Online appendix for "Foreign exchange interventions and their impact on expectations: Evidence from the USD/ILS options market"

A Intervention regimes since 2008

As we can learn from Figure 1 in the paper, the Bank of Israel (BOI) has been intervening since 2008 to contain the sustained appreciation trend that has characterized the Israeli new shekel (ILS) since the "Great Financial Crisis" (GFC). In this period, the BOI has changed its intervention regime[1] several times. We document the different intervention regimes in the following.

A.1 Overt interventions

Although the first intervention was not pre-announced, we include it here as part of the overt interventions to maintain the chronological order. After more than a decade without intervening in the spot foreign exchange market, the BOI started purchasing foreign currency on March 13-14, 2008 as a response to disorderly markets[2] in order to stabilise them.[3]

A.1.1 Intervention regime I

On March 20, 2008, the BOI announced that it would build up its foreign exchange reserves – which amounted to 29 billion US dollars (USD) at the end of February 2008 – over the next two years from March 24 onwards until reaching a level in the range of USD 35-40 billion.

A.1.2 Intervention regime II

On July 10, 2008 – against the backdrop of a steep appreciation of the ILS vis-à-vis the USD – the BOI announced that it would increase its daily USD purchases to USD 100 million.

[1] Or intervention strategy.

[2] As identified by several market indicators. These include intra-day volatilities, spreads and non-linear changes in the spot rate.

[3] See Flug and Shpitzer (2013) for details.

A.1.3 Intervention regime III

On November 11, 2008, the BOI announced that it raised the targeted range of its foreign exchange reserves to USD 40-44 billion. The BOI added that it would continue to purchase USD 100 million each day.

A.2 Secret interventions

A.2.1 Intervention regime IV

In August 2009, the BOI announced that it would no longer carry out the daily spot purchases of USD 100 million that it had committed to in July 2008. The BOI emphasized that it would intervene in the foreign exchange market in periods of extraordinary exchange rate fluctuations, whenever these were incompatible with domestic macroeconomic fundamentals. This policy change was in part motivated by the BOI's aim of gradually withdrawing the exceptional policy measures that it had adopted in response to the GFC. At some point in July 2011, the BOI stopped intervening for the following two and a half years.

A.3 Overt and secret intervention

A.3.1 Intervention regime V

On May 13, 2013, the BOI announced that it would restart USD purchases to offset the expected improvement in the current account (i.e. capital inflows) due to the surge in natural gas production over the coming years as an aftermath of the start of commercial production of the Tamar gas field on March 30, 2013.[4] The BOI announced that it expected to purchase USD 2.1 billion in total by the end of that year to offset the capital inflows associated with these additional gas sales. On top of that, the BOI explained that it would intervene in the market secretly.

A.3.2 Intervention regime VI

On January 14, 2021, the BOI announced that it planned to purchase USD 30 billion in total in 2021. Although the exact amount of these USD purchases was publicly announced by the BOI, it did not disclose when it would enter the market during the year. In other words, the BOI remained silent about the timing and the size of these USD purchases over the year 2021.

A.4 Background information

As shown in Amador, Bianchi, Bocola, and Perri (2020), the costs of an FX intervention regime can easily be estimated. We have estimated these costs for the different intervention regimes (see Section I). The results suggests that by historical standards, intervention

[4]This gas field was discovered in deep water near Haifa in 2009. Readers who are not familiar with the Israeli economy are referred to the Wikipedia entry titled "Natural gas in Israel" (Wikipedia, 2020) for details.

regime V (i.e. the regime that we analyze in our paper) is characterized by low costs in terms of, for instance, domestic GDP (see Figure I.1).

B Variable definition and data source

Variable	Description	Source
FXI_t	Daily net USD purchases in the USD/ILS spot market. In USD billion.	Bank of Israel.
USD/ILS	1 USD in terms of ILS calculated at 17:00 New York time (midnight in Israel).	Bloomberg.
EUR/USD	1 EUR in terms of USD calculated at 17:00 New York time (midnight in Israel).	Bloomberg.
NEER	Nominal effective FX rate (NEER) of the ILS computed as the trade-weighted arithmetic average of the foreign value of the ILS vis-à-vis a basket of 24 currencies (31 countries). The FX rates are calculated at 17:00 New York time. Our index includes 97.3% of Israel's trading partners. A higher index indicates a weaker ILS.	Bloomberg & own calculations.
RR/BF/ATMV	Risk reversal/butterfly spread/at-the-money option contracts on the USD/ILS spot rate for six maturities. In the case of the first two contracts, we have options with a delta of 10 and 25. The prices are quoted in implied volatilities (in percent) and equal the midpoint of the bid and ask, calculated at 17:00 New York time.	Bloomberg.
$\overline{RR}/\overline{BF}$	Risk reversal/butterfly spread divided by ATMV.	Bloomberg.
ΔProb. of appr.$_{t-11,t-1}$	One-day lagged two-week change of the right tail of the RND. It is 5%, 8%, 10%, 13% and 20% for the one-month up to the twelve-month horizon.	Own calculations.
ΔProb. of depr.$_{t-11,t-1}$	One-day lagged two-week change of the right tail of the RND. It is 5%, 8%, 10%, 13% and 20% for the one-month up to the twelve-month horizon.	Own calculations.
CDS	5-year CDS spread on Israeli external debt. In basis points.	Bloomberg.
TELBOR	One-month Israeli interbank rate. In percent.	Bank of Israel.
LIBOR	One-month US LIBOR rate. In percent.	Bloomberg.
Foreign and inst. flows	Net purchases of ILS in terms of USD by foreign and institutional investors. In USD millions.	Bank of Israel.
VIX	Implied volatility from S&P 500 index options. In percent.	CBOE.

C Two popular foreign exchange option strategies

C.1 Risk reversals

Risk reversals (RRs) are a widely used option strategy composed of a long out-of-the-money call and a short out-of-the-money put option on the same underlying with identical option deltas (in absolute percentage terms) and time to maturity.[5] The RR is thereby quoted in terms of implied volatilities (IV):[6]

$$RR_t \equiv \sigma_t^C - \sigma_t^P . \tag{C.1}$$

In our paper, the call and the put option refer to a USD call ILS put option and a USD put ILS call option, respectively.

From Equation (G.6) we can see that a RR captures any asymmetry of the implied volatility-moneyness function.[7] In other words, a non-zero RR results whenever an asymmetric volatility smile exists. Hence, RRs reflect the implied skewness of the risk-neutral probability density (RND) of exchange rate returns at the expiry date.[8] A positive RR, for instance, indicates a skewed expected return distribution for the USD/ILS exchange rate, that is, a tilt of expectations towards a large USD appreciation. The RR buyer then gains (loses) on a gross basis[9] when the USD appreciates (depreciates) vis-à-vis the ILS over the lifetime of the option contract.

This strategy also implies a position that is close to vega-neutral, as the option vegas of the call and the put options that constitute a RR are approximately equal in the Garman and Kohlhagen (1983) (GK) framework, which is the market standard for computing the quoted prices of FX options and their risk parameters (e.g. option deltas). Hence, under the GK framework, any change in IVs should only have a negligible effect on the RR.

