instances where the policy was active and instances when it was inactive, conditional on being near the policy rule cutoff. Appendix B proves consistency of $\hat{\theta}_j$ for θ_j, establishes the limiting distribution and derives the optimal bandwidth. Unless otherwise noted we use a triangular kernel and the optimal bandwidth is shown to be similar to Imbens and Kalyanaraman (2012).

4.3 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 auto-correlated. 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.

4.3.1 Correlation of Fundamentals with Intervention

Interventions generally tend to be correlated with underlying fundamentals. Table 2 tests this assumption. Consider a simple regression of a put intervention dummy on fundamentals measured just prior to the day triggering intervention: one-day exchange rate trends, appreciation built into forward contracts exercised on that day, the interbank interest rate, and credit default swap premiums. Column (1) displays this regression for the full sample. As expected, intervention is correlated with fundamentals. For puts, three of the four variables predict the probability of intervention, and a joint F-test of their statistical significance rejects the null that they collectively do not relate to the probability of intervention (F = 11.2, p < 0.0005). Clearly, a simple regression of exchange rates on an intervention dummy would confound the effects of intervention with the predictive power of lagged fundamentals.

However, if the CBoC's cutoff rule generates random variation in interventions near the cutoff, then the likelihood of interventions should be uncorrelated with fundamentals near that cutoff, conditional on the running variable, $X_{P,t}$. If we control for the running variable and narrow the sample to days with values of the running variable near the cutoff, the correlation between intervention and fundamentals should disappear. Columns (2) through (5) demonstrate how this assumption holds empirically. Column (2) controls for the running variable linearly. Columns (3-5) provide narrower windows around the cutoff. In column (5) we regress an intervention dummy on the vector of fundamentals and the running variable, focusing on a sample of days for which the running variable is within 0.2 of the cutoff. Conditional on the running variable and being near the cutoff, the fundamentals predict the probability of intervention neither individually nor jointly (F = 0.9, p = 0.48). Note that the limited predictive power of fundamentals is not just because of a small sample. The running variable itself remains a powerful predictor of intervention (F = 159.1, p < 0.0005). The bottom panel of Table 2 shows similar results for interventions on the call side. The simple regression again shows a raw correlation between intervention and fundamentals. Controlling for the running variable and narrowing the sample, this correlation disappears. In a narrow neighborhood of the cutoff, intervention appears unrelated to underlying fundamentals.

4.3.2 Baseline Balance

A related 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.

Panels (a) and (b) of Figure 3 examine 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. Rows 3 and 8 of Table 1 quantify these changes. As can be seen in the top half of the table for put options and the bottom half 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.[17] Altogether, the results show that

[17]Similarly, in Figure G.5 in the supplementary appendix, we show baseline balance for forward exchange rates.

there is no noticeable baseline difference between days on which new auctions are triggered and those on which they are not.

4.3.3 Distribution of the Running Variable Near the Cutoff

Following McCrary(2008), we test whether the density of the running variable exhibits 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 (of the running variable) and provides a Wald estimate for which the null hypothesis is continuity at the cutoff. Our results produce a p-value of 0.80, for which we do not reject the null.[18] Our results are consistent with exchange rates that are allocated randomly around the cutoff and with no manipulation by market participants.

4.3.4 Strategic Trading Behavior

Still, financial institutions might differentially manipulate the exchange rate to trigger CBoC interventions only when profitable to them. Recall that the CBoC intervenes using a cutoff rule for the average exchange rate over the entire day. When the exchange rate is close to the cutoff near the end of the day, firms could strategically trade in large volumes, at outlier prices, or in collusion so as to intentionally trigger CBoC intervention when profitable.[19] Manipulation by firms could bias the RDD estimates if firms intervene to encourage CBoC intervention when it would be idiosyncratically profitable and balance this by discouraging intervention when it would be idiosyncratically unprofitable. Such manipulation would need to occur at the very end of the trading day, since the exchange rate continues to vary through the day.[20]

Hence, we use data on individual foreign exchange market trades to test for strategic trading and find no evidence of manipulation at the scale necessary to affect our identification strategy. Similar to the above discussion of baseline balance, we test whether FX trades in the last few minutes before the policy rule is barely met or barely triggered look different. The first panel of Table 3 displays these results for puts. Each column corresponds to a different trading behavior outcome (measured in units per minute), and each row displays estimates for different time periods just prior and just after intervention. If traders

[18]Figure G.6 in the supplementary appendix depicts this result when estimating the density separately on either side of the cut-off (absolute value of 1).

[19]Though such manipulation would carry both reputational risks and the possibility of regulatory sanction. The regulatory institutions overseeing the financial sector in Colombia include the CBoC, the Financial Superintendency (*Superintendencia Financiera de Colombia*) and the Stock Market Regulatory Commission (*Autoregulador de Mercado de valores*).

[20]Figure G.7 in the supplementary appendix shows the typical range of exchange rate variation through the day.

wish to push for intervention on some days rather than others, trading records should display an increase in the volume of trade at the end of triggered versus not triggered days.

The first column of Table 3 shows that the volume of trade is statistically greater in the last minute. However, this effect is very small, less than 1% of the average daily volume of 715 million USD. Traders might collude using over-the-counter trades, rather than traditional bids and asks. However, the second, third, and fourth columns demonstrate that any increase in volume in the final minute comes from bids. Finally, increased trading at outlier prices would suggest manipulation. We define outliers as rates more than 3 standard deviations from the average hourly rate. We find some suggestive evidence that outliers increase, but again this change is small. The volume in outlier trades increases by at most 5.16 million USD (0.086 per minute * 60 minutes) in the final hour, or roughly .7% of daily volume. These trades occur at an exchange rate of roughly 0.5 percent different from the average rate. Hence, even if all outliers go in the same direction, they move the daily average by roughly 0.004%, which is very small relative to normal variation in the spot rate. The lower panel of Table 3 similarly shows small changes in trading behavior before auctions of call options. Altogether, we conclude that any attempts to manipulate CBoC intervention are of too small magnitude to influence actual policy significantly.

5 Effects on the Spot Exchange Rate

5.1 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. Panels (c) and (d) of Figure 3 display 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. Panel (c) of Figure 3 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. Panel (d) of Figure 3 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 spot rate varies more smoothly around the +1 cutoff, perhaps jumping up slightly to depreciate the peso.

We now extend our analysis to the entire day following the triggering of FXI. Panels (a) and (b) of Figure 4 show the impulse response function 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). The outcome is the difference between the log exchange rate at the listed time and the average for the previous day.[21] 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 right to left). 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.

Table 1 quantifies the average effect over the entire day using local linear regressions. The fourth 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 fifth row shows that this effect persists if we change from a triangular to a rectangular kernel.[22] A similar effect of auctioning call options is shown in the lower part of Table 1. The 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 immediate significant effects after dollar purchases but no observable effects after sales. However, in the next section we explain that this delayed reaction of dollar sales may be due to the fact that sales are sometimes offset by other mechanisms of intervention (i.e. simultaneous purchases).

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. For both call and put options, market participants exercising the options has no noticeable effect on the spot exchange rate. Column 2 of Table 1 displays this result. While issuing options may affect the exchange

[21] Measuring the difference relative to the previous day's close rather than the average yields very similar results (compare Figure G.8 in the supplemental appendix to Figure 4).

[22] Results are also qualitatively similar with different bandwidths.

rate, we do not measure an effect of exercising options. While not definitive, this result suggests that the manner in which options manage expectations of future intervention matters as much or more than the actual purchasing of dollars.

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.

5.2 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 of 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 panels (c) and (d) of Figure 4. Panel (c) 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.

