Foreign Exchange Interventions, Exchange-Rate Expectations, and Risk Premia

PRELIMINARY AND INCOMPLETE

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Abstract

This paper employs the event study method to test if interventions cause changes in expectations of the exchange rate. Potential endogeneity of interventions are addressed by synthetic control. Expectations are risk-adjusted futures prices of foreign exchange. Using a panel of 9 countries, we find that an intervention leads the market to revise expectations by an average of 50 basis points in the direction predicted by the intervention. Interventions that are large relative to GDP and that reinforce short-term trends in the exchange rate have a success rate of 90% and cause an average change in expectations of 80 basis points. Significant changes in risk premia are also detected, but are less systematic, suggesting that interventions may contribute to foreign exchange market uncertainty.

Keywords: Foreign Exchange Intervention, Monetary Policy, Event Study, Synthetic Control

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1. Introduction

Sterilized foreign exchange interventions (FXI) have long puzzled academic international economists. The academic literature does not agree on the mechanism through which interventions might work, and the more optimistic studies suggest the effects are ephemeral. On the other hand, central banks do not seem at all puzzled by sterilized interventions. Many have intervened more or less regularly since the move to generalized floating and continue to do so. The Bank of Israel, in particular, makes such frequent use of interventions that its governor has suggested that FXI be considered a conventional monetary policy tool.[1]

This paper empirically examines the effectiveness of FXI. We employ the event-study method to assess if FXI causes changes in expectations of the exchange rate at a fixed future date. Exchange-rate expectations are FX futures prices adjusted by our estimates of the risk premium. Our daily data is an unbalanced panel of 9 countries, spanning from 1979 to 2016. We strongly reject the hypothesis that interventions are ineffective. 70% of interventions cause a change in expectations in the direction predicted by whether the intervention is to buy or sell the domestic currency. 24% cause at least a one standard deviation change in the predicted direction. Conditional on the FXI being large (at least 0.005% of GDP) and reinforcing the one-week trend in the spot price, the directional success rate improves to 89%.

Futures prices are a natural starting point to measure daily market expectations, but in a world of risk-averse market participants, the risk premium on the foreign currency causes futures prices to be biased predictors of the exchange rate. Exploiting the term structure of futures contracts, we estimate risk premia using the affine term structure model of Hamilton and Wu (2014). A set of daily market expectations of (log) future exchange rates are obtained by adjusting (log) futures prices by the

[1] Karnit Flug, opening remarks,
http://www.boi.org.il/en/Research/ConferencesAndSeminars/Documents/Flug%20-%20openning%20remarks.n.pdf

estimated risk premium. We then employ the expectations in the event study and test whether central bank interventions cause expectations of the future exchange rate to change.[2]

Foreign exchange interventions are not random but are responses to economic conditions. Endogenous interventions can lead to biases that overstate or understate the effectiveness. If the intervention is intended to reverse the trend of the exchange rate, momentum of the trending exchange rate could dominate the intervention. This 'leaning against the wind' practice can result in attenuation bias. On the other hand, concerns about credibility can lead a central bank to strategically intervene when it thinks the intervention will be most successful, leading to amplification bias. To control for endogeneity, we employ the *synthetic control method* developed by Abadie et al. (2010) and recently introdued to the FXI literature by Chamon et al. (2017). The idea is to compare the intervention episode to a comparison group not affected by interventions, but mimics the pre-intervention observations as close as possible.

The empirical literature on the effectiveness of foreign exchange intervention is vast and mixed. Excellent surveys of the literature have been written by Edison (1993), Sarno and Taylor (2001), Neely (2005), Disyatat and Galati (2007), Neely (2011), Menkhoff (2013), Engel (2014), and Daude et al. (2016). One obstacle faced by previous studies is data availability. Until recently, only the US, Japan, Switzerland, and Germany made their intervention data available. More recently, many countries have released official daily intervention data. Proxies for intervention data such as news reports are known to miss official interventions (Fischer (2006)), while central bank foreign reserves are better suited for low-frequency studies (e.g. Adler et al. (2015) and Blanchard and Adler (2015)).

Three recent papers study the effectiveness of interventions by individual cen-

[2]The event study is also employed by Dominguez and Frankel (1993), Kaminsky and Lewis (1996), Fatum and Hutchison (2003), Fatum and Hutchison (2006), Fratzscher et al. (2018) and Dominguez (2003).

tral banks, and one uses a panel. Using daily data, Kuersteiner (2016) employs a regression discontinuity design to study the Central Bank of Colombia's rule-based interventions and finds interventions to be short-lived, but effective at moving the contemporaneous spot rate. Caspi et al. (2017) also employ high-frequency data and report evidence that the Bank of Israel's interventions affect the level of the USD-ILS exchange rate for up to 40 trading days. Chamon et al. (2017) employs the synthetic control method and finds effectiveness in Brazil's pre-announced and fairly continuous interventions on the spot rate. Our paper is most similar to Fratzscher et al. (2018). Fratzscher et al. (2018) builds off the methodologies of Fatum and Hutchison (2003) and (2006) to study daily interventions for a panel of 33 countries, and find that only 60% of interventions achieve the correct direction of change predicted by the direction of intervention. Higher success rates can be achieved when the FXI is pre-announced and large.

Our paper contributes to the literature by finding foreign exchange interventions to be effective, but differs from recent papers in that our focus is on the effect on market expectations of the spot rate rather than on the contemporaneous spot rate. While high-frequency data helps to attenuate the endogeneity problem (Dominguez (2003)), it can make it more difficult to assess the durability or persistence of intervention. In the late 1990s several developed countries stopped intervening, precisely because the academic evidence suggested intervention was weak and ephemeral (Neely (2005)). By studying the effect on market expectations we can assess the perceived durability or persistence of the interventions. If the intervention significantly changes the expected one-year ahead spot rate, the market is expecting the intervention to last for at least one year. Further, our panel of 9 countries enhances the external validity of our findings.

While not our primary focus, a by-product of our analysis is that we can also study how intervention affects the risk premium. 65% of FX purchases (sales) cause the risk premium to increase (decrease). Similar to the case with expectations, success rates of up to 80% can be achieved when the FXI is large and reinforces the one week trend in the spot price. Moreover, 60% of interventions cause at least a one standard deviation deviation change in the risk premia, regardless of the direction of intervention. This suggests FXI may contribute to market uncertainty.

To summarize our main results, we find that by traditional measures of success, interventions are effective at moving expectations in the direction of the intervention. We find higher unconditional success rates compared to Fratzscher et al. (2018)'s panel (70% versus 60%), but our data sets and methodologies differ so the source of the differences is not obvious. Intervening in large amounts that reinforce short term trends in the spot price, significantly improve success rates. Interventions are durable in the sense that they move expectations of the exchange rate 52 weeks in the future. The effect on expectations is similar to the effect on the contemporaneous spot rate. However, the average size of the response is small: 0.5%. If success is defined as causing at least a one standard deviation change in the expected exchange rate in the correct direction, the results appear less rosy. Only 25% cause a significant change in the correct direction, which is statistically better than random, but less impressive than the directional success rates. Finally, FXI changes the equilibrium compensation of foreign exchange risk, but the direction of the effect is less systematic than for expectations. We interpret this difficulty for the market to interpret the intervention's conseqences for risk as an increase in uncertainty.

The remainder of the paper is as follows. The next section gives an overview of three alternate theoretical channels through which sterilized foreign exchange interventions might operate. Section 3 discusses features of our intervention data. Section 4 presents our two-step empirical methodology–adjusting futures foreign exchange prices with the estimated risk premium and the synthetic control method. Section 5 presents our main results. Section 6 presents some auxilliary results on the effects of FXI on expected future interest rates. Section 7 concludes.

2. Potential Channels for Intervention Effectiveness

Interventions are typically sterilized. If the intent is to depreciate, the initial sale of the domestic currency is offset by a sale of domestic government bonds so as to leave the monetary base unchanged. The result is a change in the composition of the central bank's assets, but no change in the overall size of its assets or liabilities. The literature discusses three possible primary channels through which a sterilized intervention can be effective; they are the signaling channel, the portfolio channel, and the coordination channel.

The idea behind the signaling channel (Mussa (1981)) is that the central bank uses sterilized intervention to signal a future change in monetary policy. In the class of models that price the exchange rate as the present value of future monetary fundamentals, today's exchange rate is seen to change in response to the expected future change in monetary policy signaled by the intervention. Kaminsky and Lewis (1996) ask whether Fed interventions signal changes in future monetary policy by testing whether interventions predict changes in various monetary policy variables. They find the signs of the changes are opposite of what theory would suggest, which could suggest endogeneity bias.

In the portfolio balance channel (see Branson (1979) and Dornbusch (1980)), the public views domestic and foreign currency denominated bonds as imperfect substitutes. Sterilized intervention results in a swap of domestic currency bonds for foreign currency bonds in the central bank's asset holdings. In order for the public to willingly take the other side of the asset swap, relative bond returns change through an adjustment in the exchange rate. Dominguez and Frankel (1993)'s seminal paper finds that Fed and Bundesbank intervetions cause deviations from uncovered interest parity, indicating that interventions may operate through a portfolio balance channel. They do not distinguish between sterilized and unsterilized interventions.

The coordination channel (Sarno and Taylor (2001)) considers an environment populated by rational and irrational agents. Irrational traders can launch the exchange rate on a non-fundamentals (bubbly) path. The bubble can persist when dispersed and atomistic rational agents have no incentive to take the opposing currency trade. The central bank intervenes to signal its belief that the exchange rate is mis-aligned and on a non-fundamentals path. The intervention then provides a coordinating mechanism for rational traders to take the opposite side of the irrational trades which brings the exchange rate back in line with the macroeconomic fundamentals.