With regards to the effect of the BOI's intervention activity, any unexpected FX spot market transaction targeted to weaken the foreign value of the ILS should lead to an increase in the RR,[10] whenever interventions are effective in affecting second-moment market expectations in the intended direction. Hence, the estimated coefficient should be positive when regressing the FX intervention data on the change in RRs.

C.2 Butterfly spreads

A butterfly (BF) spread is constructed by buying an option with a strike price K_1 and an option with a higher strike price K_3 (that is $K_1 < K_3$). In parallel, two options with a

[5]The moneyness of the call (put) option are chosen such that the strike price K_2 (K_1) of the call (put) is larger (smaller) than the FX forward rate F_t, that is, $K_1 < F_t < K_2$.

[6]Note that FX options are quoted in terms of implied volatilities for historical reasons, whilst equity options are quoted in nominal terms.

[7]This function measures the slope of the implied volatility smile across moneyness (Carr and Wu, 2007).

[8]see Appendix H for details on how to extract the RND with FX options.

[9]Ignoring the size of the premium paid for this option strategy.

[10]In the case of the BOI: a more pronounced tilt towards an USD appreciation. As shown in the paper, the RR has been mostly positive throughout the period of interest. Markets have therefore on average been willing to pay more for protection against a strong appreciation of the USD than for a strong depreciation of the USD.

strike price $K_2 = (K_1 + K_3)/2$ are sold to reduce the initial costs of this option trading strategy.[11,12]

The BF spread measures the difference between the average implied volatility of two (e.g. 10-Δ) options and the delta-neutral straddle implied volatility. The BF spread therefore captures the implied excess kurtosis of the implied volatility-moneyness function.

For the long position, this strategy leads to profits on a gross basis whenever the realized volatility at expiry is lower than the implied volatility at inception.[13] Consequently, the larger the BOI's FX intervention volumes are (and provided these intervention activities are unexpected throughout the time to maturity of the BF spread), the more profitable BF spreads should be,[14] as interventions are expected to stabilize the targeted FX rate.[15]

[11]See chapter 10 in Hull (2006).

[12]Thus, $K_1 < K_2 < K_3$.

[13]Indeed, the payoff of this strategy is maximized if the spot exchange rate at the expiration date equals K_2.

[14]That is, their quoted prices should increase.

[15]See the success criteria in the FX intervention strand of literature, for instance, Humpage (1999), Fatum and Hutchison (2003), Fratzscher (2005), Fatum and Hutchison (2006), Galati, Higgins, Humpage, and Melick (2007), Fatum (2008), Fratzscher (2008) and Fratzscher, Gloede, Menkhoff, Sarno, and Stöhr (2019).

D Daily cross-correlation between the main variables and the options data

This section shows the daily cross-correlations between the main variables (Table D.1) and the price quotes of the option trading strategies (Tables D.2-D.4) that we use in the paper. The first observation is that the main variables in our paper are rather weakly correlated in the cross-section, as evidenced in Table D.1:

Table D.1: Cross-correlation between the main variables

	ΔUSD/ILS	ΔEUR/USD	ΔNEER	ΔForward$_{3m}$	Foreign flows - total	Local flows - real sector	Local flows - financial sector	Local flows - inst. investors	Δ5-year Israeli CDS	ΔLIBOR	ΔTELBOR
Spot and forward exchange rates:											
ΔUSD/ILS	1										
ΔEUR/USD	-0.50	1									
ΔNEER	0.79	0.05	1								
ΔForward$_{3m}$	0.89	-0.42	0.74	1							
Flows:											
Foreign flows - total	0.13	-0.07	0.10	0.15	1						
Local flows - real sector	-0.18	-0.01	-0.19	-0.22	-0.55	1					
Local flows - financial sector	-0.04	0.06	-0.03	-0.04	-0.16	-0.09	1				
Local flows - inst. investors	0.23	-0.01	0.23	0.23	-0.28	-0.22	0.04	1			
Misc:											
Δ CDS	0.05	-0.01	0.03	0.09	0.04	-0.07	0.05	0.05	1		
ΔLIBOR	-0.05	-0.03	-0.08	-0.05	-0.01	0.09	-0.03	-0.13	-0.02	1	
ΔTELBOR	-0.04	0.01	-0.04	-0.05	-0.07	0.03	-0.04	0.03	-0.02	0.04	1

Notes: The table presents the cross-correlation between selected variables. For details on the variables, see Appendix B in the present online appendix. The data span the period from January 1, 2013, to January 31, 2020.

Table D.2 presents the cross-correlation between the price quotes of the 10-Δ and the 25-Δ risk reversals (“RR10” and “RR25”) for six different maturities, ranging from one week (“1w”) to twelve months (“12m”). We also include the correlation between these price quotes and the log return of the USD/ILS spot rate (“Δ USD/ILS”).

Table D.2: Cross-correlation between the USD/ILS risk reversals and the USD/ILS spot rate

	RR101w	RR101m	RR103m	RR106m	RR109m	RR1012m	RR251w	RR251m	RR253m	RR256m	RR259m	RR2512m	ΔUSD/ILS
10-Δ:													
RR101w	1												
RR101m	0.818	1											
RR103m	0.720	0.970	1										
RR106m	0.658	0.931	**0.987**	1									
RR109m	0.621	0.908	**0.975**	**0.996**		1							
RR1012m	0.599	0.886	0.961	**0.990**	**0.994**	1							
25-Δ:													
RR251w	0.916	0.929	0.870	0.825	0.797	0.780	1						
RR251m	0.811	**0.998**	0.972	0.935	0.912	0.890	0.927	1					
RR253m	0.716	0.967	**0.999**	**0.987**	**0.975**	0.960	0.867	0.971	1				
RR256m	0.658	0.930	**0.987**	**0.999**	**0.995**	**0.990**	0.824	0.934	**0.988**	1			
RR259m	0.628	0.910	**0.976**	**0.996**	**0.999**	**0.995**	0.802	0.915	**0.977**	**0.997**	1		
RR2512m	0.600	0.886	0.960	**0.989**	**0.992**	**0.999**	0.780	0.892	0.963	**0.990**	**0.995**	1	
Spot exchange rate:													
ΔUSD/ILS	0.096	0.056	0.043	0.033	0.028	0.026	0.089	0.057	0.044	0.034	0.030	0.026	1

Notes: The table displays the cross-correlation between the price quotes of the daily USD/ILS risk reversals (in percent) for six maturities ranging from one week (“1w”) to twelve months (“12m”) and two option deltas of ± 10% (“RR10”) and ± 25% (“RR25”). The correlation between these price quotes and the log return of the USD/ILS spot rate (“$\Delta USD/ILS$”) is displayed in the last row. Cross-correlations that are larger than or equal to 0.975 are in bold letters. The data span the period from January 1, 2013, to January 31, 2020. Data source: Bloomberg.

Table D.3 presents the cross-correlation between the price quotes of the 10-Δ and the 25-Δ butterfly spreads (“BF10” and “BF25”) for six different maturities, ranging from one week (“1w”) to twelve months (“12m”). We also include the correlation between these price quotes and the log return of the USD/ILS spot rate (“Δ USD/ILS”).