Rational expectations do not affect the validity of our empirical strategy as long as expectations about the probability of intervention do not differ just before the announcement. In this case, market participants develop some beliefs about the probability of intervention. The announcement shifts expectations from a common probability of intervention to zero and one for control and treatment days, respectively. So, the difference in outcomes between the two groups still has the interpretation of the effect of moving the probability of intervention from zero to one. The overall effect of intervention includes both the jump up for treated days and the jump down for control days. The relative magnitude of these jumps gives some sense of market expectations regarding intervention.[23] In our data, the jump up for treatment days is larger than the jump down for control days, 61 percent of the total effect, indicating that the market expected less than even odds of intervention. Given the relatively rare interventions we study, low perceived odds of intervention make sense.

5.3 60-Day Effects

We can measure the effect of intervention over a longer time period, though any reduced form impulse response analysis combines the direct policy response parameters with the dynamics of subsequent policy interventions. 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. Panels (a) and (b) of Figure 5 demonstrate 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 4 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. Hence, we cannot fully rule out the explanation that temporary exchange rate effects result from only temporary intervention.

In panels (c) and (d) of Figure 5 we extend our time horizon for the main results, showing impulse response functions for exchange rate appreciation out to 60 days. After issuance of put options, exchange

[23] Formally, consider a day of trading that ends at t_0 at which time the central bank announces whether intervention will occur. Define e_0 as the spot rate just before the announcement and e_T and e_C as the spot rate just after the announcement with and without intervention, respectively. Market participants expect the probability of intervention to be p. Arbitrage by risk neutral participants would require that $e_0 = pe_T + (1-p)e_C$. This implies that $p = \frac{e_0 - e_C}{[(e_0 - e_C) + (e_T - e_0)]}$. In other words, the market's perception of the probability of intervention is equal to the proportion of the total treatment effect attributable to the jump down for the control group. In this case, the implied probability of intervention is 0.39.

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.[24] As before, Table 4 quantifies these effects more precisely. The effects that we measure for puts suggest that central bank intervention can move exchange rates in noticeable and significant magnitudes. We observe a roughly 1% 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 5 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.

Panel (d) of Figure 5 shows 60-day results for issuing call options. From theory, we might expect sales of dollars to have a negative effect, symmetric to the effect on purchases. The measured effect of intervention actually becomes positive and briefly pointwise statistically significant 2-4 days after intervention. This effect quickly reverses to the expected direction, though, and dollar sales generate a negative effect, which is statistically significant 8-13 days after the intervention. The estimated effects become less precise after this point, but generally remain negative. Formal statistical tests confirm the qualitative pattern. We can reject a null that the put and call effects are symmetric during the first 5 days. After that point, we cannot reject a null of symmetric effects.[25]

The CBoC's use of discretionary mechanisms could explain the asymmetry between puts and calls in the days just after intervention. During 2000-2012, the CBoC used discretionary mechanisms to purchase dollars totaling \$28.1 billion but only sell \$0.3 billion.[26] This one-sided discretionary mechanism gives CBoC the freedom to offset rule-based intervention on the call side but not the put side. As an example, the rule-based mechanism issued \$180 million dollars through call options on October 2, 2002. Then, on October 21, 2002, the central bank also purchased \$50 million dollars through discretionary put options intended to accumulate reserves. The overall numbers are noisy but are consistent with this story. The fourth column of Table 4 measures whether the CBoC purchased more or less dollars through discretionary mechanisms after the rule-based intervention was triggered. While not statistically significant, the effects

[24] Results are qualitatively similar using different kernels and bandwidths.

[25] Formally, for each day we estimate the put and call local linear regressions as seemingly unrelated regressions. Using those results, we test the null that the two effects sum to zero with a χ^2 test.

[26] These figures correspond to all forms of discretionary intervention, as exemplified in Uribe (2016).

for call auctions in panel B indicate that on average CBoC used discretion to purchase dollars after call auctions. In panel A, the effects for put auctions are positive but statistically insignificant, indicating that, if anything, the CBoC used discretionary mechanisms to reinforce rule-based purchases. Similarly, the two periods during which CBoC suspended rule-based intervention (see discussion above in data section) coincided with depreciation of the peso which would have led the rule to sell dollars.

This general preference for using discretion to buy rather than sell dollars could generate asymmetric uncertainty about CBoC's commitment to rule-based intervention. Such uncertainty could make intervention temporarily ineffective in the days immediately following a call side intervention until uncertainty resolves. If true, this view would imply different prices for call and put options issued through the rule-based auctions. Recall that options can only be exercised when the rule is triggered and the strike price of the options is the average spot rate for the day before the options are exercised. So, options are more valuable if central bank intervention is not credible and the market expects the spot rate to continue trending. In fact, auction data indicate that the winning bid for call options exceeded that for put options by 40%. Finally, we also find in Figure G.9 in the supplemental Appendix that the initial positive effect for calls disappears when excluding episodes in which the central bank simultaneously conducted both purchases and sales of foreign currency. Differences in the ability of the central bank to commit to sales versus purchases of dollars may drive asymmetric effects in the days immediately following an intervention.

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 put options. In addition, we observe an initial response lasting a couple of days that goes in the opposite direction, likely because of uncertainty about the central bank's commitment to call-side intervention.

5.4 Sterilization and Signaling

We confirm that interventions by the CBoC represent sterilized interventions that do not affect interest rates. The third column of Table 4 shows responses of the Colombian interbank rate to FXI after 1, 10, 20, 30, and 60 days. Impulse response functions show that the response is not statistically significant for either put and call auctions.[27] For put auctions we observe some downward trend in the 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

[27]Results are reported in Figure G.10 in the supplemental appendix.

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 supplemental appendix (Figure G.11) 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 FXI 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 figures, 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.

These results also rule out a signaling mechanism. If FXI affects the exchange rate only because it signals future changes in monetary intervention, then we should observe differences in future interest rates between intervention and non-intervention days. As shown above, we do not observe such effects for the interbank rate. This result holds for market interest rates for Colombian Treasury bonds as well; for which we find no evidence that market interest rates move in response to FXI.[28]

6 Mechanisms of Foreign Exchange Market Intervention

6.1 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, which in principle should be reflected in departures from the covered interest parity (CIP) condition. As noted in Section 1, the monetary trilemma indicates that policymakers can regain control of the exchange rate if they abandon monetary policy or enact capital controls. Thus, we investigate whether sterilized FXI is more effective when arbitrage is hindered. In the related literature, Farhi and Werning (2014) show 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).[29]

[28]These results are reported in figures G.12 and G.13 in the supplemental appendix. In particular, we display impulse response functions over a 1-day time horizon using high frequency data on bond trades and 60-day time horizons using daily averages.

[29]Recent empirical work investigating the effectiveness of capital controls includes Montiel and Reinhart (1999), Kaplan and Rodrik (2002), Ostry, Qureshi, Ghosh and Chamon (2011), You, Kim and Ren (2014), and Engle (2015). 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.

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% (*Posición Propia de contado -PPC*). This and other measures were implemented to control for speculative attacks on the currency (see data appendix D).

We measure frictions preventing arbitrage using an empirical distinction between periods when CIP holds and does not hold. This allows us to isolate periods when capital does not flow freely. We compare the spot peso/dollar exchange rate over our sample period against the spot rate implied under CIP by Colombian interest rates, US interest rates, and forward contracts for the peso/dollar exchange rate. In the middle of our sample from mid-2003 through mid-2008, CIP appears to hold.[30] 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 hedge 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. We thus categorize these early and late periods as times when CIP was violated.

Interventions remain effective even when CIP holds closely but have greater effects when it does not. Figure 6 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 6 (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 5 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 6 (b) and (d) and the second panel of Table 5 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 FXI 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.

Other measures of capital controls exist. We focus on whether CIP holds for three reasons. First, existing measures of capital controls from Magud, Reinhart and Rogoff (2011) and Aizenman, Chinn, and Ito (2011) are negatively correlated for Colombia during our sample period. Second, practically, the time period defined by existing measures create a very short capital controls period, which generates

[30]Figure G.14 provides graphs of this comparison.

small sample problems empirically. Finally, most 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. In any case, our measure is correlated with that of Aizenman, Chinn, and Ito (2011), and we detect similar positive effects of purchasing dollars during the period that Magud et al. (2011) categorize as having no capital controls. Our results are not sensitive to how we measure capital controls.