3. The Data

Our sample includes the nine countries/central banks displayed in Table 1. These are countries whose central banks either publically provide daily intervention data or who responded to our requests for that data, and for which foreign exchange futures prices were available for at least five consecutive years.[3]

Table 1: FX intervention data and coverage

Country / Area	Source	Currencies	Frequency	Intervention Data	Futures
Australia	FRED	AUD-USD	Daily	1983-2016	1992-2015
Canada	On request	CAD-USD, CAD-JPY	Daily	1970-2011	1979-1999
ECB	Website	EUR-JPY	Daily	1999-2016	1999-2016
Japan	FRED	JPY-USD, EUR-JPY	Daily	1991-2015	1986-2015, 1999-2016
Poland	Website	PLN-EUR	Daily	2004-2015	2006-2016
Switzerland	FRED	CHF-USD, JPY-USD	Daily	1975-2008	1986-2015, 1992-2015
Turkey	FRED	USD-TRY	Daily	2002-2015	2005-2016
United Kingdom	On request	EUR-GBP, GBP-JPY,	Daily	1977-2016	1999-2016, 1998-2013
		GBP-USD, JPY-USD			1990-2015, 1986-2015
United States	FRED	EUR-USD, JPY-USD	Daily	1973-2016	1999-2016, 1986-2015

The size of foreign exchange intervention in our data are small relative to total market volume. The typical daily intervention is less than 0.04% of *daily* foreign exchange trading volume of the corresponding currency. Interventions are also quite common. Of the nearly 65,000 daily observations in our sample, nearly 1,300 (2%)

[3]Foreign exchange futures prices are obtained from Thompson Reuter's *Datastream*

contain a currency intervetion intervention. 51% of interventions are net sales of the domestic currency. 60% appear to "lean against the wind," meaning the intervention is in the direction to reverse the preceding 5-week trend of the exchange rate.

Less than 1% of intervention days in our sample are followed by interventions in the subsequent 2 weeks. In their analyses, Dominguez and Frankel (1993), Fatum and Hutchison (2003) and Fratzscher et al. (2018), employ daily observations and define an intervention "episode" by requiring there to be a fixed number of days with zero interventions before a new episode begins. Following this convention, we require a minimum of five days between intervention episodes. This leaves us with nearly 440 intervention episodes, the vast majority of which are single-day events.[4]

4. Empirical methodology

We proceed in two steps. First, we estimate a term-structure of foreign exchange risk premia. These estimated risk-premia are then used to adjust the futures prices to obtain estimates of the expected future spot rates. Second, we conduct an event study using these expected future spot rates to assess the effectiveness of foreign exchange intervention. The synthetic control method is used to control for intervention endogeneity. Section 4.1 discusses the methodology we employ to estimate the risk premia used to adjust futures prices. Section 4.2 discusses the synthetic control event-study methodology.

4.1. Risk premia estimation

We adapt the affine oil-futures term-structure model of Hamilton and Wu (2014) to estimate foreign exchange risk premia. The difference is that oil futures expire

[4]There is some evidence that frequency matters for intervention effectiveness. Ito (2003) finds that the Bank of Japan's small frequent interventions were less effective than its large infrequent interventions. Dominguez et al (2013) find that the Czech National Bank's discretionary, infrequent interventions are ineffective, but sales carried out daily lead to an economically and statistically significant appreciation. The interventions we analyze are small and infrequent.

every month, whereas currency futures mature quarterly, on the second business day before the third Wednesday of the contract month. The appendix contains a full description of the model and estimation. Here, we provide a brief description of the essential features.

Let v_t be a k-dimensional vector of latent factors whose dynamics are governed by the first-order vector autoregression,

$$v_{t+1} = c + \rho v_t + \Sigma u_{t+1},$$

where ρ is a $k \times k$ matrix, Σ is a lower triangular $k \times k$ matrix, and $u_t \overset{iid}{\sim} N(0, I_k)$. The time t log price of a foreign exchange futures contract that expires in h periods f_t^h, has the factor representation,

$$f_t^h = a_h + \beta_h' v_t,$$ [5]

If investors are conditional mean-variance optimizers, expected returns on the futures contract have the beta-risk representation,

$$E_t\left(f_{t+1}^{h-1} - f_t^h\right) = \beta_{h-1}' \lambda_t$$

where

$$\lambda_t = \lambda + \Lambda v_t,$$

is the vector of factor risk prices, and the factor loadings β_h' and a_h, are functions of the risk-prices, λ and Λ,

$$\beta_h' = \beta_{h-1}' \rho - \beta_{h-1}' \Lambda, \tag{1}$$

$$a_h = a_{h-1} + \beta_{h-1}' c + (1/2)\beta_{h-1}' \Sigma\Sigma' \beta_{h-1} - \beta_{h-1}' \lambda. \tag{2}$$

The implied risk-neutral (log) futures price is defined as

$$\tilde{f}_t^h = \tilde{a}_h + \tilde{\beta}_h' \nu_t.$$

[5] There is no idosyncratic term, $e_{h,t}$. The first two contracts are assumed to be priced exactly as the model predicts, while the third contract is priced with error. See Appendix A.

where $\tilde{a}_h$ and $\tilde{\beta}_h$ correspond to equations (1) and (2) with $\Lambda = \lambda = 0$. Thus $\tilde{f}_t^h$ is the estimated expected future spot price, and the estimated risk premium is

$$RP_{t+h} = \tilde{f}_t^h - f_t^h.$$

We assume a two-factor structure, so ν_t is a 2×1 vector consisting of the level and the slope of the term structure of futures contracts. With two factors, estimation requires at least three futures contracts to identify the structural parameters. Consequently, we use the three futures contracts nearest to expiry which we denote as $(f_t^h, f_t^{h+13}, f_t^{h+26})$. The level factor is $\frac{1}{2}(f_t^{26-j} + f_t^{39-j})$, and the slope factor is $f_t^{39-j} - f_t^{26-j}$, for $j \in \{1, ..., 13\}$, which is the calendar week within the set of quarters. The structrual parameters are estimated by the minimum chi-square method, which is asymptotically equivalent to maximum likelihood.[6] This yields three sets of expectations for each country, each set corresponding to a different contract maturity. Since contracts are quarterly, this yields a set of 13, 26, and 39 week expectations. Employing these estimates in the recursions (1) and (2) also allows us to obtain 52 week ahead expectations, as well as daily estimates of expectations for each horizon.

4.2. The Synthetic Control Method

When interventions are not random but undertaken in response to developments in the foreign exchange market, estimates of intervention effectiveness may be biased. To control for potentially endogenous interventions, we employ the *synthetic control method* developed by Abadie et al. (2010). The method was also used by Chamon et al. (2017) in their study of Brazillian foreign exchange interventions. The idea is to compare post-intervention observations on exchange rate expectations against alternative sequences that mimics the pre-intervention observations but were not affected by an intervention.

[6] See Hamilton and Wu (2012) for a detailed discussion of this procedure.

In event time, let τ_0 be the length of the pre-event window, measured in days, and let τ_1 be the length of the post-intervention window. Let $T = \tau_0 + \tau_1$ be the number of observations surrounding the event. We denote the $T \times 1$ vector of exchange rate expectations "treated" by a single intervention at time t as:

$$Y = (\underbrace{\tilde{f}_1^h, \tilde{f}_2^{h-1}, ..., \tilde{f}_{\tau_0-1}^{h-\tau_0+2}, \tilde{f}_{\tau_0}^{h-\tau_0+1}}_{\text{Pre-intervention, } X'}, \underbrace{\tilde{f}_{\tau_0+1}^{h-\tau_0}, ..., \tilde{f}_{\tau_1}^{h-\tau_1+1}}_{\text{Post-intervention, } Z'})'$$

Next, let X be the set of pre-intervention observations, and Z be the set of post-intervention observations. The "event" is the daily intervention between τ_0 and $\tau_0 + 1$.[7]

For a given currency, let there be N available length T sequences of exchange rate expectations not affected by an intervention. These form the set of artificial sequences which we denote by the $T \times N$ matrix $\mathbf{Y}$.

$$\mathbf{Y} = \begin{pmatrix} \tilde{f}_{1,1}^h & \tilde{f}_{1,2}^{h-1} & ... & \tilde{f}_{1,\tau_0-1}^{h-\tau_0+2} & \tilde{f}_{1,\tau_0}^{h-\tau_0+1} & \tilde{f}_{1,\tau_0+1}^{h-\tau_0} & ... & \tilde{f}_{1,\tau_1}^{h-\tau_1+1} \\ \tilde{f}_{2,1}^h & \tilde{f}_{2,2}^{h-1} & ... & \tilde{f}_{2,\tau_0-1}^{h-\tau_0+2} & \tilde{f}_{2,\tau_0}^{h-\tau_0+1} & \tilde{f}_{2,\tau_0+1}^{h-\tau_0} & ... & \tilde{f}_{2,\tau_1}^{h-\tau_1+1} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \underbrace{\tilde{f}_{N,1}^h \quad \tilde{f}_{N,2}^{h-1} \quad ... \quad \tilde{f}_{N,\tau_0-1}^{h-\tau_0+2} \quad \tilde{f}_{N,\tau_0}^{h-\tau_0+1}}_{\text{Pre-intervention, } \mathbf{X}'} & & & & & \underbrace{\tilde{f}_{N,\tau_0+1}^{h-\tau_0} \quad ... \quad \tilde{f}_{N,\tau_1}^{h-\tau_1+1}}_{\text{Post-intervention, } \mathbf{Z}'} \end{pmatrix}' = \begin{pmatrix} Y^1 \\ Y^2 \\ \vdots \\ Y^N \end{pmatrix}'$$

Decompose the control group $\mathbf{Y}$ into $\mathbf{X}$, a $\tau_0 \times N$ matrix of τ_0 observations to match the pre-intervention observations and $\mathbf{Z}$, a $\tau_1 \times N$ matrix to match the post-intervention observations. The synthetic control method chooses an $N \times 1$ vector of weights, $W = (w_1, ..., w_N)'$, to minimize the quadratic distance between X and $\mathbf{X} \cdot W$,

$$\min_W \quad (X - \mathbf{X} \cdot W)'\mathbf{V}(X - \mathbf{X} \cdot W)$$

$$\text{s.t.} \quad \sum_{i=1}^{N} w_i = 1 \text{ and } \quad 0 \leq w_i \leq 1 \; \forall \; i$$

[7] Our estimates are based on closing prices of FX futures, so $\tilde{f}_{\tau_0+1}^{h-\tau_0}$ is the first observed price affected by an intervention.

where $\mathbf{V}$ is diagonal positive-definite matrix selected to minimize the mean-squared prediction error of $\mathbf{X} \cdot W$. The weights, w_i, are non-negative and sum to one. Having obtained W, we construct the vector of intervention treatment effects

$$\alpha = Y - \mathbf{Y} \cdot W,$$

which measures the percent difference between the vector of observed expectations, Y, 'treated' by the event and the vector $\mathbf{Y} \cdot W$, 'untreated' by the event. Now split α into pre-and post-intervention observations, $\alpha^{pre} = X - \mathbf{X} \cdot W$ and $\alpha^{post} = Z - \mathbf{Z} \cdot W$. By construction, $\alpha^{pre} \approx \mathbf{0}$. Then the effect of the intervention is reflected in movements in α^{post}.