Table D.3: Cross-correlation between the USD/ILS butterfly spreads and the USD/ILS spot Rrte

	BF101w	BF101m	BF103m	BF106m	BF109m	BF1012m	BF251w	BF251m	BF253m	BF256m	BF259m	BF2512m	ΔUSD/ILS
10-Δ:													
BF101w	1												
BF101m	0.402	1											
BF103m	0.400	0.925	1										
BF106m	0.421	0.893	**0.984**	1									
BF109m	0.371	0.891	**0.977**	**0.984**	1								
BF1012m	0.393	0.862	0.959	**0.984**	**0.983**	1							
25-Δ:													
BF251w	0.734	-0.025	-0.056	-0.058	-0.075	-0.074	1						
BF251m	0.326	0.914	0.898	0.872	0.884	0.850	-0.064	1					
BF253m	0.318	0.882	0.953	0.938	0.950	0.926	-0.095	0.946	1				
BF256m	0.352	0.859	0.944	0.961	0.965	0.961	-0.095	0.915	**0.977**	1			
BF259m	0.331	0.850	0.933	0.948	0.969	0.962	-0.096	0.906	0.969	**0.991**	1		
BF2512m	0.352	0.815	0.908	0.937	0.951	0.967	-0.107	0.868	0.938	**0.978**	**0.983**	1	
Spot exchange rate:													
Δ USD/ILS	0.087	0.049	0.036	0.036	0.025	0.024	0.071	0.024	0.017	0.016	0.015	0.005	1

Notes: This table displays the cross-correlation between the price quotes of the daily USD/ILS butterfly spreads (in percent) for six maturities ranging from one week (“1w”) to twelve months (“12m”) and two option deltas of ± 10% (“BF10”) and ± 25% (“BF25”). The correlation between these quoted option prices and the change in the log USD/ILS spot rate (“$\Delta USD/ILS$”) is displayed in the last row. Cross-correlations that are larger than or equal to 0.975 are in bold letters. The data span the period from January 1, 2013, to January 31, 2020. Data source: Bloomberg.

Finally, Table D.4 presents the cross-correlation between the at-the-money volatility measures ("ATMV") for six different maturities, ranging from one week ("1w") to twelve months ("12m"). We also include the correlation between these price quotes and the log return of the USD/ILS spot rate ("Δ USD/ILS").

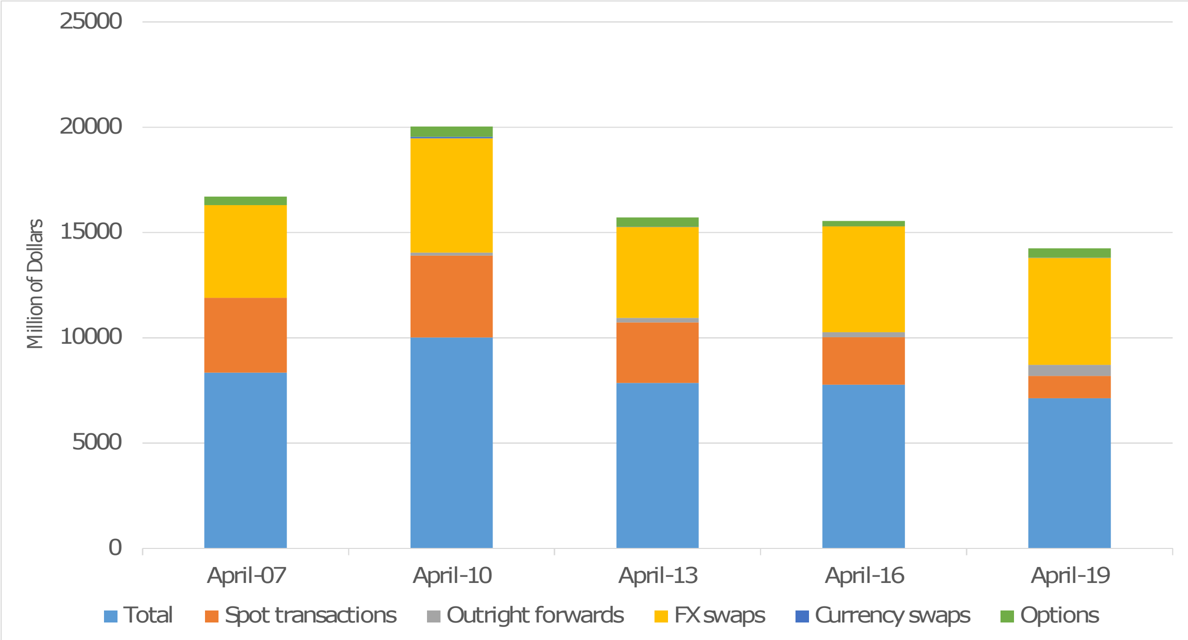
Table D.4: Cross-correlation between the USD/ILS at-the-money implied volatilities and the USD/ILS spot rate

	ATMV1w	ATMV1m	ATMV3m	ATMV6m	ATMV9m	ATMV12m	ΔUSD/ILS
ATMV1w	1						
ATMV1m	0.952	1					
ATMV3m	0.920	**0.984**	1				
ATMV106m	0.885	0.957	**0.989**	1			
ATMV109m	0.861	0.933	**0.975**	**0.996**	1		
ATMV1012m	0.835	0.910	0.958	**0.988**	**0.997**	1	
Spot exchange rate:							
ΔUSD/ILS	0.040	0.030	0.015	0.004	0.000	0.000	1

Notes: This table displays the cross-correlation between the price quotes of the daily USD/ILS at-the-money implied volatilities (in percent) for six maturities ranging from one week ("1w") to twelve months ("12m"). The correlation between these price quotes and the log return of the USD/ILS spot rate ("$\Delta USD/ILS$") is displayed in the last row. Cross-correlations that are larger than or equal to 0.975 are in bold letters. The data span the period from January 1, 2013, to January 31, 2020. Data source: Bloomberg.

E Foreign exchange transaction volumes and relative bid-ask spreads for the three option strategies

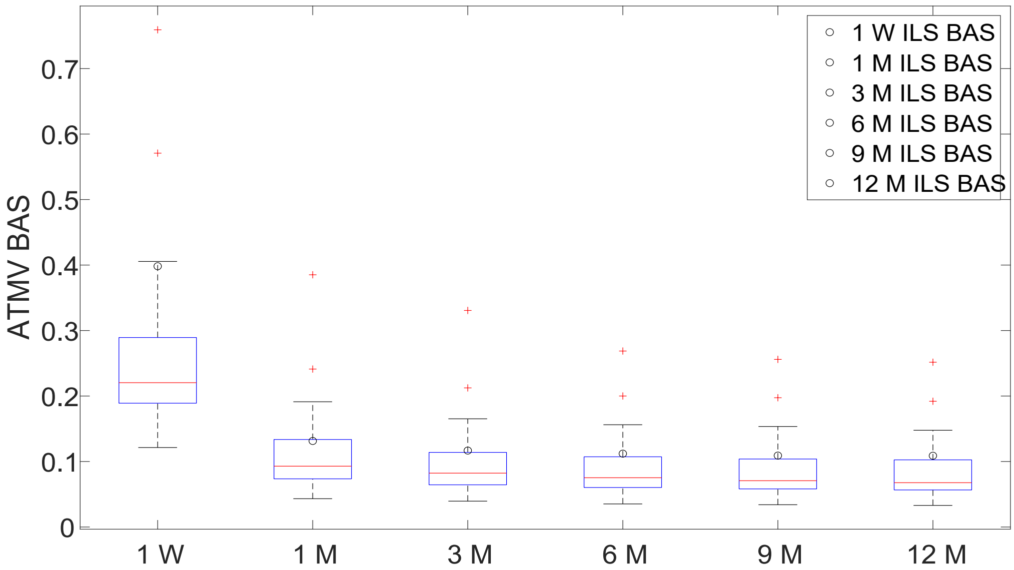
Figure E.1: Daily foreign exchange transaction volume



Notes: The figure shows the daily average volume of over-the-counter foreign exchange (FX) transactions in the spot, forward, FX swap, currency swap and option market in April of the corresponding year, where one of the currencies involved is the ILS. The data is retrieved from the BIS triennial central bank survey, which is carried out every three years. Source: https://www.bis.org/statistics/rpfx19.htm.