6.2 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 FXI change the effects of order flow on price while Girardin and Lyons (2008) investigate the effects of FXI on order flows. Here we similarly investigate whether FXI 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.[31] For any hour we can thus compute order flow as the difference in volume of bids and asks. We find no evidence that central bank intervention affects order flow. The estimated coefficients show no clear pattern and are generally statistically insignificant. [32]

6.3 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 FXI 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

[31] 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.

[32] Figure G.15 in the supplemental appendix shows the results of applying our regression discontinuity strategy using order flow as the outcome. Figure G.15(a) shows the results for issuing put options and G.15(b) for issuing call options.

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 find some evidence consistent with an active, but temporary, portfolio balance channel. We use a daily panel of asset reports by the 5 largest Colombian banks 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. The first column of Table 6 shows the response of this asset ratio to FXI. While the results are noisy and should be interpreted with caution, intervention through put options appears to decrease domestic banks' relative holdings of foreign assets for the first 20 days, but this effect disappears by 60 days. The second column shows results for a similar asset ratio that now includes forward contracts for dollars as dollar-denominated assets. No such decrease appears. These results suggests that Colombian financial institutions re-balance their assets temporarily. 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.

Results for capital flows are also consistent with a temporarily active portfolio balance channel. The third and fourth columns of Table 6 show effects on capital flows from domestic investors investing in foreign assets and foreign investors investing in Colombia. Again, the results are noisy but the effects for foreign investors suggest an interesting mechanism. 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. Foreign investors appear to respond with significant capital flows after some delay.

The responses are consistent with predictions of portfolio balance models, including the Gamma model advocated by Gabaix and Maggiori (2015). We see evidence consistent with 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. 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 allows sterilized FXI to move the exchange rate, but only temporarily.

7 Conclusion

Foreign exchange interventions remain an important tool of central banks aimed at stabilizing the domestic economy and shielding it from global shocks. Yet, recent evidence suggests that there exists 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 Central Bank of Colombia 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. In particular, central bank purchases of dollars via the issuance of put options leads to an approximately 0.8 percent depreciation of the peso. On the other hand, dollar sales via call options show a less consistent effect: a small initial depreciation during the first week and a subsequent appreciation, as expected, after the first week. We attribute this last result to the offset of dollar sales by other mechanisms of intervention, i.e. simultaneous purchases of foreign currency. Finally, we find that capital controls amplify the effect of intervention, though some effect remains even in the presence of free capital flows.

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A Local Nonlinear Impulse Response Functions

This section provides an interpretation of our estimates when the underlying model of central bank interventions is of a general nonlinear form. 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, 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.[33]

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 $X_t = g\left(\chi_t\right)$ 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 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.[34] For δ fixed and $\varepsilon = \varepsilon\left(\delta\right)$ the impulse response of y_{t+j} then is defined as

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

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 $\varepsilon\left(\delta\right)$ as $\delta \downarrow 0$. It is also the case that $\theta_j\left(\varepsilon, \chi_t\right)$ will be zero at the limit as

[33] 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 $F_{t,j}\left(D_t, \chi_t\right) = F^j\left(v_{t+j}, ..., v_{t+1}, D_t, \chi_t\right)$.

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

$\delta \downarrow 0$ 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 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

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

If $F_{t,j}(0, \chi_t)$ were linear in χ_t and θ_j^D was a constant parameter we might be able to 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 (2016) 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 $E[F_{t,j}(D, \chi_t) | X_t = x]$ 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 $E\left[\theta_j^D(\chi_t)\right]$. 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[35]

$$\lim_{\delta \downarrow 0} E[y_{t+j} | X_t = c + \delta] - \lim_{\delta \downarrow 0} E[y_{t+j} | X_t = c - \delta] = \lim_{\delta \downarrow 0} E[\theta_j(\varepsilon(\delta), \chi_t) | X_t = c] = E\left[\theta_j^D(\chi_t) | X_t = c\right]. \tag{4}$$

[35] A formal result is given in Appendix B.

The relationship in (4) shows two things: how a local average of y_{t+j} around $X_t = c$ can be used to identify the average impulse response $E\left[\theta_j^D(\chi_t)|X_t = c\right]$ and that variation in χ_t local to $X_t = c$ is required to identify the parameter of interest. 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.

An extension of the estimator presented in the main text to estimate the full impulse response function is as follows. Define the impulse response coefficients $\theta = (\theta_1, ..., \theta_J)'$ and the estimator $\hat{\theta}$ which is obtained by solving the problem

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

We use a triangular kernel and optimal bandwidth similar to Imbens and Kalyanaraman (2012) and we conduct inference as defined in Appendix B

B 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

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

where $K(.) \geq 0$ 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 $W = \operatorname{diag}(K((X_1 - c)/h), ..., K((X_{T-J} - c)/h))$. Then, similar to Masry and Fan (1997, p.167), the estimator can be written in closed form as

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

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 $\Sigma(x) = \operatorname{Var}(Y_t | X_t = x)$ 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* $\Sigma^+(x_0) = \lim_{x \to x_0^+} \operatorname{Var}(Y_t|X_t = x)$, $\Sigma^-(x_0) = \lim_{x \to x_0^-} \operatorname{Var}(Y_t|X_t = x)$ *and assume that* $\Sigma^+(x_0)$, $\Sigma^-(x_0)$ *are positive definite for* $x_0 = c$.

C 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 $\operatorname{vec}\hat{\Pi}'$ 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

$$\Omega^+ = \begin{bmatrix} V^+ & V^+ \\ V^+ & V^+ \end{bmatrix}, \ \Omega^- = \begin{bmatrix} V^- & 0 \\ 0 & 0 \end{bmatrix}$$

Also define

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

and

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

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 $m''^{-}\left(c\right)=\left(m_{0}''^{-}\left(c\right),....,m_{J}''^{-}\left(c\right)\right)'$ and similarly for $m''^{+}\left(c\right)$. 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 $\sigma_{+j}^{2}\left(c\right)$ be the corresponding diagonal element of $\Sigma^{+}\left(c\right)$ and $\sigma_{-j}^{2}\left(c\right)$ the corresponding diagonal element of $\Sigma^{-}\left(c\right)$. We obtain the following result.[36]

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

$$\sqrt{Th}\left(\hat{\theta}_{j}-\theta_{j}-\frac{h^{2}}{2}\left(m_{j}''^{-}\left(c\right)b^{-}+m_{j}''^{+}\left(c\right)b^{+}\right)\right)\rightarrow_{d}N\left(0,f\left(c\right)^{-1}\left(\sigma_{+j}^{2}\left(c\right)\omega^{+}+\sigma_{-j}^{2}\left(c\right)\omega^{-}\right)\right)$$

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

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

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

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

which corresponds to the plug in formula of Imbens and Kalyanaraman (2012). For example, for the Bartlett kernel $K\left(u\right)=\left(1-\left|u\right|\right)1\left\{\left|u\right|\leq1\right\}$ it can be shown that $\omega^{+}=\omega^{-}=24/5$ and $b^{-}=-b^{+}=1/10$ which leads to $\left(\omega^{+}/\left(b^{+}\right)^{2}\right)^{1/5}=2\left(15\right)^{1/5}\approx3.4375$. This is the same as the constant obtained in Imbens and Kalyanaraman (2012).

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

D 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.[37]

7. Capital Controls: The central bank introduced controls on outflows during December 2004 - June 2006, requiring all foreign investment to remain in the country for one year. Later, between May 7, 2007 and October 8, 2008, capital controls on inflows were enacted (see Magud, Reinhart and Rogoff 2011). 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.

Additionally, Table G.1 summarize these data, broken down by episodes in which the rule was barely missed and barely triggered.