To test if post-intervention movements are signifcant, we compare α^{post} to the distribution of control sequences. To generate this distribution, replace the Y sequence 'treated' by the intervention with first 'untreated' sequence Y^1, remove Y^1 from the matrix $\mathbf{Y}$ and repeat the process described above. This produces a sequence α^1 where synthetic control has been applied to a no-intervention sequence. Repeating with $Y^2, ..., Y^N$ gives the null distribution $(\alpha^1, ...\alpha^N)$.

We set the pre-event window to be five days, $(\tau_0 = 5)$, and the post-event window to be six days, $(\tau_1 = 2)$.[8] The analysis is repeated for each contract horizon and for every intervention in the sample.

We noted that Chamon et al. (2017) also employ the synthetic control method to study the effect of Brazil's sterilized interventions on the spot exchange rate, and they control for various financial variables meant to capture the state of the economy at the time of intervention. Our study differs in that we are focused on the effect on exchange rate expectations. Since our expectations are risk-adjusted futures prices, the state of the economy should be contained in our risk premium estimates.[9]

[8] A long pre-event window reduces the bias of the synthetic control estimator. We found no gains from extending the pre-event window beyond five days. However, pre-event windows shorter than five days failed to caputure short-term exchange rate trends, suggesting that counterfactuals generated over shorter periods are likely biased.

[9] Failure to control for the state of the economy in the risk premia estimates may explain the

5. Results

This section contains the main empirical results. Section 5.1 assesses the quality of our expected future spot rates with an out-of-sample forecasting exercise. Section 5.2 reports the results of three event studies on the expectations, the risk premia, and for comparison with the literature, on the contemporaneous spot rate.

5.1. The risk-premium adjustment

We follow Baumeister and Kilian (2017) and assess the use of the adjusted futures prices as estimated expectations with an 'out-of-sample' forecast experiment.[10] It is well-known that exchange rates are difficult to predict. The conventional benchmark for forecast accuracy is the random-walk forecast. A time-varying risk premium will cause the raw futures price to be a biased predictor. If our estimates of the risk premium are any good, our adjusted futures prices will outperform both the random walk forecasts and the unadjusted futures price forecasts.

Since exchange rate futures expire on specific dates, the expectations we obtain are are "fixed-event" forecasts. That is, we end up with sequences of forecasts of the exchange rate at a specific future date. As the event approaches, the forecast window shrinks. However, statistical tests of accuracy are formulated for fixed-horizon forecasts. To enable the use of such tests, we follow Rossi et al. (2017), Dovern et al. (2012), Patton and Timmermann (2010), and Ang et al. (2007), by averaging expectations over each contract to approximate fixed-horizon forecasts. For a given quarterly contract with a fixed expiration, we average the 13 weekly forecasts contained within the quarter. This gives a single forecast for the quarter. Repeating this over every contract results in a set of quarterly expectations with fixed horizons, which allows us to use Clark and West (2005) to test the hypothesis

inconsistent response of risk premia to FXI we observe. E.g., see Sarno et al (2012). As FX risk premia properties are not the focus of our paper, we leave this question open to future researchers.

[10]This is not a true out-of-sample experiment because estimation employs the full sample.

that our forecasts are significantly more accurate than the random walk forecasts.[11]

Forecast accuracy is evaluated by mean-square prediction error. Forecasts are generated for 26, 39, and 52 weeks ahead. Table 2 shows Theil's U-statistics for fixed-event forecasts generated by the adjusted and the unadjusted futures prices. The table also shows the forecasting sample period, which varies by data availability of the various currencies. Significance in forecast accuracy over the random walk is determined by running Clark and West (2005) on the fixed-horizon forecasts.

For AUD-USD expectations (row 1), the U-statistics on expectations are less than one at each horizon, whereas, the U-statistics for unadjusted futures forecasts all exceed one. This pattern generally holds across the the other currency pairs. The success rate for beating the random-walk is 89 percent, and 69 percent of the U-statistics are less than one are significant at the 10 percent level or better.

To summarize, the raw futures prices are no more accurate in forecasting than the random walk. Risk-adjusted futures prices are signifncantly more accurate than the random walk. This suggests that our measured expectations are superior estimates of the true market expectations. We now examine how the expected future spot rates are affected by intervention.

5.2. The effect of interventions on exchange rate expectations

This section contains the main results of the paper. We calculate an α for each intervention event for every country. We split the results into purchases and sales of foreign exchange. Results are reported graphically in Figure 1. The figure plots the average value, $\bar{\alpha}$. Results for domestic currency sales are shown in the left column, and for domestic currency purchases in the right column. Interventions that purchase the domestic currency should cause a decline in $\tilde{f}_t^h$. The vertical line indicates the

[11] Say, for an an $h = 26$ week contract, there will be 13 weekly contracts predicting the same date but of different forecast horizons. The averaged forecast over the contract is $\bar{f}_t = \frac{1}{12}\sum_{j=0}^{12} f_{t+j}^{26-j}$. We also repeat this exercise by averaging over the first, second, and third four weeks of the contracts, and the patterns are the same. These tables were not reported to conserve space, but are available on request.

time of the intervention. The dashed lines show the mean of the null distribution, plus and minus one standard deviation.

The mean change in expectations is consistent with the direction of intervention, but within one standard deviation from the null response. For domestic currency sales (left column), positive post-event deviations from the synthetic control counterfactual can be seen at each horizon. The average peak expected depreciation is 25, 24 and 24 basis points (bps) at the 26, 39, and 52 week horizons, respectively. The right column of the figure shows results for domestic currency purchases. We see similar patterns with slightly larger effects: the average peak expected appreciation is −63, −58 and −46 bps at the 26, 39, and 52 week horizons, respectively.

Table 4 reports success rates across forecast horizons. A sale (purchase) of the home currency is successful if the expected future spot increases (decreases). The top panel shows success rates for the day of an event, and the bottom panel shows the same success rates 5 days after the initial FXI. Under the null hypothesis that the interventions have no effect, the success rate should be 0.5. The success rate for achieving a one standard deviation change in the correct direction should be 0.16. At the 26-week horizon, the raw success rate is 0.70 and the proportion of significant successes is 0.24. P-values from the associated binomial test are also shown.[12] Under both criteria for success, the hypothesis that interventions are ineffective is rejected.

Iterventions also appear persistent. The observed level-shift in the term structure of expectations, and success rates for each contract horizon, suggest that market participants expect the change to be permanent.

Next we ask under what conditions FXI can be more successful. If we condition on large FXI (at least 0.005% of GDP) and FXI that reinforces the existing one-week spot price trend, then the likelihood of success as measured by the directional criteria is greatly improved, but the probability causing a large change in the expected

[12]Hypothesis testing was also conducted using a non-parametric sign test. These tests bolster the results from the binomial test, and are available upon request.

spot price does not significantly improve. Conditional on a large intervention, the directional success rate improves from 70% to 85%. Conditional on reinforcing the 1 week spot price trend, success improves from 70% to 82%. Conditional on both, the success rate improves to 89%. The success rate for causing a larger than one-standard deviation change improves modestly from 24% to 27% when the FXI is large and the trend in the spot is reinforced.

Figure 2 shows the mean response of a "best case scenario". That is, conditional on the directional criteria, and conditional on large FXI that reinforces the one week spot trend, how large is the average response? The conditional peak response is about twice as large as the unconditional response (or roughly one standard deviation).

In summary, it appears to be relatively easy to achieve directional success, but much more difficult to cause a large change in the spot price.

5.2.1. Individual country results

Figure 3 shows the mean response of interventions on 26 week expectations for both FX purchases and FX sales. Results are separated by country. Peak responses for FX purchases range from 0.02 (Switzerland) to 2.16 (Poland). FX sales appear to be more successful, with peak responses ranging from -0.41 (Australia) to -3.33 (Switzerland). The mean peak response 0.53 and -1.21 for FX purchases and sales respectively.[13]

More heterogeneity is observed in the success rates. Raw success rates for altering 26 week expectations in the direction predicted by intervention (one day after the event) range from 0.49 (Japan) to 0.86 (Canada). Success rates for causing a one standard deviation change in the predicted direction range from 0.13 (Turkey) to 0.50 (Poland). The mean success rates for these two criteria are 0.59 and 0.26 respectively. 72% of this cross-country heterogeneity in success rates is explained by whether a country's set of interventions lean predominantly with or against the one week trend in the spot price. For example, 93% of the top performing country's

[13]The ECB has been excluded from this section due to small sample size.

(Canada) interventions reinforce short-term trends, while only 46% of the lowest performing country's interventions reinforce short-term trends.[14]

5.2.2. The effect of interventions on risk premia

Several studies have documented an increase in uncertainty following intervention. Fatum and Hutchison (1999) find that Fed interventions raise the conditional variance of Fed funds futures prices, and Bein et al. (2007) find that interventions are followed by an increase in the heterogeneity of survey forecasts of JPY-USD and DEM-USD exchange rates. Rogers and Silkos (2003) find that interventions raise the implied volatility of currency futures options for Australia but not Canada, while Galati et al. (2005) find similar results for the Fed and Japan. Chari (2007) finds that Fed and Bank of Japan interventions lead to increased volatility and a widening of bid-ask spreads in the intra-day FX market. Although it is not our primary focus, this section evaluates the effect of interventions on estimated risk premia.

Figure 4 graphically presents the results for the pooled sample. The left column of the figure shows results for home currency sales and the right column shows results for home currency purchases. If intervention affects currency risk, we expect a domestic currency sale to raise the risk premium. Since the price of the futures contract on the foreign currency is increasing in the risk premium, the writer of that contract should require more compensation to lock in delivery against the more risky domestic currency. The pattern of responses are as expected.