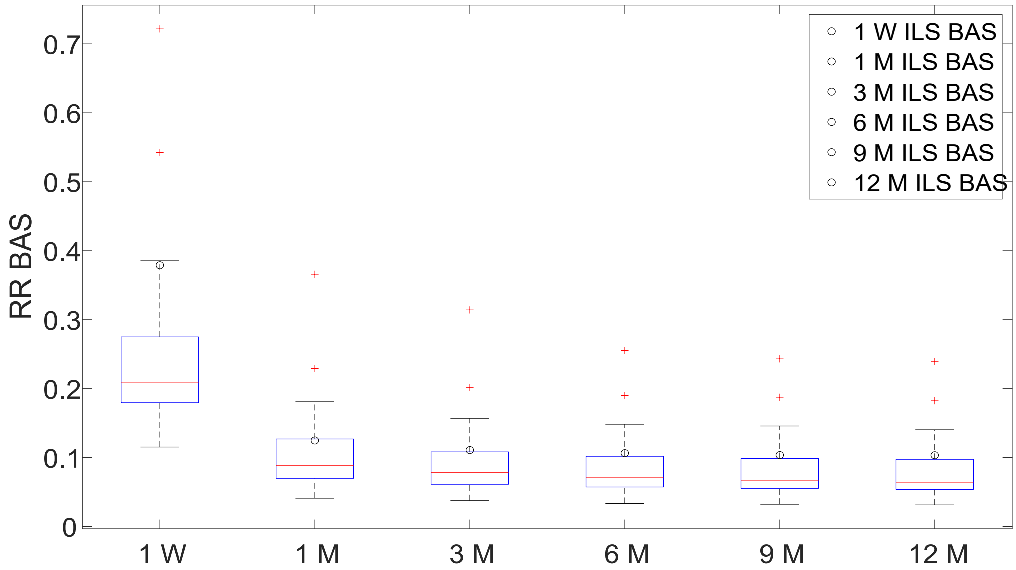
We also display the box plots of the relative bid-ask spread (BAS) for the three option strategies that we use in the paper for 28 currency pairs across six maturities, ranging from one week ("1 W") to twelve months ("12 M"). The currency pairs are retrieved from Bloomberg and are the following: Australian dollar (AUD)/USD, euro (EUR)/Czech koruna (CZK), EUR/pound sterling (GBP), EUR/Japanese yen (JPY), EUR/Norwegian kroner (NOK), EUR/Swedish krona (SEK), EUR/USD, GBP/Swiss franc (CHF), GBP/JPY, GBP/USD, USD/Canadian dollar (CAD), USD/Chilean peso (CLP), USD/Colombian peso (COP), USD/CZK, USD/Danish krone (DDK), USD/Hungarian forint (HUF), USD/Icelandic krona (ISK), USD/ILS, USD/JPY, USD/Mexican peso (MXN), USD/New Zealand dollar (NZD), USD/NOK, USD/Polish zloty (PLN), USD/SEK, USD/South-Korean won (KRW), USD/CHF, USD/Turkish lira (TRY).

Figure E.2: Relative bid-ask spread for at-the-money implied volatility options with different maturities



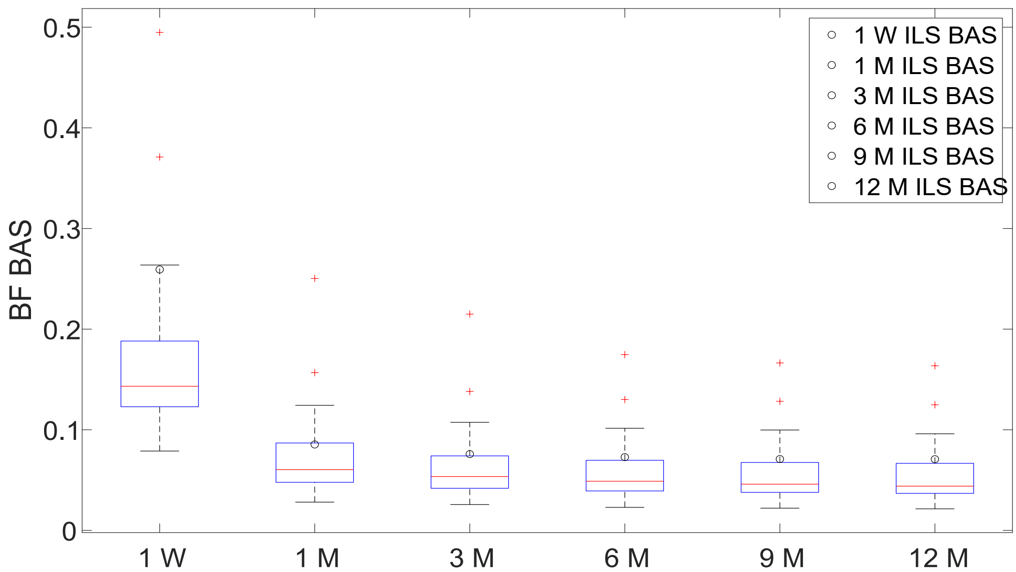
Notes: The figure displays the box plot of the quoted bid-ask spreads of the at-the-money implied volatility options divided by the corresponding midquote for 28 currency pairs across six maturities, ranging from one week ("1 W") to twelve months ("12 M"). Source: Bloomberg.

Figure E.3: Relative bid-ask spread for the risk reversals with different maturities



Notes: The figure displays the box plot of the quoted bid-ask spreads of the risk reversals divided by the corresponding midquote for 28 currency pairs across six maturities, ranging from one week ("1 W") to twelve months ("12 M"). Source: Bloomberg.

Figure E.4: Relative bid-ask spread for the butterfly spreads with different maturities



Notes: The figure displays the box plot of the quoted bid-ask spreads of the butterfly spreads divided by the corresponding midquote for 28 currency pairs across six maturities, ranging from one week ("1 W") to twelve months ("12 M"). Source: Bloomberg.

F Long-horizon regressions and the impact of past interventions

F.1 Specification 1

The following equation is from Boudoukh, Israel, and Richardson (2021), adjusted so that the coefficients also capture the contemporaneous effect of FX interventions:

$$\sum_{j=0}^{J} r_{t+j} = \alpha_J + \beta_J X_t + \sum_{j=0}^{J} \epsilon_{t+j}. \tag{F.1}$$

In our paper, the left-hand side of the equation equals the h-period log return of the USD/ILS spot rate and X_t the intervention volume. When interpreting X_t as a vector, it could include other relevant explanatory variables.