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

E Tables

Table 1: Same Day Effects of Intervention

Outcome	Full Sample	Outstanding Options	No Outstanding Options
A. Put 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 Lag	0.001	0.002	0.001
(COP/USD)	(0.001)	(0.002)	(0.002)
Log Exchange Rate 1-day Lead	0.004**	-0.001	0.008***
(COP/USD)	(0.002)	(0.002)	(0.003)
Log Exchange Rate 1-day Lead	0.004**	0.001	0.009***
(COP/USD) [Rectangular Kernel]	(0.002)	(0.002)	(0.003)
B. Call 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 Lag	0.001	0.002	0.001
(COP/USD)	(0.001)	(0.002)	(0.002)
Log Exchange Rate 1-day Lead	0.001	-0.001	0.003*
(COP/USD)	(0.002)	(0.003)	(0.002)
Log Exchange Rate 1-day Lead	0.002	0.000	0.003*
(COP/USD) [Rectangular Kernel]	(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: December 24, 2001 to February 3, 2012. 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. 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). All estimates use a triangular kernel unless otherwise noted. Heteroskedasticity-robust standard errors are in parentheses.

Table 2: Regression of Intervention Dummy on Fundamentals

	(1) All	(2) All	(3) BW = 0.8	(4) BW = 0.4	(5) BW = 0.2
A. Puts					
Put Lag Log Change in Spot Rate	2.88***	-0.98	-1.01	5.55	-15.6
	(0.82)	(0.66)	(2.99)	(6.18)	(11.9)
Lag Exercised Forward Rate	-5.77	-6.99*	-21.7	-1.18	173.1
	(4.48)	(4.01)	(29.1)	(79.7)	(614.7)
Lag Interbank Rate	0.013***	0.013***	0.026***	0.022	0.0021
	(0.0020)	(0.0017)	(0.0076)	(0.014)	(0.019)
Lag Credit Default Swap Spread	-0.012***	-0.011***	0.027***	0.036	0.021
	(0.0021)	(0.0017)	(0.0060)	(0.023)	(0.043)
Running Variable		-0.15***	-0.70***	-1.80***	-3.90***
		(0.017)	(0.039)	(0.12)	(0.31)
Fundamentals = 0, F	11.2	12.5	10.7	1.2	0.9
Fundamentals = 0, p-value	0.000	0.000	0.000	0.332	0.480
Run. Var. = 0, F		82.3	316.1	211.2	159.1
Run. Var. = 0, p-value		0.000	0.000	0.000	0.000
R-Squared	0.04	0.26	0.61	0.64	0.69
N	2429	2350	458	120	63
B. Calls					
Call Lag Log Change in Spot Rate	-2.05**	0.49	2.58	3.40	-8.56
	(0.84)	(0.50)	(2.91)	(6.57)	(11.2)
Lag Exercised Forward Rate	23.9*	-1.47	-13.8	-116.3	-850.7
	(13.0)	(3.80)	(38.6)	(330.3)	(884.1)
Lag Interbank Rate	-0.021***	0.0066***	0.0010	-0.014	-0.016
	(0.0025)	(0.0015)	(0.0070)	(0.021)	(0.025)
Lag Credit Default Swap Spread	-0.0094***	-0.0066***	-0.0049	0.00036	0.033
	(0.0012)	(0.0014)	(0.0046)	(0.014)	(0.039)
Running Variable		0.075***	0.64***	1.68***	3.33***
		(0.014)	(0.060)	(0.13)	(0.31)
Fundamentals = 0, F	17.6	4.7	2.3	0.7	0.5
Fundamentals = 0, p-value	0.000	0.000	0.048	0.643	0.757
Run. Var. = 0, F		27.1	114.0	176.3	112.6
Run. Var. = 0, p-value		0.000	0.000	0.000	0.000
R-Squared	0.06	0.12	0.55	0.72	0.77
N	2429	2350	327	80	31

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. Each column runs a linear regression with a treatment dummy as the dependent variable using daily data. Coefficients for all covariates are listed (except for a year dummy at the beginning of our sample when credit default swap data are not available). The first F-statistic and p-value provide a joint test of the null that coefficients on the fundamentals variables are zero. The second F-statistic and p-value does the same for coefficients on all powers of the running variable. This test uses heteroskedasticity-robust standard errors.

Table 3: Differences in Trading Behavior between Intervention and Non-Intervention Days around the Time of Potential Intervention

	Volume	Bid	Ask	OTC or Simult.	Outlier
A. Put Options					
Last Hour	0.72	0.17	-0.0039	0.16	0.086**
	(0.46)	(0.14)	(0.17)	(0.14)	(0.035)
Last Min.	6.14***	2.81	0.16	0.17	0.24
	(2.33)	(1.82)	(0.50)	(0.62)	(0.26)
B. Call Options					
Last Hour	0.13	-0.11	-0.038	0.058	0.025
	(0.51)	(0.10)	(0.13)	(0.20)	(0.039)
Last Min.	2.62	0.27	2.57	1.28**	0
	(2.12)	(0.51)	(2.19)	(0.59)	(.)

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. All outcomes are measured as millions of USD per minute in the final minute/hour of trading before the rule could trigger CBoC intervention. Outlier trades are trades at an exchange rate more than 3 standard deviations from the average rate for that hour. 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 4: Short and Medium Run Effects of FXI: Interventions and Spot Exchange Rate

	Options Issued	Log Exchange Rate	Interbank Rate	Discretionary FXI
A. Put Options				
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. Call Options				
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. 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). For discretionary FXI on the call side, we use the same bandwidth as options issued because the optimal bandwidth cannot be computed. 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 5: 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. Put Options				
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. Call Options				
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. 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 6: Short and Medium Run Effects of FXI: Capital Flows

	Dollar/Peso Assets	Dollar/Peso (w/ forwards)	Domestic Flows	Foreign Flows
A. Put Options				
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. Call Options				
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. 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.

F Figures

Figure 1: Rule-Based Intervention Program 2001-2012

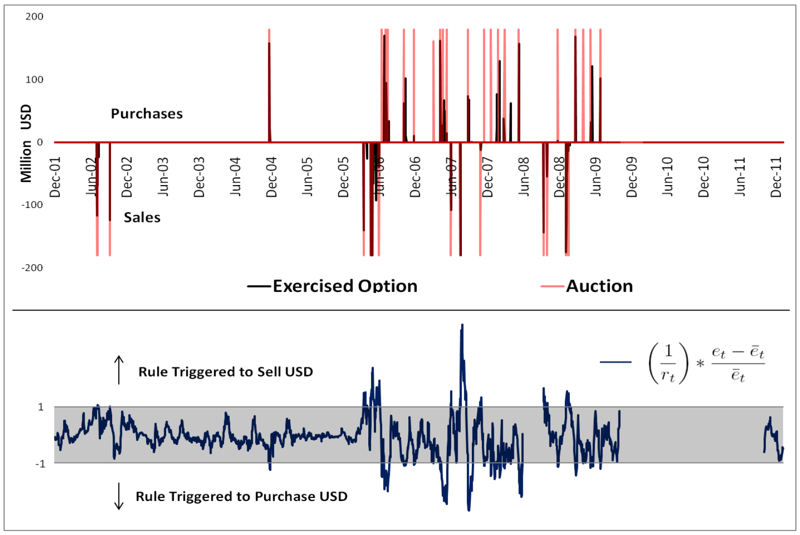
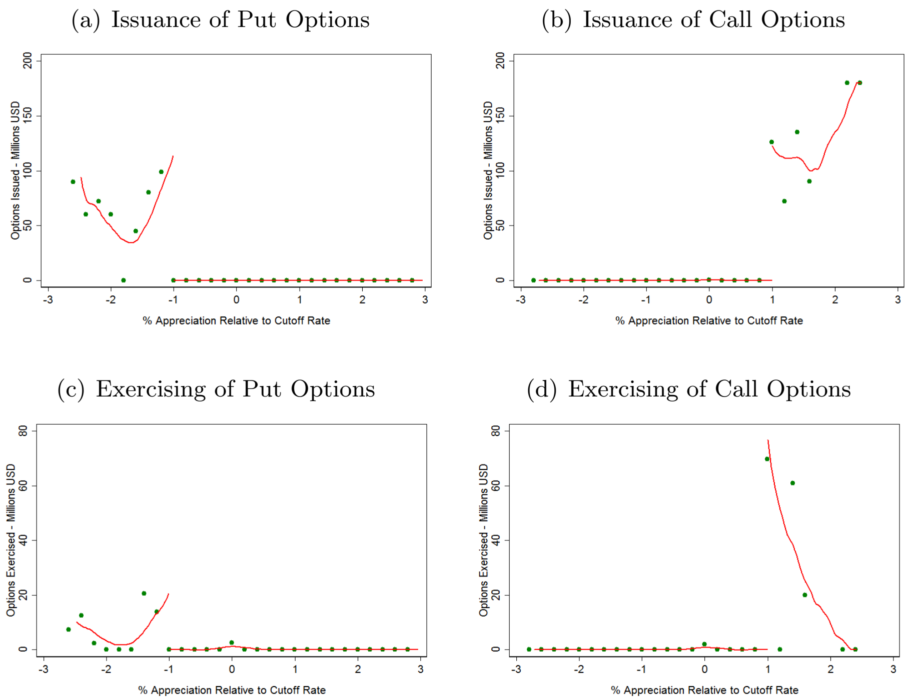