The magnitude of changes in the risk premium is smaller than that of the risk-adjusted futures prices. Average peak responses for, domestic currency sales are 0.16%, 0.20%, and 0.26% at the 26, 39, and 52 week horizons respectively, while domestic currency purchase lower the risk premium by 0.13%, 0.15%, and 0.23% at those same horizons.

Table 5 shows the interventional success rates on the risk premia. The raw success

[14] Similar heterogeneity is observed in risk premia responses. This heterogeneity is also explained by whether a country predominantly reinforces existing spot price trends.

rate ranges from 0.64 to 0.68. Many of the interventions induce the risk premium to move opposite the predicted direction. However, the proportion of significant changes that go in the predicted direction ranges from 0.39 to 0.44.

To test for a change in uncertainty we test what proportion of interventions cause significant changes in the risk premium, regardless of the direction of intervention. Under the null that intervention does not cause uncertainty, the proportion should be 0.32. Instead, we find "success rates" of 0.60. This widening of the cross-sectional risk premia distribution suggests that FXI contributes to market uncertainty.[15]

5.3. The effect of interventions on contemporaneous exchange rates

To compare our results on expectations and with the recent literature, we perform the event study on the contemporaneous spot exchange rate. The results are shown in Figure 5. Similar to the expectations, we find deviations from the counterfactual following intervention. The deviation is 0.46% for domestic currency sales and −0.52% for domestic purchases. This patterns of the change in direction are consistent with those of the expectations.

Success rates of spot price changes are slightly higher than those of the expectations changes: 76% of changes in the spot price is consistent with the direction of intervention, and 28% of changes are consistent with the direction of intervention and statistically significant.

We conclude that in our data, the effect of foreign exchange intervention on the spot rate is consistent with effects on expected future exchange rate, and with the recent empirical literature.

[15] We also find higher conditional success rates when FXI is large and reinforces the existing spot price trend. Directional criteria success rates approach 80%. Success rates for achieving large changes in the correct direction approach 60%. Upwards of 70% of interventions cause uncertainty to increase.

6. Foreign Exchange Interventions and Expected Future Interest Rates

This section presents auxiliary results examining the effects of interventions on expected future interest rates. The motivation is two-fold. First, whether a foreign exchange intervention has a durable and persistent effect on (expectations of) future interest rates can shed light on the alternative mechanisms discussed in Section 2. If either the signaling hypothesis or the portfolio balance channel are operative, the intervention should lead to a durable change in domestic interest rates, and hence in expected future interest rates. Second, if a foreign exchange intervention is sterilized, it should not have a lasting effect on the interest rate.

The data that we use are prices of 90-day interbank interest rate futures contracts. The data source is Thompson Reuter's *Datastream*. We choose 90-day interbank futures because they have the broadest coverage across countries and time.[16] Interest rate futures are quoted in terms of the corresponding zero-coupon bond price. We estimate expected future bond price by adjusting the futures price with estimated risk premia using the methodology of Section 4.1.[17] This estimates become the observations that form an unbalanced panel covering 1987 to 2016.

Let $\tilde{b}_t^h$ be the log risk-adjusted future bond price on a country i contract that expires at $t + h$. As with the foreign exchange contracts, we are using interest-rate futures with expirations at 13, 26, 39, and 52 weeks ahead. Let I_{it} be a dummy variable that is 1 if the central bank sells its currency in a foreign exchange intervention -1 if it buys its currency.

We assume that central banks do not engage in foreign exchange intervention in response to money-market conditions so that endogeneity is not a concern here. Absent the endogeneity, the synthetic control is unnecessary. Here, we exploit the panel and estimate the fixed-effects regression of the post-intervention change in the

[16] We use eurobond futures for the United States. The correlation between the daily eurobond rate and the daily Fed Funds rate is 0.99.

[17] The interest rate risk premia are *not* term premia. It is compensation required to induce a futures contract writer to guarantee a future 90-day interest rate.

expected bond price,

$$\tilde{b}^{h-k}_{i,t+k} - \tilde{b}^{h}_{i,t} = \gamma_i + \delta \cdot I_{it} + \sum_{j=1}^{2} \beta_j \tilde{b}^{h}_{i,t-j} + \epsilon_{i,t}. \tag{3}$$

Our interest centers on the coefficient δ. The regression includes two lagged changes in expected bond prices as controls. We run two-such regressions. One for the $k = 1$ period change in the expected future bond price and one for the $k = 5$ period change. Interventions are excluded from the regression if the five days preceding or following are "contaminated" by another intervention.

We also run the analogous regression of the post-intervention change in our estimated bond risk premium, $\rho^{h}_{i,t}$.

$$\rho^{h-k}_{i,t+k} - \rho^{h}_{i,t} = \gamma_i + \delta \cdot I_{it} + \sum_{j=0}^{2} \beta_j \Delta\rho^{h}_{i,t-j} + \epsilon_{it} \tag{4}$$

Table 6 reports the results. The point estimate of the one-week change in the expected 26 week ahead bond price induced by foreign exchange intervention is $\delta = -0.020$, or 2 basis points. While the result is statistically significant, the magnitude is small, and explains virtually none of the variation in the data. None of the estimated intervention effects on expected future bond prices and risk premia that we considered are statistically significant. These results support the findings of Kaminsky and Lewis (1996) and Fatum and Hutchison (1999). While the failure to find a result doesn't mean it's not present, the insignificance of these results are a lack of support for the signaling hypothesis and for the portfolio balance channel. The regression results are not inconsistent with Sarno and Taylor's (2001) coordination channel. In that world, the central bank intervention signals to the public it's belief that exchange rate movements are out of line with market fundamentals. Since interest rates are (at least a component) of the fundamentals, coordinating rational traders to take positions that offset the noise traders in foreign exchange should have no effect on expected future interest rates.

On the issue of sterilization, statements on the websites of the central banks that constitute the overwhelming of our sample, including the New York Fed, Bank of Canada, Bank of England, the ECB, all claim to sterilize intervention. The extensive case studies of Japan also claim sterilization. The results in this section empirically confirm these statements.

7. Conclusion

This paper estimates daily exchange rate expectations and risk premia, which become objects of interest in an event study. We provide evidence that sterilized foreign exchange interventions are highly effective at affecting the direction of change in expected future spot prices, but less effective at causing a sizable change. Large FXI that reinforces short-term trends in the spot price achieve directional success rates of nearly 90%, but do not significantly improve the likelihood of causing large changes.

Interventions are found to change the risk premium, but the direction of the effect is less consistent. The inconsistent market interpretation may be a sign that interventions contribute to uncertainty in the foreign exchange market.

Finally, we find that foreign exchange interventions do not change expected future interest rates. This evidence confirms central bank claims that their interventions are sterilized, and offers a shred of evidence that interventions operate through the coordination channel of Sarno and Taylor (2001).

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Figure 1: Mean Response of Adjusted Futures Prices