This equation leads to the following OLS coefficient:

$$\beta_J = \frac{\text{Cov}\left(\sum_{j=0}^{J} r_{t+j}, X_t\right)}{\text{Var}\left(X_t\right)}. \tag{F.2}$$

F.2 Specification 2

Boudoukh et al. (2021) rewrite Equation (F.1). Again, adjusting their specification to account for the contemporaneous effect of FX interventions, we get:

$$r_t = \mu_J + \gamma_J \sum_{j=0}^{J} X_{t-j} + \xi_t, \tag{F.3}$$

taking advantage of an insight from Jegadeesh (1991) and Hodrick (1992), who noticed that the covariance term associated with the parameter β_J is equal to the covariance term associated with γ_J for stationary time series. This specification corresponds to the specification in e.g. Galati, Melick, and Micu (2005), Disyatat and Galati (2007) and Galati et al. (2007) to assess the persistence of FX interventions on the first four moments of the RND and are very influential empirical papers in the FX intervention literature.

Now the regressor represents the cumulated sum of interventions from time $t - J$ up to date t. Note that the error terms ξ_t are now non-overlapping, contrary to the case in Equation (F.1). Hence, the parameters of this equation can be estimated using standard OLS, and so γ_J reflects how the cumulated intervention volume over J trading days is related to the one-day log return of the USD/ILS spot rate between day $t - 1$ and t (i.e. J trading days after the first intervention was carried out at time $t - J$).

This equation leads to the following OLS coefficient:

$$\gamma_J = \frac{\text{Cov}\left(r_t, \sum_{j=0}^{J} X_{t-j}\right)}{\text{Var}\left(\sum_{j=0}^{J} X_{t-j}\right)}. \tag{F.4}$$

Note that in small samples the one-period variance estimator in Equation F.2 (i.e. the denominator) may be closer to the true variance of X_t than its J-period counterpart in Equation F.4, as put forward in Boudoukh and Richardson (1994), who have this "intuition" from Richardson and Stock (1989). In the latter paper, Richardson and Stock (1989) show that the J-period variance estimator may even be inconsistent.

F.3 Parameters

In a second step, Boudoukh et al. (2021) show that the parameter γ_J equals β_J, scaled down by a variance ratio:

$$\gamma_J = \beta_J \frac{\text{Var}(X_t)}{\text{Var}\left(\sum_{j=0}^{J} X_{t-j}\right)},$$

where we have again adjusted the equation so that it corresponds to the specification in our paper.

In small samples, the long-run estimator $\widehat{\gamma}_J$ is much more biased than the long-run estimator $\widehat{\beta}_J$, as shown in Boudoukh et al. (2021). This is the first (and most important) reason why we prefer to run the OLS regression as specified in Equation (F.1). The second reasons brings us to the next topic.

F.4 Standard errors

In Boudoukh and Richardson (1994) it is shown that the variance of $\widehat{\gamma}_J$ is larger than the variance of $\widehat{\beta}_J$ in small samples, even for small Js.[16] The unreliability of the J-period variance estimator thereby increases with the length of the horizon J (Boudoukh and Richardson, 1994). Note also that the more serially correlated the regressors are, the more unreliable this estimator becomes (Boudoukh and Richardson, 1994).

F.5 Discussion

Summarizing the previous two sections, we now know that the estimator $\widehat{\beta}_J$ provides less biased parameter estimates and more efficient standard errors than its counterpart $\widehat{\gamma}_J$.[17] We therefore prefer to use the first estimator that results from running the regression specification in Equation (F.1). Moreover, Boudoukh et al. (2021) provide a bias-correction for $\widehat{\beta}_J$ that we also use in our paper. The standard errors are corrected using the approach recommended by Hjalmarsson (2011). This correction works well for highly autocorrelated regressors (Boudoukh et al., 2021).[18]

To conclude: our discussion suggests that future empirical papers analyzing the longer-term effect of FX interventions on FX spot, FX forward or FX option markets using a time series approach should rather use the regression specification in Equation (F.1) and apply the two aforementioned corrections.

[16] In as simulation study with 760 observations and J ranging from 12 to 360.

[17] This conclusion suggests that many empirical papers that have assessed the longer-term effect of FX interventions in small samples using Equation (F.3) may have obtained results that were somehow biased.

[18] Otherwise, use the correction proposed in Boudoukh and Richardson (1994) that assumes that the regressor X_t follows an AR(1) process. These authors show the adequacy of the resulting corrected variance estimator in small samples.

G The higher moments of the risk-neutral density

This appendix shows how risk reversals (RR) and butterfly (BF) spreads are related to the implied skewness and excess kurtosis of the RND. The RR and the BF spread (also the ATMV) are usually highly liquid option strategies (Bossens, Rayée, Skantzos, and Deelstra, 2010) and are typically available for six different maturities, ranging from one week up to one year.[19]

The idea of using the price quotes of option contracts instead of calculating the higher-order moments after extracting the RND from option prices was put forward by e.g. a referee in Morel and Teïletche (2008) to reduce the model-dependence that you are more exposed to in the latter case. This referee, nevertheless, suggested to use the price quotes directly. In Section G.4 we will show that implementing the referee's suggestion gives proxies of the implied moments of the RND that are proportional to the ATMV level. In line with this finding, we will show that the price quotes of the RR and the BF spread will approximate the implied skewness and the implied kurtosis of the RND only after scaling these prices by the ATMV level.

G.1 Option-implied volatility curve

Backus, Foresi, and Wu (2004) show that the option-implied volatility curve[20] approximately equals:[21]

$$IV_{t,T}(d) \approx ATMV_{t,T}\left[1 - \frac{1}{6}s_{t,T}d - \frac{1}{24}k_{t,T}(1-d^2)\right], \qquad \text{(G.1)}$$

where $IV_{t,T}$ and $ATMV_{t,T}$ are the implied volatility and an estimate of the price quote of the ATMV at time t of the options maturing at time T. It is common market practice to replace the ATMV metric by a constant value (Carr and Wu, 2003)[22] to make quotes comparable different assets (that is, exchange rates in our paper):[23]

$$ATMV_{t,T} = \sigma.$$

The other expressions in Equation (G.1) represent the skewness ($s_{t,T}$), the excess kurtosis

[19] The six maturities equal one week, one month, three months, six months, nine months and twelve months.

[20] Or option-implied volatility smile, that is, the graph that displays the implied volatility-moneyness function.

[21] See their Equation (16). They use a Gram-Charlier expansion to allow the density of the logarithm of the spot exchange rate to deviate from a normal density, by allowing for densities with non-zero skewness and excess kurtosis. A similar approach has been advanced by Zhang and Xiang (2008) to model the implied volatility smirk for equity index options. They propose a second-order polynomial that leads to a similar formula; see their equations (2) and (7)-(9).

[22] For instance, equal to the average historical (or realized) volatility of the underlying asset over a specific period.

[23] Subsequent papers also impose this calibration, see for instance Zhang and Xiang (2008).

($k_{t,T}$) and the z-value (d) of the daily log spot rate return r_t:

$$s_{t,T} = \frac{E(r_t - \mu)^3}{\sigma^3},$$
$$k_{t,T} = \frac{E(r_t - \mu)^4}{\sigma^4} - 3,$$
and
$$d = \frac{\ln(\frac{F}{X})}{IV\sqrt{T-t}} + \frac{1}{2}IV\sqrt{T-t}.$$

The first two expressions represent the skewness and the excess kurtosis,[24] both centred at the mean μ and scaled by the third and fourth power of the volatility σ of the underlying spot exchange rate.