Figure 2: Cutoff Rule for Issuance and Exercising Options



(a) Issuance of Put Options

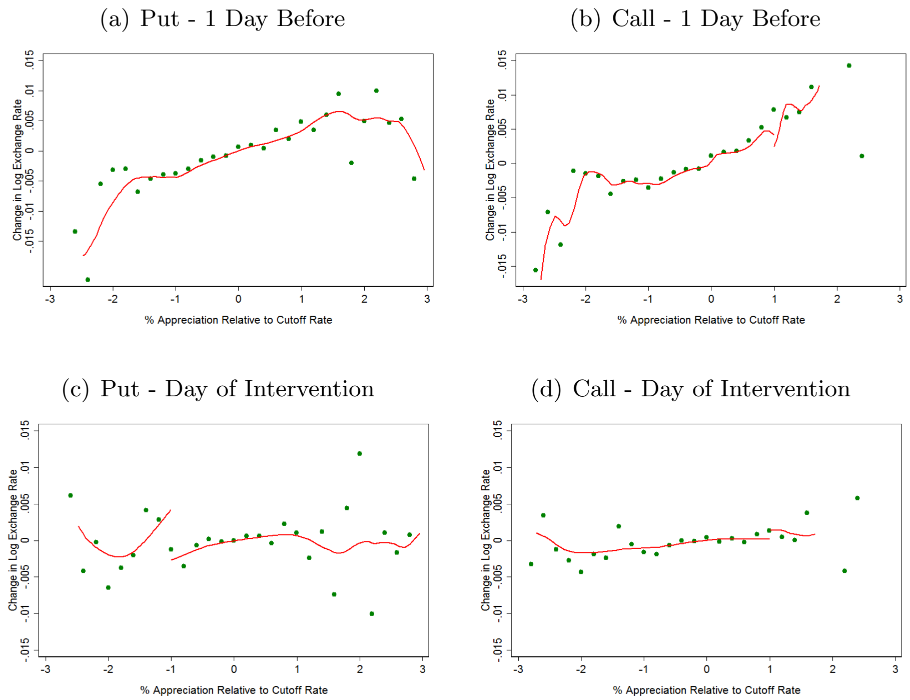
(b) Issuance of Call Options

(c) Exercising of Put Options

(d) 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 issued and exercised on the running variable with optimal bandwidth from Imbens and Kalyanaraman (2012).

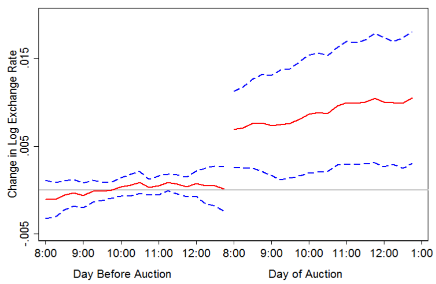
Figure 3: Baseline Balance: Effect of Issuing Options on Lagged Exchange Rates



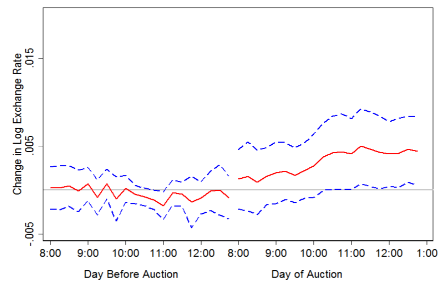
The 1-day lag outcome is the difference between the log average spot rate from 8:00 a.m. to 8:15 a.m. on the day before issuance and the log average spot rate for the entire day two days before issuance. The day of intervention outcome is the difference between the log average spot rate from 8:00 a.m. 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 4: IRF of Effects on Exchange Rate Appreciation: +/- 1 Day From Auctions

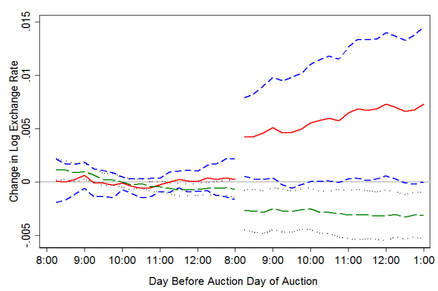
(a) Put - Diff. between Treated and Not



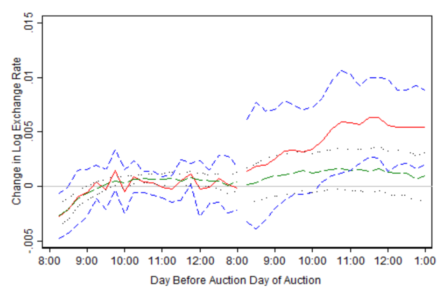
(b) Call - Diff. between Treated and Not



(c) Put - Separating Treated and Not



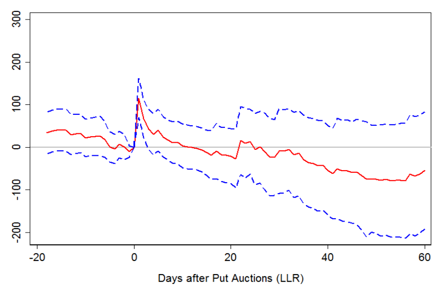
(d) Call - Separating Treated and Not



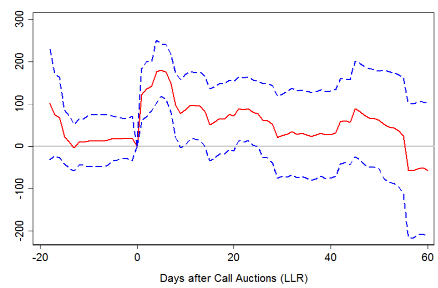
The spot rate is measured as the log of a volume-weighted average in 15-minute increments minus the log of the volume-weighted average for the day before the auction. In sub-figures (a) and (b), the solid curve presents a series of regression discontinuity estimates of the difference between triggered and not triggered days, implemented using local linear regression of the dependent variable on the running variable. In sub-figures (c) and (d), the solid (red) and long-dash (green) curves present a series of estimates of the mean of the dependent variable at the cutoff for treatment and control groups, respectively, These estimates are from local linear regressions of the dependent variable on the running variable. The short-dash curves display 95% confidence intervals of the estimates.