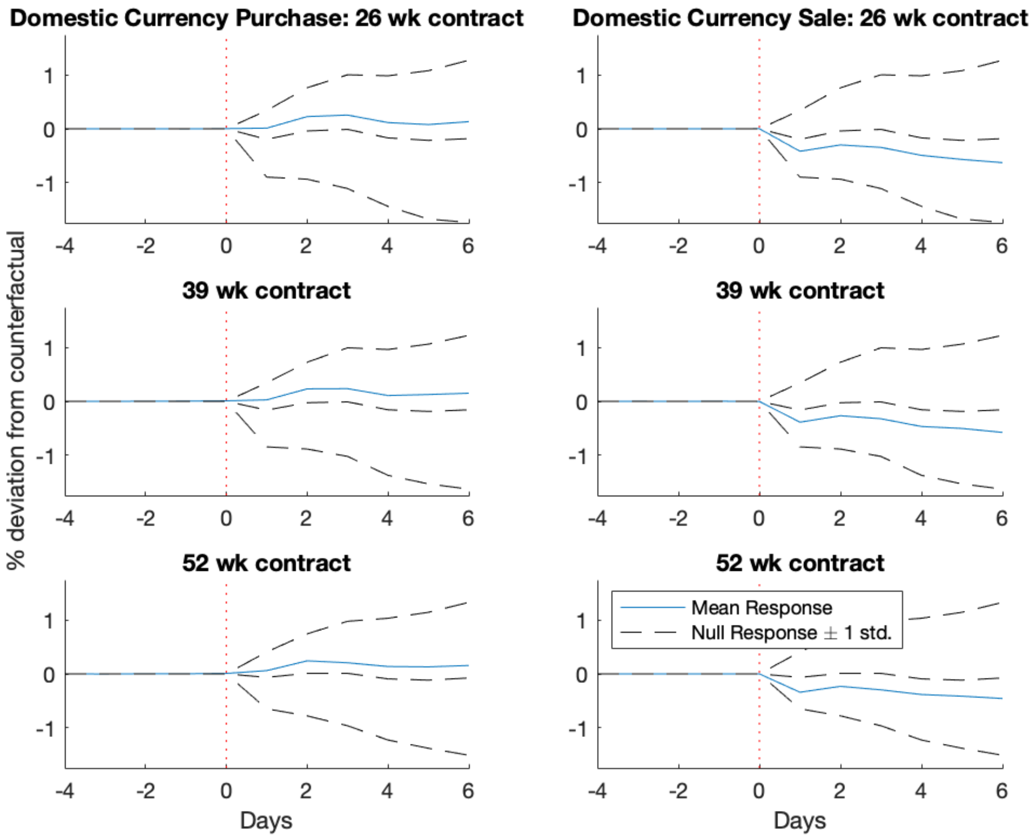

Figure 2: Conditional Response of Adjusted Futures Prices

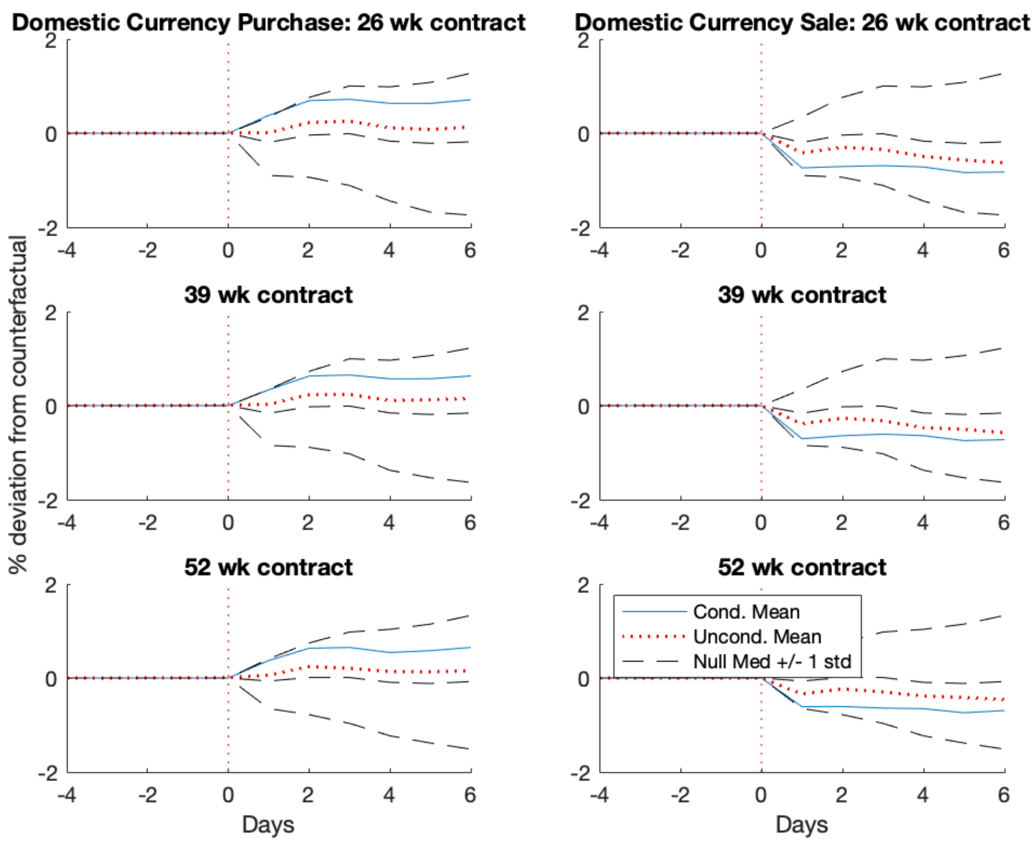

Figure 3: Mean Response of 26 Week Adjusted Futures Prices by Country

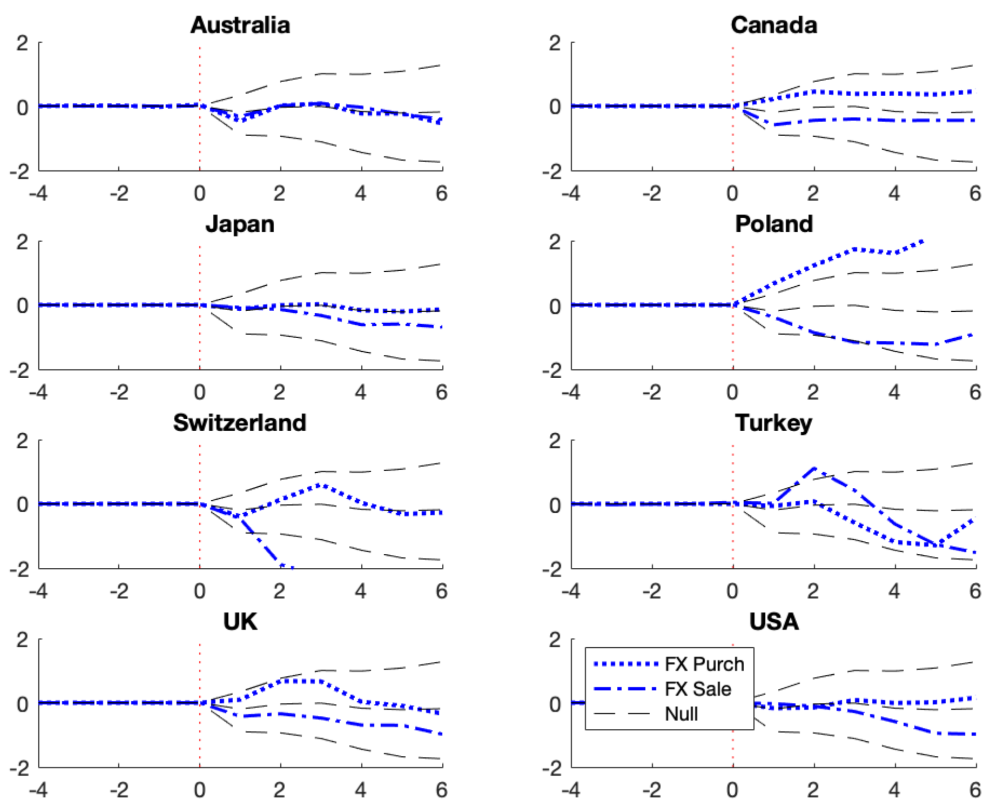

Figure 4: Mean Response of Estimated Risk Premia

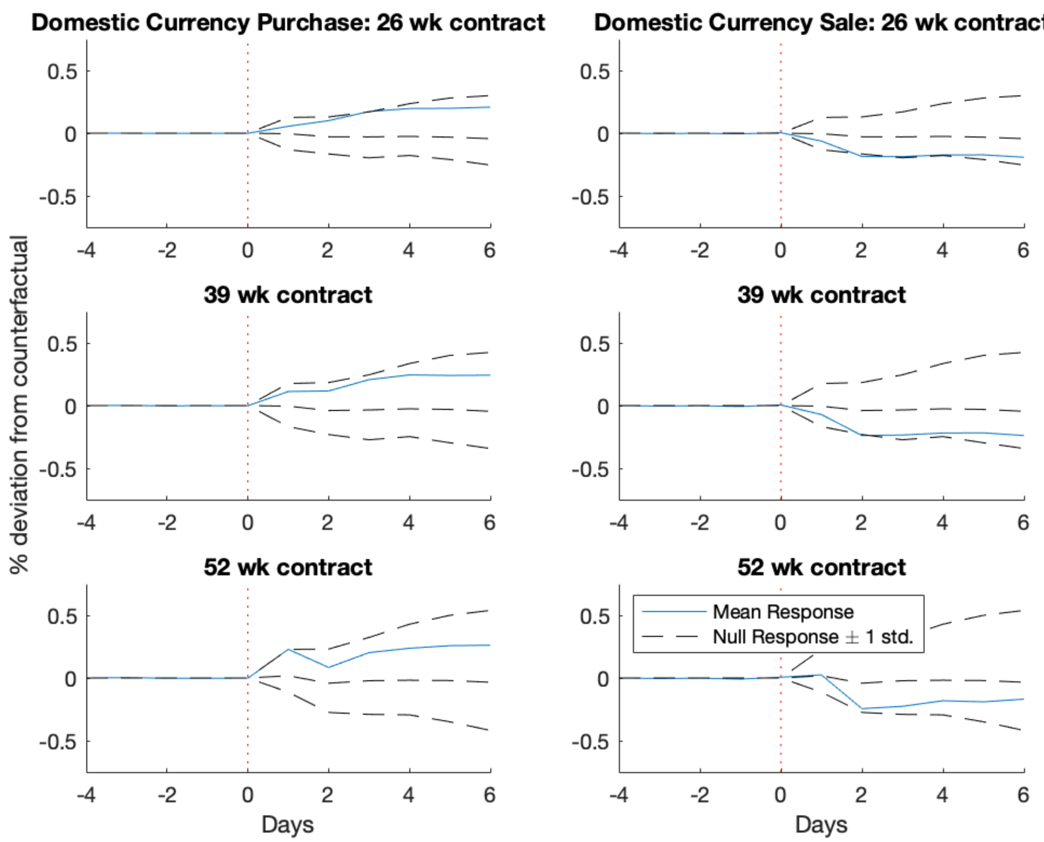

Figure 5: Mean Response of Contemporaeous Spot Prices

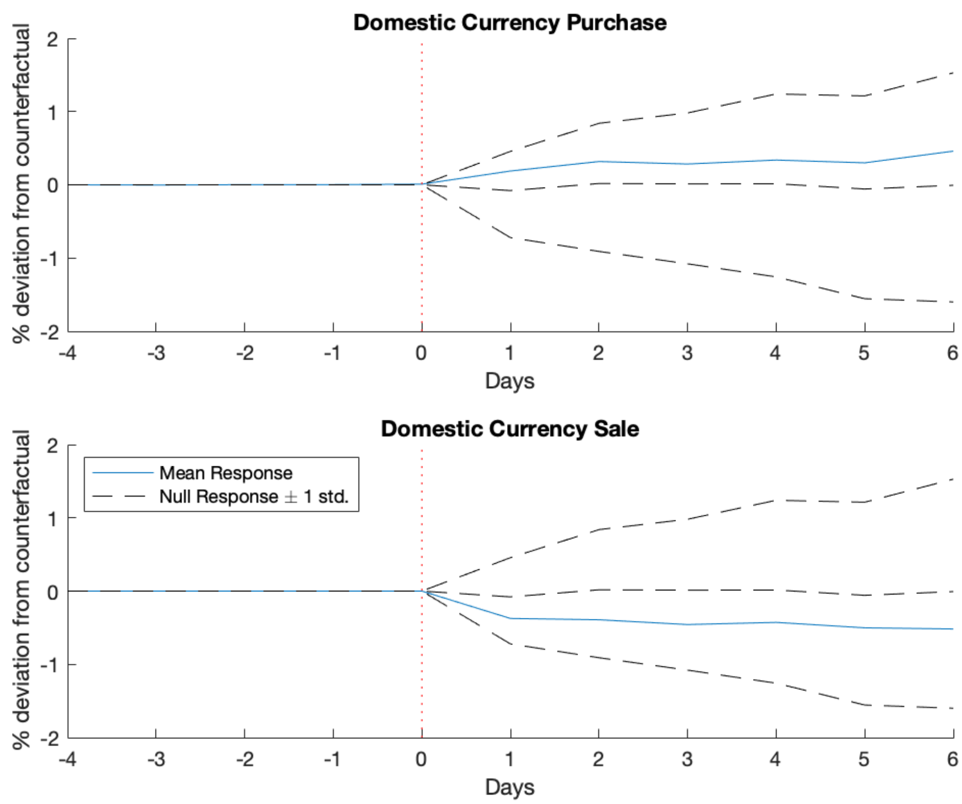

Table 2: Theil's U for Raw and Adjusted Futures Prices at Fixed Horizon, h week, Forecasts