Notice that changes in the mean μ will not affect the skewness $s_{t,T}$ and the excess kurtosis $k_{t,T}$, as both metrics are centred at μ.

G.2 Market quoting convention

In OTC markets, FX option quotes refer to the IVs according to the Garman and Kohlhagen (1983) pricing formula (Carr and Wu, 2007). The call and put option deltas in this pricing framework are equal to:

$$\Delta_C \equiv \exp^{-r^f\tau} \Phi(d), \quad \text{(G.2)}$$
$$\Delta_P \equiv -\exp^{-r^f\tau} \Phi(-d) = \Delta_C - \exp^{-r^f\tau}. \quad \text{(G.3)}$$

By market convention, the ATMV is defined as the value of the smile curve that represents the price of a delta-neutral straddle in terms of IVs. Hence,

$$ATMV = IV(0). \quad \text{(G.4)}$$

For readers that are not familiar with option strategies, a straddle is a portfolio composed of a long call and a long put option with identical strike prices and maturity.[25] A straddle is delta-neutral, if d is equal to zero.[26]

The 25-Δ BF spread reflects the difference between the arithmetic mean of two 25-Δ options (a call and a put) plus the IV of the delta-neutral straddle:

$$BF25 = 0.5\,[IV(d(25c)) + IV(d(25p))] - ATMV, \quad \text{(G.5)}$$

where the numbers in parenthesis refer to the call and put option's z-value.

[24] Capturing the slope and the curvature of the IV smile.

[25] Therefore this option strategy is usually termed the ATM straddle or ATM "delta-neutral" (Bossens et al., 2010). Similarly, the ATMV is also termed the delta-neutral straddle IV (Carr and Wu, 2007).

[26] This market convention implies that the strike prices of ATM options K_{ATMV} are equal to neither the spot nor the forward rates and in fact exceed the latter: as just mentioned, the z-value of a straddle must be equal to zero. Re-arranging this z-value to express the strike as a function of the underlying, we see that the ATMV strike price is equal to a factor that is strictly larger than one for options that have not yet expired, times the FX forward rate. Hence, the ATMV strike price is always larger than the forward rate but can be equal to the spot rate, albeit only in very exceptional cases.

The 25-Δ RR equals the difference in IVs between a 25-Δ call and a 25-Δ put option. This option strategy can be expressed as:[27,28]

$$RR25 = IV(d(25c)) - IV(d(25p)). \tag{G.6}$$

G.3 Moneyness

We follow Backus et al. (2004) and use d as a measure of the degree of moneyness for mathematical convenience, contrary to industry convention, where only the negative of the first summand of d is used to compute the moneyness of options.[29,30] As a consequence, the sign of the d is switched compared to the conventional sign of d (i.e. we get an IV smile that is grosso modo the mirror image of the conventional IV smile).[31]

Notice that d is negative for typical market parameters and maturities not exceeding two years (Bisesti, Castagna, and Mercurio, 2005):

1. For instance, for a 25-Δ call option, the option delta $\Delta_C = \exp\left(-r^f\tau\right)\Phi\left(d(25c)\right)$ equals 0.25 under the GK framework.[32]
2. After re-arranging and inverting this equation, we get $d(25c) = \Phi^{-1}\left(0.25 \cdot \exp\left(r^f\tau\right)\right)$.[33]
3. For representative parameters and maturities, we see that $0.25 \cdot \exp\left(r^f\tau\right) \overset{!}{<} 0.5$, as otherwise r^f would have to be larger than $\ln(2)/\tau$ ($\approx 34.7\%$ for a period of $\tau = 2$ years).[34]
4. Hence, $d(25c)$ will be negative in standard applications.[35]
5. Also notice that $d(25c) > d(10c)$, unless $r^f = 0$.

[27] See Section 2 in Carr and Wu (2007).

[28] The time index is suppressed in the present online appendix for the sake of clarity.

[29] See e.g. Carr and Wu (2003), Carr and Wu (2007) and Zhang and Xiang (2008).

[30] Notice that the degree of moneyness can be expressed by the strike price or any transformation of it, e.g. the forward-moneyness, the log-moneyness or the option delta (Reiswich and Wystup, 2010).

[31] For e.g. the call option, we get a negative d, whilst it is positive by industry convention.

[32] Similarly, for a put option, we get: $\Delta_P = \Delta_C - \exp\left(-r^f\tau\right)$ (hint: simply take the derivative of the put-call parity with respect to the underlying).

[33] For a put option: $d(25p) = -d(25c) = \Phi^{-1}\left(0.75 \cdot \exp\left(r^f\tau\right)\right)$.

[34] Similarly, $0.75 \cdot \exp\left(r^f\tau\right) \overset{!}{>} 0.5$, as otherwise r^f would have to be smaller than $\ln(2/3)/\tau$ ($\approx -20.3\%$ for a period of $\tau = 2$ years).

[35] Similarly, $d(25p)$ will be positive in standard applications.

G.4 Link between the three option strategies and the higher moments of the risk-neutral density

Substituting the IV smile expression (Equation (G.1)) in equations (G.4), (G.6) and (G.5), we get

$$\begin{aligned}
ATMV &= ATMV_{t,T}(= \sigma \text{ by market convention}), && \text{(G.7)}\\
BF25 &= \frac{-ATMV_{t,T}}{24} k_{t,T}\left(1 - \left[d(25c)^2\right]\right), && \text{(G.8)}\\
&\begin{cases} \geq 0 & k_{t,T} \leq 0, \\ < 0 & k_{t,T} > 0. \end{cases} && \text{(G.9)}\\
RR25 &= \frac{-ATMV_{t,T}}{6} s_{t,T}\left(d(25c) - d(25p)\right), \\
&= \frac{-ATMV_{t,T}}{3} s_{t,T} d(25c), && \text{(G.10)}\\
&\begin{cases} \geq 0 & s_{t,T} > 0, \\ < 0 & s_{t,T} < 0. \end{cases} && \text{(G.11)}
\end{aligned}$$

From Table 4 in the paper, we learn, that the excess kurtosis must be negative, because the minima and maxima are in most cases less than three standard deviations below and above the mean. According to Equation (G.9), the BF spread must then be non-negative, in line with the descriptive statistics in Table 4 in the paper.

We can similarly learn that the mean is greater than the median for all the RRs that we consider. This suggests that the RND is on average right-skewed, that is, the RND on average exhibits a positive skewness. From that table we also learn that the RRs are most often positive throughout our sample period. This finding is in line with the aforementioned inequalities, whereby a positive skewness is associated with non-negative price quotes for the RRs (Equation (G.11)).

If we scale $BF25$ and $RR25$ by $ATMV$ and re-arrange both expressions, we get:

$$\begin{aligned}
\widetilde{BF25} &\equiv \frac{-24}{(1 - [d(25c)^2])} \frac{BF25}{ATMV}, \\
&= k_t, && \text{(G.12)}\\
\widetilde{RR25} &\equiv \frac{-3}{d(25c)} \frac{RR25}{ATMV}, \\
&= s_t. && \text{(G.13)}
\end{aligned}$$

As mentioned in Section G.1, the skewness and the excess kurtosis are both unaffected by changes in the mean. Therefore, in theory, neither the scaled BF spread nor the scaled RR should change when FX interventions affect the mean of the RND (or expected future spot rate distribution). This contrasts, however, with the empirical evidence, where the RR and the spot rate seem to be positively correlated in FX option markets, as emphasized in the paper. In other words, the price quote of a RR must also be affected by additional factors.