Figure 5: IRF of Effects of Triggering the Rule, 60 Days

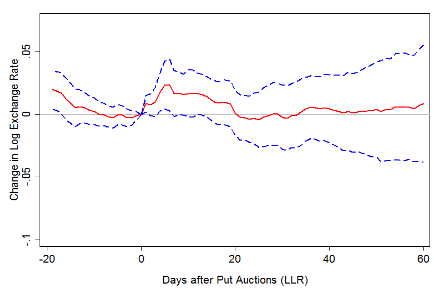
(a) Put - Cumulative Options Issued



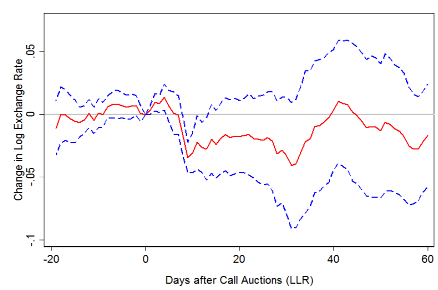
(b) Call - Cumulative Options Issued



(c) Put - Log Exchange Rate



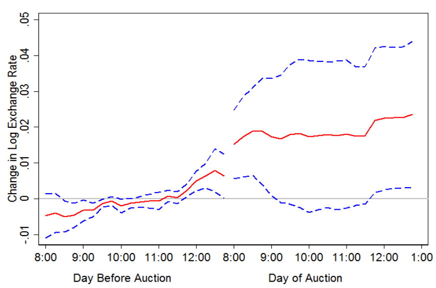
(d) Call - Log Exchange Rate



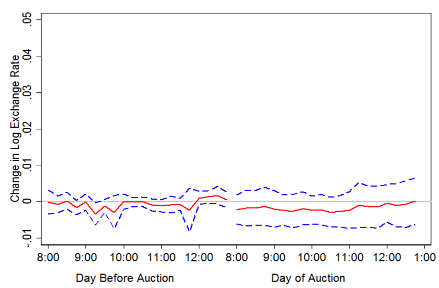
In sub-figures (a) and (b) the dependent variable is the volume of options issued, in millions of dollars, between the date in question and the auction. In sub-figures (c) and (d) the dependent variable is the log daily average spot rate relative to the log average spot rate the day before the auction. The solid curves present 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 6: IRF of Log Exchange Rate depending on the CIP condition: +/- 1 Day

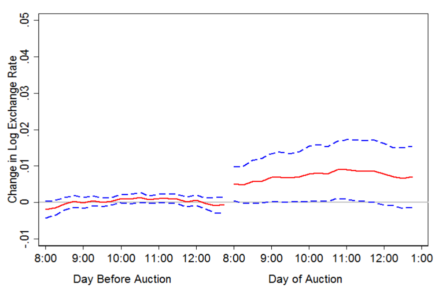
(a) Put - CIP Does Not Hold



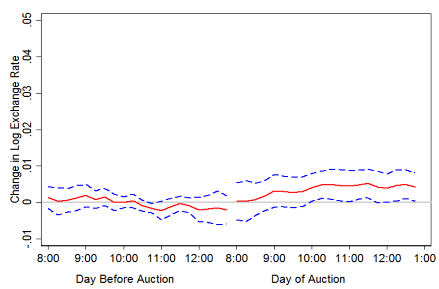
(b) Call - CIP Does Not Hold



(c) Put - CIP Holds



(d) Call - CIP Holds

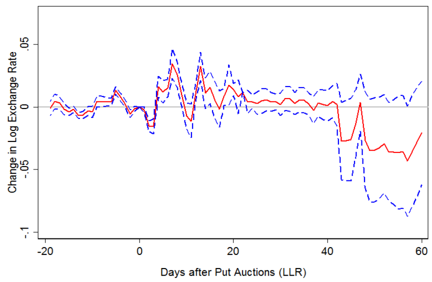


The dependent variable is the log average spot rate in 15-minute increments relative to the log average spot rate the day before the auction. The solid curve presents a series of regression discontinuity estimates implemented using local linear regression of the dependent variable on the running variable. 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.

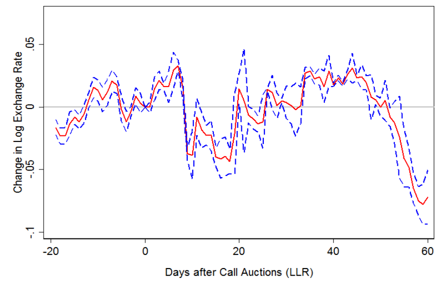
G Supplemental Appendix: Additional Figures and Tables

Figure G.1: IRF of Log Exchange Rate, 60 Days, Only Period with 4% Cutoff

(a) Issuance of Put Options



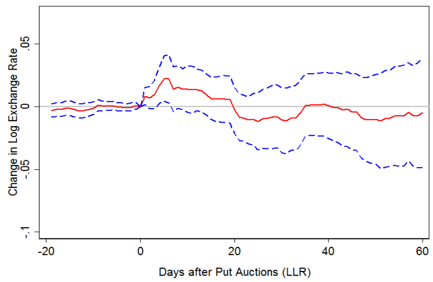
(b) Issuance of Call Options



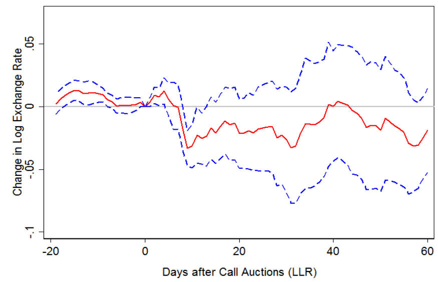
The dependent variable is the log daily average spot rate relative to the log average spot rate the day before the auction. The solid curve presents a series of regression discontinuity estimates implemented using local linear regression of the dependent variable on the running variable using daily data. Dashed curves display 95% confidence intervals of the estimates. The sample is restricted to periods when the cutoff for intervening was set at its original level of 4% appreciation or depreciation.

Figure G.2: IRF of Log Exchange Rate, 60 Days, with Control Variables

(a) Issuance of Put Options



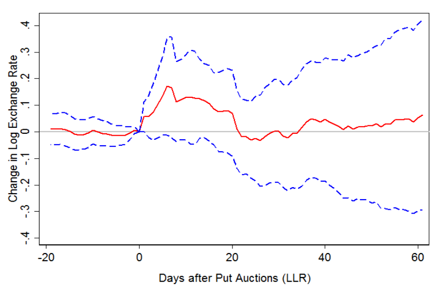
(b) Issuance of Call Options



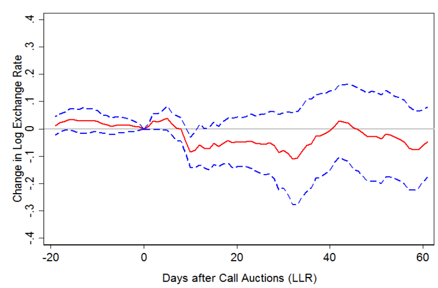
The dependent variable is the log daily average spot rate relative to the log average spot rate the day before the auction. The solid curve presents a series of regression discontinuity estimates implemented using local linear regression of the dependent variable on the running variable using daily data. Dashed curves display 95% confidence intervals of the estimates. For comparison, bandwidths are kept identical to the main text specifications that have no controls. Controls include dummies for the cutoff rate period (2%, 4%, 5%, or rule not in effect) as well as two lags of log spot exchange rate changes, average appreciation rates in negotiated forward contracts, average appreciation rates in exercised forward contracts, and the interbank interest rate.