		Risk-adjusted			Futures price		
Exchange Rate	Period	26 wk	39 wk	52 wk	26 wk	39 wk	52 wk
AUD-USD	1992 to 2015	**0.944***	**0.891****	**0.818****	1.037	1.058	1.096
CAD-JPY	2009 to 2016	**0.984**	**0.950**	**0.924**	1.024	1.059	1.090
CAD-USD	1979 to 1999	**0.968*****	**0.862*****	**0.763*****	1.132	1.162	1.189
CHF-USD	1992 to 2015	**0.991**	**0.942***	**0.865****	1.018	1.033	1.058
EUR-GBP	1999 to 2016	**0.948*****	**0.919****	**0.866****	**0.970***	**0.956***	**0.934***
EUR-JPY	2009 to 2016	**0.995**	**0.995****	**0.992***	**0.990**	**0.981**	**0.971***
EUR-USD	1999 to 2016	1.030	**0.975**	**0.925**	1.021	1.029	1.038
GBP-JPY	1998 to 2013	**0.957**	**0.942**	**0.931**	**0.947**	**0.937**	**0.932**
GBP-USD	1990 to 2015	**0.862****	**0.785****	**0.754****	**0.959**	**0.945**	**0.943**
JPY-USD	1986 to 2016	**0.909*****	**0.822*****	**0.749*****	1.038	1.074	1.106
PLN-EUR	2004 to 2016	1.010	1.008	1.006	1.016	1.012	1.002
USD-TRY	2005 to 2016	**0.925***	**0.913***	**0.880***	**0.919***	**0.962**	1.008

Theil's U is the ratio of the mean-square prediction error of the model of interest to that of the random walk prediction. Forecasts are averaged over the entire 13 weeks of a contract, then used to predict the (log) spot rate on the date of expiry. **Bold** indicates improvement over the random walk forecast.
$*$ = 10% significance, $**$ = 5% significance, $***\leq$ 1% significance, by Clark-West.

Table 3: Interventional Success Rates for Adjusted Futures Prices

Day of Initial FXI	Contract Length	Raw Success	p-value	Success among Significant in Predicted Direction	p-value
	26 wk	0.70	0.000	0.24	0.000
	39 wk	0.70	0.000	0.22	0.000
	52 wk	0.69	0.000	0.21	0.009
5 Days Following Initial FXI	Contract Length	Raw Success	p-value	Success among Significant in Predicted Direction	p-value
	26 wk	0.66	0.000	0.17	0.371
	39 wk	0.66	0.000	0.16	0.472
	52 wk	0.64	0.000	0.13	0.031

Raw success: an intervention is successful if the change in the expected future spot price following the intervention is consistent with the direction of intervention (e.g., a domestic currency sale (purchase) causes the expected spot price to increase (decrease). P-values correspond to the binomial test of $H_0 : successrate = 0.5$ against $H_a : successrate \neq 0.5$.

Success among significant in predicted direction: an intervention is successful if the observed change is at least one standard deviation from the mean null response and in the correct direction. P-values correspond to the binomial test of $H_0 : successrate = 0.16$ against $H_a : successrate > 0.16$.

Table 4: Conditional Success Rates for Adjusted Futures Prices

Condition	Contract Length	Observations	Conditional Success Rate	p-value	Conditional Success + 1 std change	p-value
(A) Large Intervention						
	26 wk	204	0.85	0.000	0.26	0.000
	39 wk	204	0.84	0.000	0.23	0.009
	52 wk	192	0.83	0.000	0.21	0.045
(B) Reinforce 1 week trend						
	26 wk	330	0.82	0.000	0.28	0.000
	39 wk	330	0.82	0.000	0.26	0.000
	52 wk	302	0.79	0.000	0.25	0.000
(A) and (B)						
	26 wk	183	0.89	0.000	0.27	0.000
	39 wk	183	0.87	0.000	0.22	0.015
	52 wk	173	0.86	0.000	0.20	0.082

Conditional success: an intervention is successful if the change in the expected future spot price following the intervention is consistent with the direction of intervention (e.g., a domestic currency sale (purchase) causes the expected spot price to increase (decrease). Interventions that do not satisfy the stated condition are not included in the sample. P-values correspond to the binomial test of $H_0 : successrate = 0.5$ against $H_a : successrate \neq 0.5$.

Conditional success + 1 std change: an intervention is successful if the observed change is at least one standard deviation from the mean null response and in the correct direction. Interventions that do not satisfy the stated condition are not included in the sample. P-values correspond to the binomial test of $H_0 : successrate = 0.16$ against $H_a : successrate > 0.16$. conditional the direction criteria, and intervention is successful

Table 5: Interventional Success Rates on the Risk Premium

Day of Initial FXI	Contract Length	Raw Success	p-value	Success among Significant in Predicted Direction	p-value	Significant Only	p-value
	26 wk	0.64	0.000	0.39	0.000	0.60	0.00
	39 wk	0.64	0.000	0.42	0.000	0.60	0.00
	52 wk	0.68	0.000	0.44	0.000	0.60	0.00
5 Days Following Initial FXI	**Contract Length**	**Raw Success**	**p-value**	**Success among Significant in Predicted Direction**	**p-value**	**Significant Only**	**p-value**
	26 wk	0.61	0.000	0.37	0.000	0.57	0.00
	39 wk	0.62	0.000	0.37	0.000	0.56	0.00
	52 wk	0.63	0.000	0.36	0.000	0.54	0.00

Raw success: an intervention is successful if the change in the risk premium following the intervention is consistent with the direction of intervention (e.g., a domestic currency sale (purchase) causes the risk premium to increase (decrease). P-values correspond to the binomial test of $H_0 : successrate = 0.5$ against $H_a : successrate \neq 0.5$.

Success among significant in predicted direction: an intervention is successful if the observed change is at least one standard deviation from the mean null response and in the correct direction. P-values correspond to the binomial test of $H_0 : successrate = 0.16$ against $H_a : successrate > 0.16$.

Significant only: an intervention is successful if the observed change is at least one standard deviation from the mean null response and in the correct direction. P-values correspond to the binomial test of $H_0 : successrate = 0.32$ against $H_a : successrate > 0.32$.

Table 6: Intervention Effect on Expected Future Bond Price and Risk

	Expected Future Price			Risk Premium		
h	13	26	39	13	26	39
	A. One-day change ($k = 1$)					
δ	-0.020	-0.020	-0.019	-0.001	-0.003	-0.004
(t-ratio)	(-3.38)	(-2.56)	(-2.37)	(-1.56)	(-1.28)	(-1.20)
R^2	0.005	0.001	0.001	0.011	0.005	0.003
	B. Five-day change ($k = 2$)					
δ	-0.038	-0.045	-0.045	-0.003	-0.007	-0.010
(t-ratio)	(-1.16)	(-1.53)	(-1.32)	(-2.25)	(-1.19)	(-0.91)
R^2	0.005	0.002	0.019	0.007	0.002	0.001

Notes: δ is the coefficient from regressions (3) and (4), and captures the $k = 1, 2$ week cumulative change in expectations or risk premia of a given horizon, h.

Appendix A. Hamilton and Wu Affine Term-Structure of Futures Contracts Model

The model consists of investors with mean-variance preferences. At time t, investors choose notional exposures, z_{th}, for each $h-$period futures contract, F_t^h. Additionally, they can take positions, q_{jt} in other assets $j = 0, 1, ..., J$, with gross returns $exp(r_{j,t+1})$. The risk-free yield is $r_{0,t+1}$. The investor's total wealth at $t + 1$ is then,

$$W_{t+1} = \sum_{j=0}^{J} q_{jt} exp(r_{j,t+1}) + \sum_{h=1}^{H} z_{ht} \frac{F_{t+1}^{h-1} - F_t^h}{F_t^h}$$

The investor then maximizes

$$E_t(W_{t+1}) - \left(\frac{\gamma}{2}\right) Var_t(W_{t+1})$$

subject to $\sum_{j=0}^{J} q_{jt} = W_t$. γ is a constant that measures the degree of risk aversion.

Assume there exists a vector of factors, v_t, that jointly determines all returns and follows a Gaussian vector autoregression (VAR):

$$v_{t+1} = c + \rho v_t + \Sigma u_{t+1}$$

where $u_t \sim$ i.i.d. $N(0, I_m)$.

Under these assumptions, and the assumption that log futures prices and returns are affine functions of these factors:

$$f_t^h = log(F_t^h) = a_h + \beta_h' v_t \qquad \text{for } h = 1, ..., H \tag{A.1}$$

and

$$r_{jt} = \xi_j + \psi_j' v_t \qquad \text{for } j = 1, ..., J,$$

it can be shown:

$$\begin{aligned} E_t(W_{t+1}) \approx \;& q_{0t}(1 + r_{0,t+1}) + \textstyle\sum_{j=1}^{J} q_{jt}[1 + \xi_j + \psi_j'(c + \rho v_t) + (1/2)\psi_j' \Sigma\Sigma' \psi_j] + \\ & \textstyle\sum_{h=1}^{H} z_{ht}[a_{h-1} + \beta_{h-1}'(c + \rho v_t) - a_h - \beta_h' v_t + (1/2)\beta_{h-1}' \Sigma\Sigma' \beta_{h-1}] \end{aligned}$$

and

$$Var_t(W_{t+1}) \approx \left(\sum_{j=1}^{J} q_{jt}\psi_j' + \sum_{h=1}^{H} z_{ht}\beta_{h-1}'\right)\Sigma\Sigma'\left(\sum_{j=1}^{J} q_{jt}\psi_j + \sum_{l=1}^{H} z_{lt}\beta_{l-1}'\right).$$