G.5 Sensitivities of the butterfly spread and the risk reversal

G.5.1 Butterfly spread

For typical (e.g. 25-Δ) out-of-the money options that constitute this option strategy, taking the derivative of the BF spread with respect to the skewness and the excess kurtosis of the RND gives:

$$\begin{aligned} \left.\frac{\partial BF}{\partial s_{t,T}}\right|_{-1<d<1} &= 0, \\ \left.\frac{\partial BF}{\partial k_{t,T}}\right|_{-1<d<1} &= \frac{-ATMV_{t,T}}{24}\left(1-[d(25c)]^2\right), \\ &< 0. \end{aligned}$$

Hence, the BF spread increases when the excess kurtosis decreases; that is, when extreme exchange rate movements in both directions become less likely over the lifetime of the BF spread. It is unaffected by changes in the skewness of the RND (or expected future spot rate distribution).

G.5.2 Risk reversal

We proceed in a similar way for the change in the price quote of the RR:

$$\begin{aligned} \left.\frac{\partial RR}{\partial s_{t,T}}\right|_{-1<d<1} &= -\frac{ATMV_{t,T}}{3} d(25c), \\ &> 0, \\ \left.\frac{\partial RR}{\partial k_{t,T}}\right|_{-1<d<1} &= 0. \end{aligned}$$

Hence, the RR increases when the skewness becomes more pronounced, whilst it is unaffected by changes of the excess kurtosis of the RND (or expected future spot rate distribution).

H Extracting the risk-neutral density

In our paper, USD/ILS call and put options are used to extract the RND[36] associated with the USD/ILS spot rate at the expiration date, with the aim of estimating tail probabilities and how these probabilities are affected by the BOI's intervention activity. In the first stage, as we show in subsection H.1, we first convert the OTC market quotes of at-the-money options (ATMV), 10- and 25-Δ RRs and 10- and 25-Δ BF spreads to call and put option IV quotes. In the second step, we show in subsection H.2 how to compute the corresponding strike prices of the 25-Δ call and 25-Δ put options.

H.1 Obtaining the quotes of the OTC call and put options

We re-arrange equations (G.5) and (G.6) and obtain the quotes for the call and put options:[37]

$$IV(d25c) = BF25 + ATMV + 0.5RR25,$$
$$IV(d25p) = BF25 + ATMV - 0.5RR25.$$

The 10-Δ call and 10-Δ put options are obtained by following the same steps.

H.2 Obtaining the strike prices

To obtain the corresponding strike prices, note that the z-value of the two options that constitute a straddle must be equal to zero to make this instrument delta-neutral. After re-arranging the z-value to express the strike as a function of the underlying, we see that the ATMV strike is equal to the forward FX rate F_t times a factor:

$$K_{ATMV} = F_t \exp\left[0.5IV(0)^2\tau\right] > F_t,$$

where τ denotes the time to maturity.

The strike prices for the 25-Δ call and 25-Δ put options are obtained after using the corresponding option deltas under the GK framework[38] and rearranging them to obtain the strike prices as a function of the forward rate:[39]

$$K_{25c} = F\exp\left[0.5IV(d25c)^2\tau - IV(d25c)\sqrt{\tau}\Phi^{-1}\left(0.25\exp\left(r^f\tau\right)\right)\right],$$
$$K_{25p} = F\exp\left[0.5IV(d25p)^2\tau + IV(d25p)\sqrt{\tau}\Phi^{-1}\left(0.25\exp\left(r^f\tau\right)\right)\right],$$

where Φ^{-1} is the inverse of the standard normal CDF (i.e. the z-value) and r and r^f are the domestic (in our paper: TELBOR) and foreign (in our paper: USD LIBOR) interest rates for a period of length τ.

[36] See Figlewski (2018) for a recent review of different techniques to extract the RND using information from option markets. A slightly older review is included in chapter 11 in Jondeau, Poon, and Rockinger (2007).

[37] Simply add -0.5 (0.5) times RR25 to BF25 and re-arrange the equation to get the first (second) expression.

[38] See equations (G.2) and (G.3).

[39] See Bisesti et al. (2005) or Jurek (2014).

Note that for typical parameters and maturities not exceeding two years:

$$\left(0.25\exp\left(r^f\tau\right)\right) < 0.5.$$

Hence, $\Phi^{-1}\left(0.25\exp\left(r^f\tau\right)\right)$ is typically negative. Therefore, we know $F_t < K_{25c}$.

Whenever $IV(10c) > IV(25c)$ and $IV(10p) > IV(25p)$, we have:

$$K_{10p} < K_{25p} < F_t < K_{ATMV} < K_{25c} < K_{10c}.$$

H.3 Obtaining the RND

After following the steps in subsections H.1 and H.2, we obtain the 25-Δ call and 25-Δ put prices, as well as the corresponding K_{25c} and K_{25p}. Hence, at this stage we have five IV quotes for each maturity. For each day, we now create a grid of strike prices from the lowest (K_{10p}) to the largest strike price (K_{10c}) with small increments $dK = 0.001$, i.e. increments of 1/10 of an ILS. Each grid point is indexed by an integer number n, ranging from 1 to $\left(K_{10c} - K_{10p}\right)/0.001 - 1$.

Next, we use the GK formula to compute a quasi-continuum of call prices from the strike × IV-space into the strike × *call*-space after converting the put to call prices using put-call parity. Figlewski (2009), using well known results by Breeden and Litzenberger (1978), shows that a good approximation of the probability density function (PDF) and the cumulative density function (CDF) of their empirical risk-neutral counterparts are:[40]

$$f^C_{\text{EMP}}\left(K_n\right) \approx e^{\left(r-r^f\right)T}\frac{C_{n+1} - 2C_n + C_{n-1}}{(\Delta K)^2}, \tag{H.1}$$

$$F^C_{\text{EMP}}\left(K_n\right) \approx e^{\left(r-r^f\right)T}\left[\frac{C_{n+1} - C_{n-1}}{K_{n+1} - K_{n-1}}\right] + 1, \tag{H.2}$$

where $f_{\text{EMP}}(K_n)$ and $F_{\text{EMP}}(K_n)$ equal the corresponding PDF and the CDF evaluated at the strike price K_n at the grid point n, r is the domestic risk-free rate with a maturity τ, and C_n is the price of a call option evaluated at strike price K_n with its estimated IV.

For put options, the corresponding PDF and CDF equal:

$$f^P_{\text{EMP}}\left(K_n\right) \approx e^{\left(r-r^f\right)T}\frac{P_{n+1} - 2P_n + P_{n-1}}{(\Delta K)^2}, \tag{H.3}$$

$$F^P_{\text{EMP}}\left(K_n\right) \approx e^{\left(r-r^f\right)T}\left[\frac{P_{n+1} - P_{n-1}}{K_{n+1} - K_{n-1}}\right]. \tag{H.4}$$

In order to obtain smooth functions, Figlewski (2009) proposes a weighting scheme.