Figure G.3: IRF of Log Exchange Rate, 60 Days, with Continuous Treatment

(a) Issuance of Put Options



(b) Issuance of Call Options

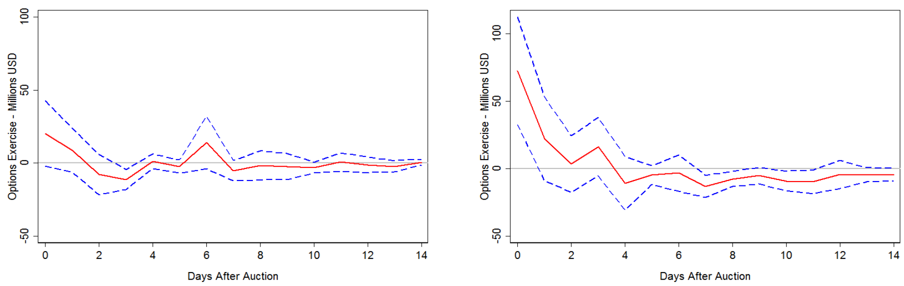


The dependent variable is the log daily average spot rate relative to the log average spot rate the day before the auction. The solid curve presents a series of fuzzy regression discontinuity estimates implemented using local instrumental variables regression. The endogenous treatment is the ratio of dollars of rule-based CBoC interventions relative to total volume. We use a dummy for being above the cutoff rate as the excluded instrument. We also control for the running variable and the running variable interacted with being above the cutoff. We use daily data. Dashed curves display 95% confidence intervals of the estimates. For comparison, bandwidths are kept identical to the main text specifications.

Figure G.4: Options Exercised: Two Weeks after Issuance

(a) Exercising of Put Options

(b) Exercising of Call Options

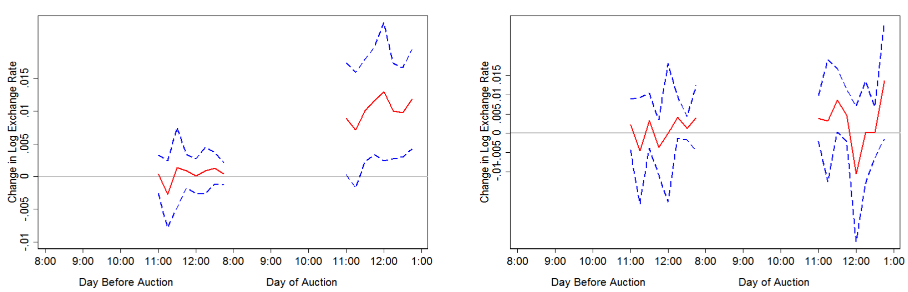


Solid curve presents a series of regression discontinuity estimates implemented using local linear regression of options exercised X days since the auction on the running variable. Dashed curves display 95% confidence intervals of the estimates.

Figure G.5: IRF of Log Forward Exchange Rate: +/- 1 Day

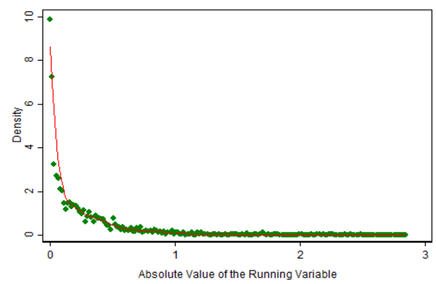
(a) Put

(b) Call



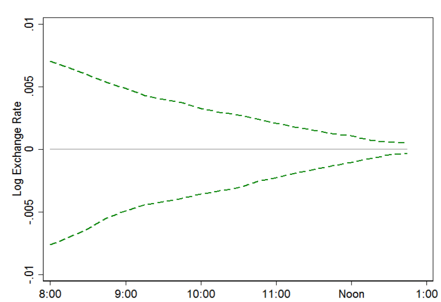
The dependent variable is the log average forward exchange rate in 15-minute increments relative to the log average forward exchange rate the day before the auction. The solid curve presents a series of regression discontinuity estimates implemented using local linear regression of the dependent variable on the running variable. Dashed curves display 95% confidence intervals of the estimates. Values shown only between 11:00 a.m. and 1:00 p.m. because forward contracts are rarely exchanged before 11 a.m.

Figure G.6: 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.

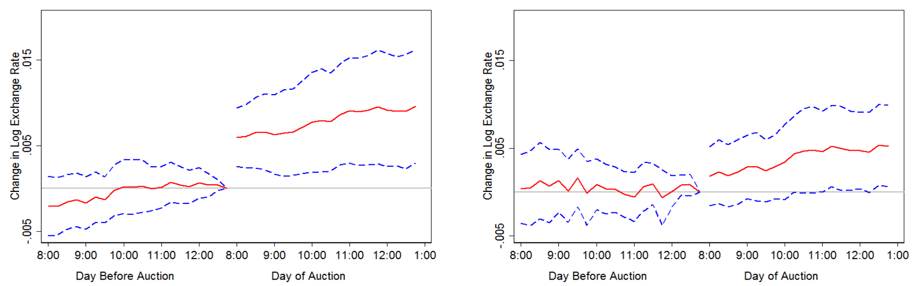
Figure G.7: Typical Range of Exchange Rate Variation through the Day



We calculate the difference between the log daily exchange rate measured as an average at the end of the day (TRM) and the log average that would be calculated at different points of the day using our tick-by-tick FX data. This difference roughly measures the percent change in TRM between a point during the day and the end of the day. We plot the 97.5th and 2.5th percentiles of this difference by the time of day.

Figure G.8: IRF of Effects on Exchange Rate Appreciation, Relative to Previous Day's Close, +/- 1 Day From Auctions

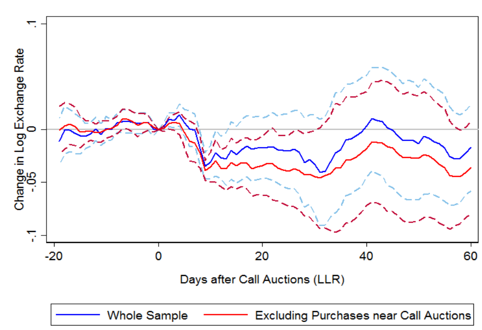
(a) Puts - Full Sample (b) Calls - Full Sample



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 between 12:45 and 1:00 p.m. the day before the auction. The solid curve presents a series of regression discontinuity estimates of the difference between triggered and not triggered days, implemented using local linear regression of the dependent variable on the running variable. The dashed curves display 95% confidence intervals of the estimates.

Figure G.9: IRF of Log Exchange Rate, 60 Days, Excluding Purchases of USD near Call Auctions

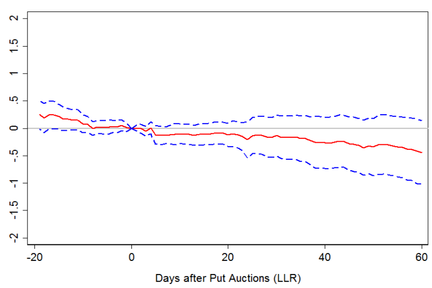
(a) Issuance of Call Options



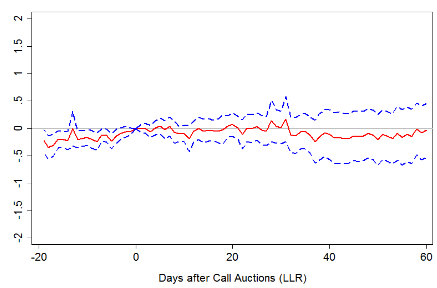
The dependent variable is the log daily average spot rate relative to the log average spot rate the day before the auction. The solid curve presents a series of regression discontinuity estimates implemented using local linear regression of the dependent variable on the running variable using daily data. Dashed curves display 95% confidence intervals of the estimates. Episodes in which the central bank purchased foreign currency within a 1-month range of call issuance were excluded, in particular, during October 2002, June 2006, November 2006 and from June 29008 henceforth.