The investor's first-order conditions are:

$$\frac{\partial E_t(W_{t+1})}{\partial q_{jt}} = 1 + r_{0,t+1} + (\gamma/2)\frac{\partial Var_t(W_{t+1})}{\partial q_{jt}} \text{ for } j = 1, ..., J$$

and

$$\frac{\partial E_t(W_{t+1})}{\partial z_{ht}} = (\gamma/2)\frac{\partial Var_t(W_{t+1})}{\partial z_{ht}} \text{ for } h = 1, ..., H,$$

which can be re-written as:

$$\xi_j + \psi_j'(c + \rho v_t) + (1/2)\psi_j'\Sigma\Sigma'\psi_j = r_{0,t+1} + \psi_j'\lambda_t$$

$$a_{h-1} + \beta_{h-1}'(c + \rho v_t) - a_h - \beta_h' v_t + (1/2)\beta_{h-1}'\Sigma\Sigma'\beta_{h-1} = \beta_{h-1}'\lambda_t \tag{A.2}$$

where

$$\lambda_t = \gamma\Sigma\Sigma'\left(\sum_{j=1}^{J} q_{jt}\psi_j + \sum_{l=1}^{H} z_{lt}\beta_{l-1}\right).$$

Suppose that in equilibrium, the investor's positions, q_{jt} and z_{ht}, are affine functions of the factors: $\lambda_t = \lambda + \Lambda v_t$. By (A.2), we have

$$\beta_h' = \beta_{h-1}'\rho - \beta_{h-1}'\Lambda, \tag{A.3}$$

$$a_h = a_{h-1} + \beta_{h-1}'c + (1/2)\beta_{h-1}'\Sigma\Sigma'\beta_{h-1} - \beta_{h-1}'\lambda. \tag{A.4}$$

Equation (A.2) is the expected return to a \$1 long position in an h-period contract entered at time t. Thus, (A.2) characterizes equilibrium returns in terms of the price of risk, λ_t:

$$E_t\left(\frac{F_{t+1}^{h-1} - F_t^h}{F_t^h}\right) \approx \beta_{h-1}'\lambda_t.$$

Equations (A.3) and (A.4) can be viewed as equilibrium conditions that would result from risk-neutral investors regarding the factor dynamics being governed by

$$v_{t+1} = c^Q + \rho^Q v_t + \Sigma u_{t+1}^Q, \tag{A.5}$$

where $c^Q = c - \lambda$, $\rho^Q = \rho - \Lambda$, and $u^Q_{t+1} \sim^Q N(0, I_m)$. For a detailed discussion on the economic interpretation of these equations, refer to HW (p. 12-14). For our purposes, it suffices to say that any economic force that induces z_{ht} to change will expose investors to different levels of risk, which changes the equilibrium compensation to risk, λ_t.

Appendix A.1. Estimation

The original model is based on oil futures contracts, which expire monthly whereas foreign exchange futures expire on the second business day preceding the third Wednesday of the contract month. We implement the model using quarterly currency futures contracts. Each quarter can be divided into exactly 13 weeks. The thirteenth week ends on the day the nearest contract expires, and the remaining weeks end accordingly. The ends of each week are determined by dividing the total number of trading days by 13.

Let $j_t \in \{1, ..., 13\}$ indicate where in the quarter t falls. An observation $\mathscr{Y}_t$ for week t can be characterized as follows:

$$\mathscr{Y}_t = \begin{cases} (f_{12t}, f_{25t}, f_{38t})' & \text{if } j_t = 1 \\ (f_{11t}, f_{24t}, f_{37t})' & \text{if } j_t = 2 \\ \vdots & \vdots \\ (f_{0t}, f_{13t}, f_{26t})' & \text{if } j_t = 13 \end{cases}$$

We use the nearest three contracts (as in the original model), and assume that the nearest two contracts are priced exactly as the model predicts. Since A.1 implies that each element of $\mathscr{Y}_t$ can be written as an exact linear combination of v_t, the system is stochastically singular. To overcome this issue, we assume third contract is priced with error. The underlying factors are assumed to be the level and slope of the term structure of the futures contract. That is, $\mathscr{Y}_{1t} = H_1 \mathscr{Y}_t$ where $H_1 = \begin{bmatrix} 0 & (1/2) & (1/2) \\ 0 & -1 & 1 \end{bmatrix}$. Since $\mathscr{Y}_t = (f_{13-j_t}, f_{26-j_t}, f_{39-j_t})'$, we also have $\mathscr{Y}_{1t} = A_{1,j_t} + B_{1,j_t} v_t$ with

$$A_{1,j_t} = H_1 \begin{bmatrix} a_{13-j_t} \\ a_{26-j_t} \\ a_{39-j_t} \end{bmatrix} \quad B_{1,j_t} = H_1 \begin{bmatrix} \beta'_{13-j_t} \\ \beta'_{26-j_t} \\ \beta'_{39-j_t} \end{bmatrix} \text{ for } j_t = 1, ..., 12 \text{ or } 13.$$

If $B_{1,j_{t-1}}$ is invertible,

$$\mathscr{Y}_{1t} = A_{1,j_t} + B_{1,j_t}c + B_{1,j_t}\rho[B^{-1}_{1,j_{t-1}}(\mathscr{Y}_{1,t-1} - A_{1,j_{t-1}})] + B_{1,j_t}\Sigma u_t.$$

Since u_t is independent of $\{\mathscr{Y}_{t-1}, ..., \mathscr{Y}_0\}$, then

$$\mathscr{Y}_{1t}|\mathscr{Y}_{t-1}, ..., \mathscr{Y}_0 \sim N(\phi_{jt} + \Phi_{j_t}\mathscr{Y}_{1,t-1}, \Omega_{j_t})$$

where $\Omega_{j_t} = B_{1,j_t}\Sigma\Sigma' B'_{1,j_t}$, $\Phi_{j_t} = B_{1,j_t}\rho B^{-1}_{1,j_{t-1}}$, and $\phi_{j_t} = A_{1,j_t} + B_{1,j_t}c - \Phi_{j_t}A_{1,j_{t-1}}$.

For the nearest contract,

$$\mathscr{Y}_{2t} = H_2\mathscr{Y}_t \text{ with } H_2 = [1\ 0\ 0],$$

differs from the predicted value by an i.i.d. measurement error with mean zero and variance σ^2_{e,j_t}. Then:

$$\mathscr{Y}_{2t} = A_{2,j_t} + B_{2,j_t}v_t + \sigma_{e,j_t}u_{e,t}$$

$$A_{2,j_t} = H_2 \begin{bmatrix} a_{13-j_t} \\ a_{26-j_t} \\ a_{39-j_t} \end{bmatrix} \quad B_{2,j_t} = H_2 \begin{bmatrix} \beta'_{13-j_t} \\ \beta'_{26-j_t} \\ \beta'_{39-j_t} \end{bmatrix} \text{ for } j_t = 1, ..., 12 \text{ or } 13.$$

Since the measurement error is independent:

$$\mathscr{Y}_{2t}|\mathscr{Y}_{1t}, \mathscr{Y}_{t-1}, ..., \mathscr{Y}_0 \sim N(\gamma_{j_t} + \Gamma_{j_t}\mathscr{Y}_{1t}, \sigma^2_{e,j_t})$$

$$\Gamma_{j_t} = B_{2,j_t}B^{-1}_{1,j_t} \text{ and } \gamma_{j_t} = A_{2,j_t} - \Gamma_{j_t}A_{1,j_t}.$$

Then the log-likelihood function, conditional on the initial observation, $\mathscr{Y}_0$, is

$$\mathscr{L} = \sum_{t=1}^{T} [\log g(\mathscr{Y}_{1t}; \phi_{j_t} + \Phi_{j_t}\mathscr{Y}_{1,t-1}, \Omega_{j_t}) + \log g(\mathscr{Y}_{2t}; \gamma_{j_t} + \Gamma_{j_t}\mathscr{Y}_{1t}, \sigma^2_{e,j_t})]$$

where $g(\mathscr{Y};\mu,\Omega)$ is the multivariate Normal density with mean μ and variance Ω evaluated at $\mathscr{Y}$.

We follow the same estimation procedure, Minimum-Chi-Squared (MCS), suggested by HW. HW (p.18-19) show that if $\phi_{j_t}, \Phi_{j_t}, \Omega_{j_t}, \gamma_{j_t}\Gamma_{j_t}, \sigma_{ej_t}$ are thought of as unrestricted parameters, rather than the values implied by the model, then the unconstrained likelihood function can be written such that it is maximized by a series of OLS regressions. The idea behind MCS is to choose structural parameters that would imply reduced-form coefficients as close as possible to the unrestricted estimates (which is asymptotically equivalent to maximum likelihood estimation).

Estimation follows these steps

1. Sort futures prices into 13 groups according to weeks until expiry. Group j is $(f_t^{13-j}, f_t^{26-j}, f_t^{39-j})$ for $j \in \{1, 2, ..., 13\}$.
2. For each group, regress the level factor $(\frac{1}{2}(f_t^{26-j} + f_t^{39-j}))$, on a constant and one level factor corresponding to the same week of the previous quarter.
3. For each group, regress the slope factor $(f_t^{39-j} - f_t^{26-j})$, on a constant and the slope factor corresponding to the same week of the previous quarter.
4. For each group, regress f_t^j on a constant, the level and slope factors.
5. OLS regression coefficients are $\hat{\phi}_{j_t}, \hat{\Phi}_{j_t}, \hat{\gamma}_{j_t}\hat{\Gamma}_{j_t}$, and the estimated variance of the residuals for the two sets of regressions are $\hat{\Omega}_{j_t}$ and $\hat{\sigma}_{ej_t}$.
6. Define ξ_1 and ξ_2 to be the eigenvalues of $\rho^Q = \rho - \Lambda$. Given this normalization and values for $\xi_1, \xi_2, \Sigma, a_0$, ρ^Q, c^Q, and $\{\beta_h, a_h\}_{h=0}^H$ can be determined. These, along with ρ, c and σ_e are sufficient for evaluating the likelihood function.
7. Collect the unknown structural parameters, $\{\xi_1, \xi_2, \rho, c, \sigma_{e1}, ..., \sigma_{e13}\}$ in the vector θ. Let $g(\theta)$ represent the values predicted by MLE. Collect the reduced form parameters (estimated via OLS) into another vector, $\hat{\pi}$.
8. Choose θ to minimize $[\hat{\pi} - g(\theta)]'\hat{R}[\hat{\pi} - g(\theta)]$, where $\hat{R}$ is the information matrix associated with the OLS estimates.

Once parameters have been estimated, factors are easily obtained, along with the risk-neutral prices (i.e., prices implied by setting $\lambda = \Lambda = 0$. The risk premium is defined as the difference between the true price and the risk-neutral price.