H.4 Modelling the tails

To estimate the tails, Figlewski proposes using the Generalized Extreme Value (GEV) distribution with three parameters (fatness of the tail, location and scale). In this subsection, we describe his methodology for modelling the right tail. The idea is to "connect"

[40]Note that we adjust his methodology so that it can be applied with FX options.

the right tail to the estimated RND in equations (H.2) and (H.4) beyond the highest and lowest strike prices of the grid.

Let $K(\alpha)$ denote the exercise price of the α quantile of the RND. We choose two parameters: α_1 and α_2. The first parameter, α_1 is the quantile where the tail of the GEV is to begin. The second parameter, α_2 will be matched to the empirical RND. In choosing the parameters, we want to make sure that $K(\alpha_1) < K(\alpha_2) \leq K(C_{N-1})$. In other words, the strikes for our chosen parameters are within the bounds of the right tail of our empirical RND. We note that Figwelski's default values for α_1 and α_2 are such that $\mathrm{F}_{\mathrm{EVR}}(\alpha_1) = 0.9$ and $\mathrm{F}_{\mathrm{EVR}}(\alpha_2) = 0.95$. However, he notes that sometimes the cross-section of strike prices yields cumulative distributions where the top quantile is less than 95%. This is particularly true in the FX market where we are only limited to five strikes where the lowest strike has a Δ of 10. Therefore, having the default upper value of 95% could be problematic. Instead, we choose to set α_2 so that $K(\alpha_2) = K(C_{N-1})$. Similarly, we follow Figwelski and set α_1 so that $F_{\mathrm{EMP}}(\alpha_1) = F_{\mathrm{EMP}}(\alpha_2) - 0.03$.

As we have to calibrate three parameters, we need to impose three constraints:

$$\mathrm{F}_{\mathrm{EVR}}\ (\mathrm{K}\,(\alpha_1)) = \alpha_1, \tag{H.5}$$

$$\mathrm{f}_{\mathrm{EVR}}\,(\mathrm{K}\,(\alpha_1)) = \mathrm{f}_{\mathrm{EMP}}\,(\mathrm{K}\,(\alpha_1))\,, \tag{H.6}$$

$$\mathrm{f}_{\mathrm{EVR}}\,(\mathrm{K}\,(\alpha_2)) = \mathrm{f}_{\mathrm{EMP}}\,(\mathrm{K}\,(\alpha_2))\,, \tag{H.7}$$

where $\mathrm{F}_{\mathrm{EVR}}$ and $\mathrm{f}_{\mathrm{EVR}}$ are the CDF and PDF of the GEV distribution for the right tail. The left tail is estimated in a similar fashion with a few tweaks. The interested reader is invited to read Figlewski.

I The costs of foreign exchange interventions

Amador et al. (2020) propose a metric Δ_t that allows central banks to quantify the resource costs associated with FX interventions carried out at time t. The metric is approximated by the covered interest parity (CIP) deviations observed for three-month-ahead assets; that is, the ILS and USD sovereign zero-coupon yields for a maturity of three months ($i_t^{ILS,3m}$ and $i_t^{USD,3m}$) and the USD/ILS forward rate F_t:[41]

$$\Delta_t = \left[\frac{\left(1 + \frac{i_t^{ILS,3m}}{4*100}\right)}{\left(1 + \frac{i_t^{USD,3m}}{4*100}\right)} \frac{S_t}{F_t^{3m}} \right]^{(1/3)} - 1. \tag{I.1}$$

The losses in period T are then calculated as

$$\text{Losses}_t = \frac{\Delta_t}{1 + \Delta_t} * \text{FXRes}_t, \tag{I.2}$$

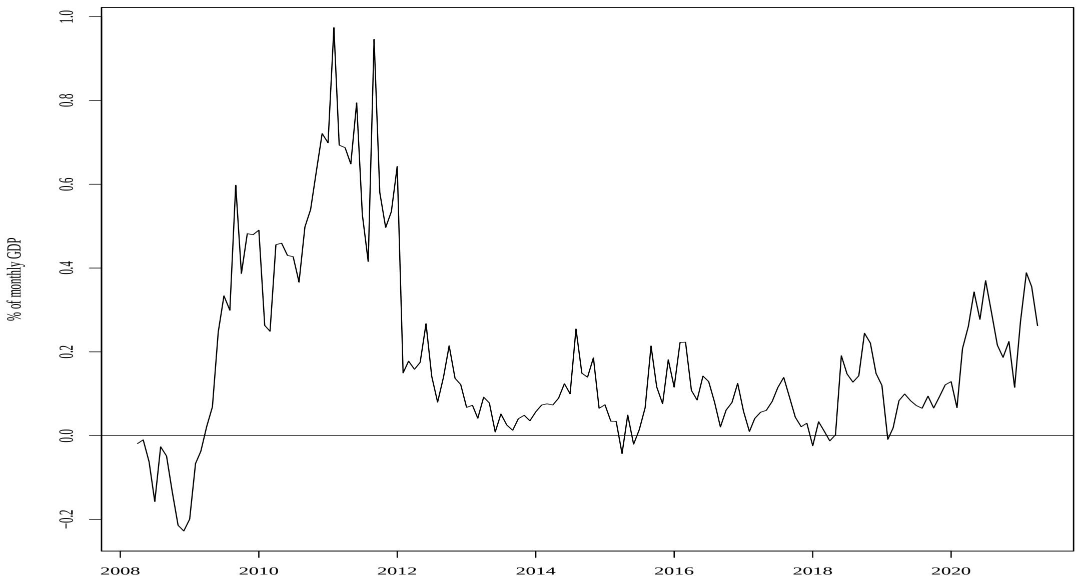
which corresponds to Equation (6.1) in Amador et al. (2020) and where FXRes_t denotes the market value of the stock of foreign reserves held at the end of period t. We proxy this variable by the USD-denominated end-of-month stock published by the BOI.[42] The loss metric is then divided by the monthly USD denominated Israeli GDP series.[43] The resulting time series is displayed in the following Figure I.1:

[41]Contrary to Amador et al. (2020) who use overnight index swap rates, we use sovereign zero-coupon yields because we cannot obtain the former for the ILS.

[42]Note that this approximation results in a loss metric that is slightly upward biased.

[43]To obtain this variable, we first downloaded the quarterly ILS-denominated Israeli GDP time series data from the Federal Reserve Economic Database (FRED) maintained by the Federal Reserve Bank of St. Louis. We then transformed this variable to get its USD denominated counterpart. This GDP variable is then HP-filtered (with a smoothing parameter of 1'600) to get the GDP trend. We then used the cubic spline interpolation method to convert the quarterly trend into monthly data after dividing the resulting time series by three. The finally obtained time series represents the costs of foreign exchange interventions in terms of GDP.

Figure I.1: Costs of foreign exchange interventions



Notes: The figure displays the costs of foreign exchange interventions. This variable is a function of covered interest parity deviations, the market value of the stock of foreign reserves held by the BOI at the end of each month and the ILS denominated monthly Israeli GDP data. The variables used to compute the CIP deviations are retrieved from Bloomberg. The data on foreign reserves is obtained from the International Monetary Fund and the GDP data from the Federal Reserve Economic Database (FRED) maintained by the Federal Reserve Bank of St. Louis. The data span the period from April 1, 2008 to April 1, 2021.

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