Figure G.10: Effects on Domestic Interest Rates

(a) Puts - Full Sample



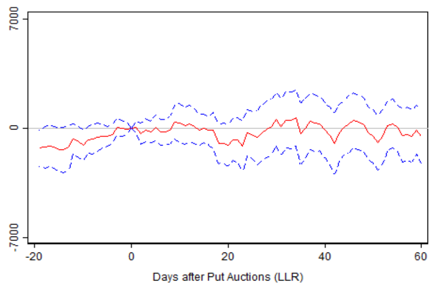
(b) Calls - Full Sample



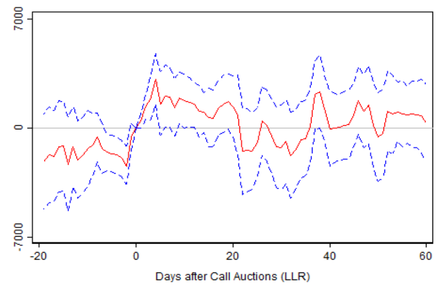
The dependent variable is the interbank interest rate, Colombia's analogue of the federal funds rate in the US, relative to its level at the time of the auction. The solid curve presents a series of regression discontinuity estimates implemented using local linear regression of the dependent variable on the running variable using daily data. Dashed curves display 95% confidence intervals of the estimates.

Figure G.11: 60 day IRFs of Sterilization Mechanisms

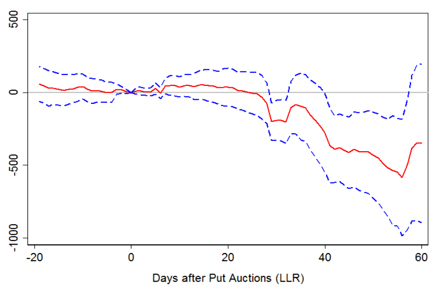
(a) REPOS Full Sample - Put



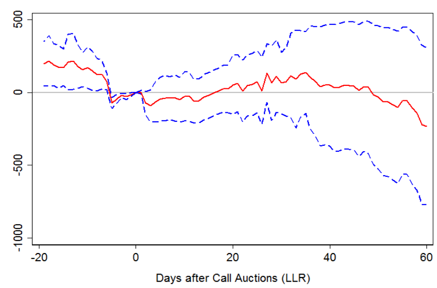
(b) REPOS Full Sample - Call



(c) Col Treasuries Full Sample - Put



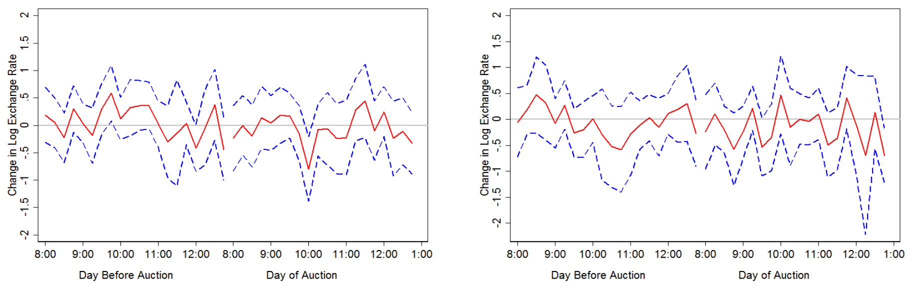
(d) Col Treasuries Full Sample - Call



Panes (a) and (b) show the effects of repurchasing agreements, while Panes (c) and (d) show the effects of domestic sovereign bonds. All variables measured in billion (10^9) pesos.

Figure G.12: IRF of Market Interest Rates for Colombian Treasury Bonds: +/- 1 Day from Auctions

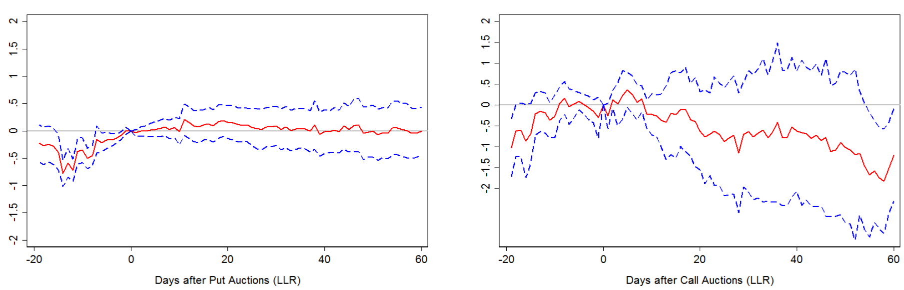
(a) Issuance of Put Options (b) Issuance of Call Options



The interest rate is measured as the simple average of market trades for Colombia Treasury Bonds in 15-minute increments minus the 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 G.13: IRF of Market Interest Rates for 1-Year Colombian Treasury Bonds, 60 Days

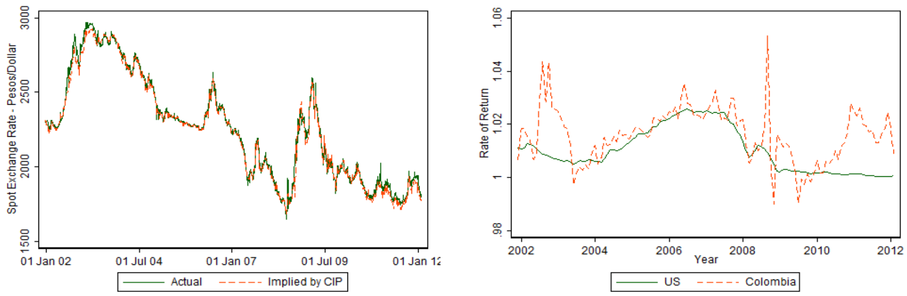
(a) Issuance of Put Options (b) Issuance of Call Options



The dependent variable is the market interest rate for 1-year Colombian Treasury Bonds relative to 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 G.14: Covered Interest Rate Parity Condition

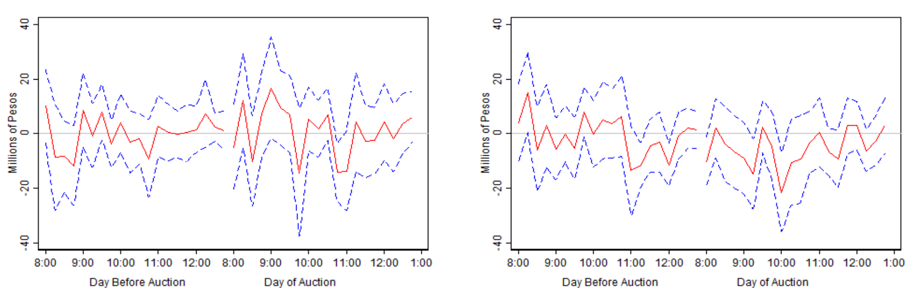
(a) CIP in Pesos (b) Implied Interest Rate



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 G.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.

Table G.1: Descriptive Statistics: ± 20% below or above threshold

	Put miss		Put trigger		Call miss		Call trigger	
Variable	Mean	St.Dev	Mean	St.Dev	Mean	St.Dev	Mean	St.Dev
Central Bank Sterilization Operations								
Repurchasing Agreements[a]	2.96	2.86	4.05	2.49	1.51	1.92	2.50	1.93
COL Treasuries[a]	-.010	.046	.001	.031	.003	.011	.006	.030
Obs 1950								
Financial Sector Balances								
COL Treasuries of 5 largest banks[a]	13.9	3.1	14.9	2.6	14.5	2.7	14.7	1.9
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
Obs 1799								
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
Obs 2433								
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[d]	19.3	38.8	20.3	3.3	15.7	5.4	17.8	5.1
Obs 2433								
High Frequency Variables								
Exchange rate (COP/USD) Amount Traded[d]	0.84	0.31	0.98	0.40	0.66	0.25	0.72	0.29
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
Obs 3.5 x 10^6								
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
Obs 2433								

Authors' Calculations. Sample period corresponds to Dec 2001-Feb 2012. ([a]) denote variables in trillions (10^{12}) of pesos -COP. ([b]) denote ratios of USD-to-COP denominated assets, expressed in COP. ([c]) denote variables in millions of dollars -USD. ([d]) denote variables in billions of dollars. PP (*Posicion Propia*) and PPC (*Posicion Propia de Contado*) include and exclude positions in derivatives, respectively.