To obtain *daily* estimates of risk premia and risk-neutral prices, we observe that once the structural parameters are estimated, a_h and β_h, which are functions of the structural parameters, can be calculated for any h. The model implied prices follow from (A.1).

Appendix B. Risk Premia Summary Statistics and Graphs

The estimated risk premia are small–generally less than a couple basis points–and slightly negative on average, and the standard errors are relatively large. All risk premia are highly autocorrelated. The graphs of the risk premia show significant time-variation. The risk-adjusted prices (i.e., the market expectations) are slightly less volatile and tend to correctly predict the direction of change in future spot prices. Thus the implied market expectation is less noisy and a less biased prediction than the raw futures prices. Graphs of the risk premia are shown below, as well as plots comparing the market expectations and futures prices.

Table B.7: Risk Premia Summary Statistics

h = weeks in contract		Mean (bp)			Std Deviation (bp)			Auttocorrelation		
Currency	Period	h = 26	h = 39	h = 52	h = 26	h = 39	h = 52	h = 26	h = 39	h = 52
AUD-USD	1992 to 2015	-1.81	-2.66	-3.49	2.81	4.04	5.18	0.98	0.98	0.98
CAD-JPY	2009 to 2016	-1.38	-2.12	-2.89	0.13	0.20	0.28	0.96	0.96	0.96
CAD-USD	1979 to 1999	0.03	0.08	0.14	2.04	2.62	3.05	0.97	0.97	0.97
CHF-USD	1992 to 2015	-0.12	-0.10	-0.03	2.43	3.41	4.25	0.98	0.98	0.98
EUR-GBP	1999 to 2016	-0.24	-0.32	-0.38	1.90	2.68	3.37	0.93	0.94	0.94
EUR-JPY	2009 to 2016	-0.12	-0.22	-0.35	0.13	0.23	0.36	0.98	0.98	0.98
EUR-USD	1999 to 2016	-1.33	-1.87	-2.35	2.57	3.67	4.67	1.00	1.00	1.00
GBP-JPY	1998 to 2013	-1.15	-1.78	-2.44	0.66	1.03	1.44	0.99	0.99	0.98
GBP-USD	1990 to 2015	-0.66	-0.95	-1.22	2.18	3.05	3.80	0.99	0.99	0.99
JPY-USD	1986 to 2016	0.43	0.75	1.11	3.66	5.27	6.75	1.00	1.00	1.00
PLN-EUR	2004 to 2016	-0.86	-1.25	-1.62	0.46	0.66	0.83	0.97	0.97	0.97
USD-TRY	2005 to 2016	1.28	1.61	1.72	4.77	6.98	9.11	0.99	0.99	0.99

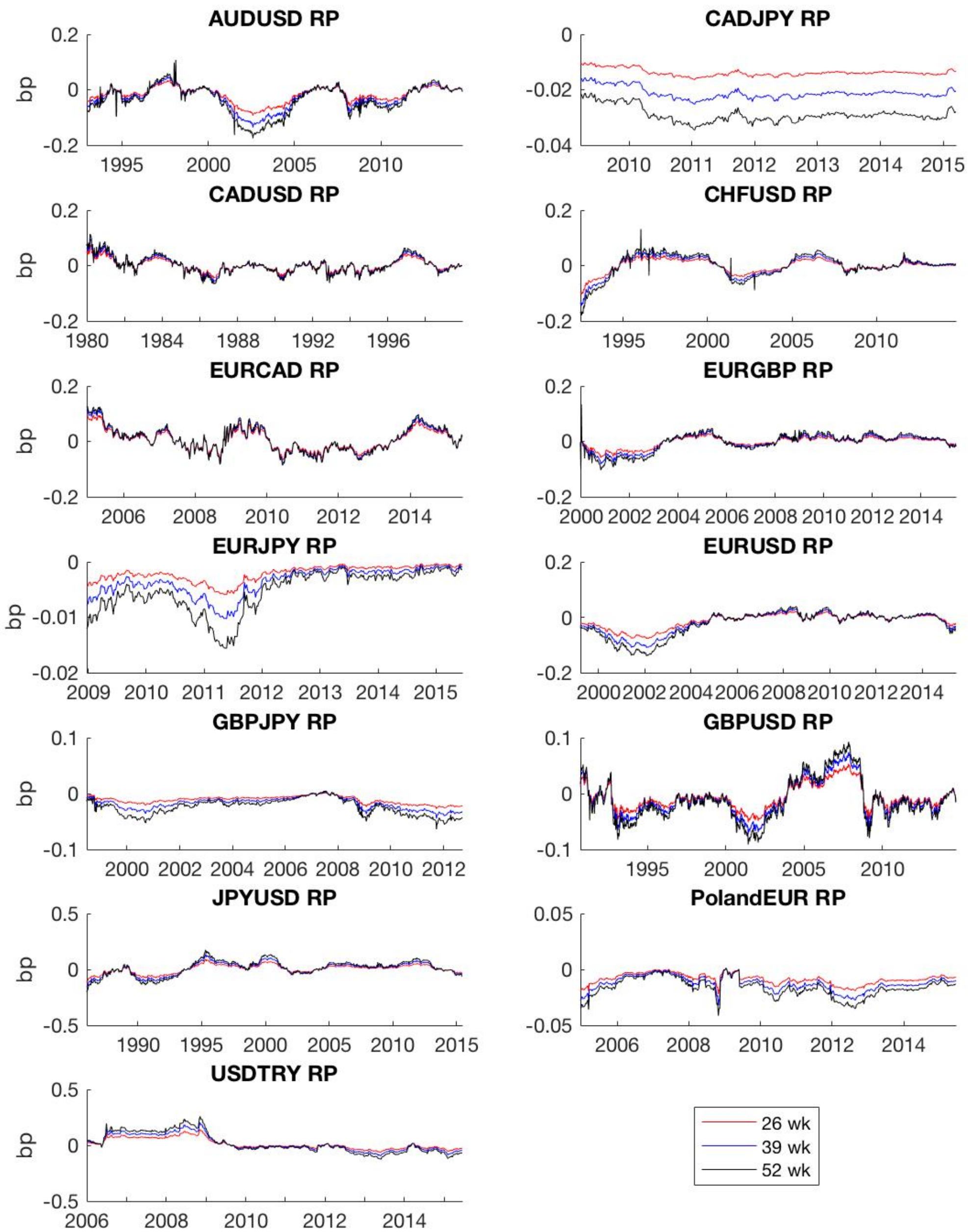

Figure B.6: Risk Premia

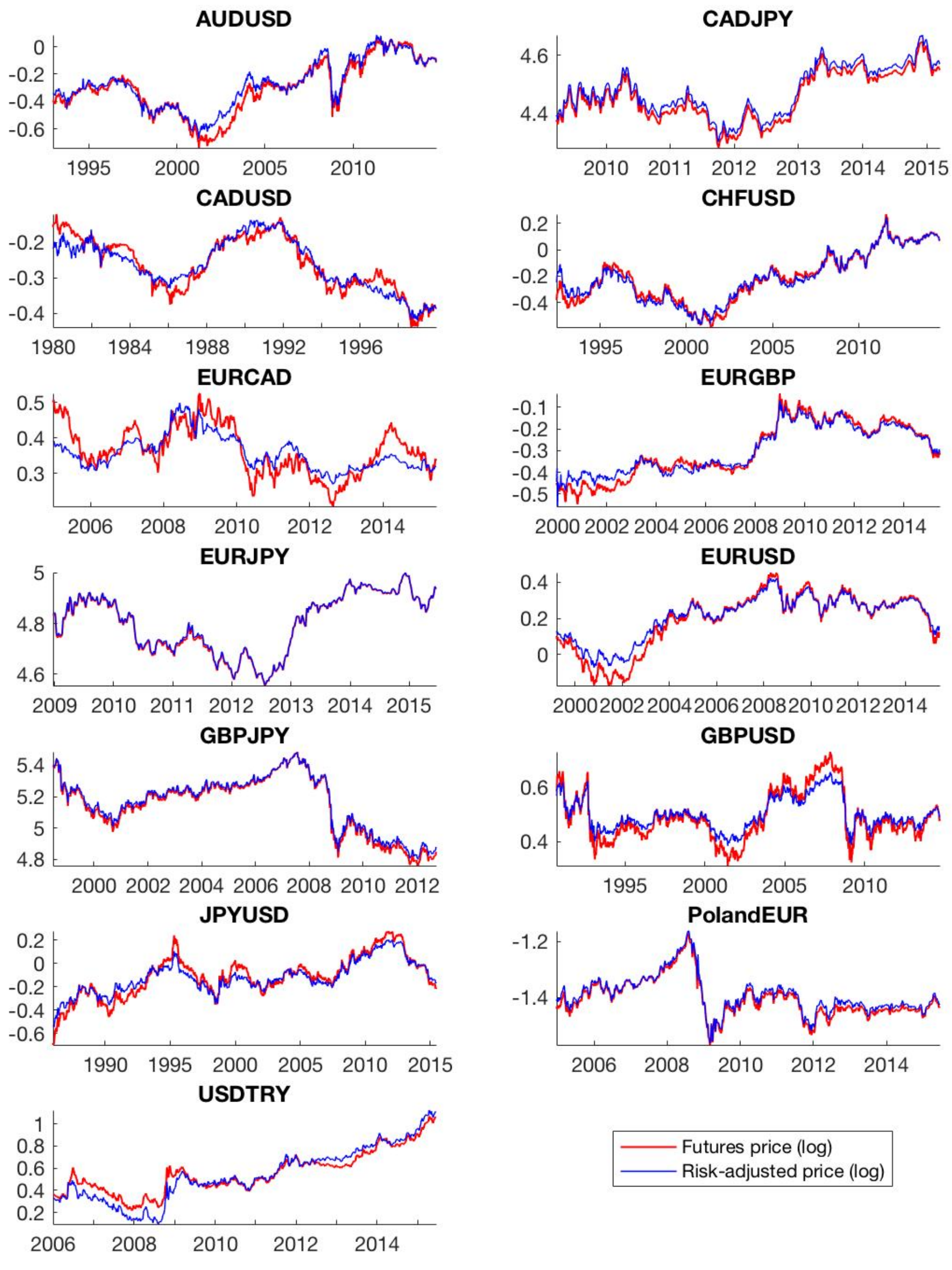

Figure B.7: 39 wk Futures Prices and Risk-adjusted Prices