King U.S. Dollar, Global Risks, and Currency Option Risk Premiums*

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Abstract

Does the primacy of the U.S. dollar affect the pricing of risks in the currency options market? Our findings rely on a daily option panel of 15 currencies. This analysis reveals that (i) put risk premiums are negative, implying across-the-board interest in hedging foreign currency depreciations; (ii) call risk premiums are of variable sign and not as pronounced as for puts; (iii) volatility risk premiums are small or insignificant; and (iv) put (call) risk premiums are more (less) negative for the portfolio of investment versus funding currencies. We formalize a theory to understand the properties of currency option risk premiums.

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1. Introduction

The role of the U.S. dollar is iconic in the international financial system. The invoicing of trade is concentrated in the U.S. dollar. Central banks lean toward holding U.S. dollar reserves, while U.S. Treasury securities serve as safe assets and facilitate collateral arrangements in financial transactions. Flow data show that sovereign entities and wealth funds are avid buyers of U.S. assets. At the same time, non-U.S. firms borrow in U.S. dollars and, thus, prefer dollar exposures. The balance sheets of foreign banks manifest dollar liabilities that are essentially at par with U.S. banks. Additionally, the price of crude oil and gold are denominated in U.S. dollars, and institutionally weaker economies have black markets for dollars. The evidence indicates that the U.S. dollar is the king of all currencies.[1]

What are the quantitative implications of the U.S. dollar being the king of all currencies? We frame this question in the context of currency option risk premiums. The implications for currency option risk premiums are in line with the intuition that (i) the United States is differentially affected in bad economic states and (ii) bad states are associated with the appreciation of the U.S. dollar. We provide a theoretical framework wherein the risk premiums of currency option claims to the downside and upside are influenced by the time-varying sign of the currency risk premium. Our framework offers flexibility in generating realistic heterogeneity in (option and currency) risk premiums together with mimicking exchange rate volatilities across currencies.

Building on these connections, we consider options data for 15 single-name currencies, including the G10 currencies (the world's largest and most traded currencies) and 6 other currencies. The richness of this currency options data set stems from its daily availability while maintaining a constant expiration of 30 days. Crucial to drawing reliable inferences, this data set contains many more option expiration cycles than most papers (nearly *4,900* per name over the sample from 2000 to 2019). In our interpretations, currency option quotes are such that the U.S. dollar is the *base* currency and the foreign currency is the *reference*.

[1] We refer the reader to the evidence in Goldberg and Tille (2008); Gourinchas and Rey (2007); Mendoza, Quadrini, and Rull (2009); Hassan (2013); Maggiori (2017); Farhi and Maggiori (2018); He, Krishnamurthy, and Milbradt (2019); Gopinath, Boz, Casas, Diez, Gourinchas, and Plagborg-Moller (2020); Maggiori, Neiman, and Schreger (2020); Anderson, Du, and Schlusche (2021); Gopinath and Stein (2021); and Du and Schreger (2022).

We employ our currency options panel to answer three questions: (1) What is the nature of risk premiums on downside movements on currencies (that is, their depreciation)? (2) Is there evidence that investors worry about risks that cause the U.S. dollar to depreciate? (3) How significant are the risk premiums for bearing currency volatility risks? Our empirical evidence reflects macroeconomic disparities across economies and incorporates state-dependent concerns about insuring currency movements.

Pertinent to our questions are the properties of option risk premiums on investment versus funding currencies during heightened economic uncertainties. These data points shape the demand for the U.S. dollar as a global safe asset and may accordingly affect risk premiums. Motivating the theory that underlies option risk premiums, we explore whether variables characterizing macroeconomic disparities among the economies can describe the cross-sectional and time-series variation in currency option excess returns.

Economy pairs associated with positive currency risk premiums display negative put risk premiums that decline at lower strikes. The average risk premium on 10 delta puts is -24.8% (respectively, -23.4%) per month across the 15 currencies (respectively, the G10). Instrumental to our theory, 14 of 15 single-name 10 delta put risk premiums are negative. Our evidence indicates broad reservations about foreign currency depreciations, a feature in line with the U.S. dollar being a central player in the global financial system.

Our data suggest a finding that 10 delta call risk premiums are, on *average*, reliably less negative in comparison to puts. We attribute this evidence on call risk premiums to the feature that markets are less concerned about U.S. dollar depreciations than appreciations.[2]

The size of the volatility risk premiums, as reflected in single-name straddle excess returns, is empirically small negative, small positive, or statistically indistinguishable from zero. The global volatility risk premium — constructed as an equal-weighted portfolio of its 15 constituents — is revealed to be smaller than that for single-name currencies, at -0.7% unconditionally (per month, insignificant). This data dimension has economic content, as the desire to hold U.S. dollars takes many forms in the international

[2]Our evidence for the Japanese yen, which manifests a *positive* (negative) risk premium for out-of-the-money puts (calls) may be decisive to macrofinance models. Our theory reconciles these empirical outcomes in the context of a significantly negative currency risk premium (that is, investors pay a premium to hold the yen), combined with negative risk premiums for upside currency movements (that is, U.S. dollar depreciations). Japan is a heavy exporter to the United States, which connects to the feature that U.S. dollar depreciations are disliked.

financial system, and overall aversion about currency volatility, when the U.S. dollar is the base currency, appears insignificant.

Because investment and funding currencies may embed different vulnerabilities to global shocks, we examine option risk premiums for currency sets obtained by dynamically sorting currencies on interest-rate differentials. This empirical treatment supports a finding that put option risk premiums are reliably more negative for investment currencies than for funding currencies. Reversing the pattern, we uncover that call option risk premiums are reliably more negative for funding currencies. The volatility risk premiums are indistinguishable between investment and funding currencies.

If, as extant theory and the literature suggest, the U.S. dollar tends to appreciate in bad states, what can be revealed about currency option risk premiums aligned with heightened economic uncertainties? Inquiring into this matter, we initiate option positions contingent on belonging to one of five bins ranging from low to high equity volatility levels. We close this position in 30 days. In our analysis, we gauge heightened economic uncertainty by a VIX breakpoint higher than 40% (about 3% of the data points). The takeaway is that funding currencies, as opposed to investment currencies, manifest more negative put, call, and volatility risk premiums when the option positions are initiated in high equity volatility states.

There are reasons to think that currency option risk premiums will not be homogeneous across economy pairs. To isolate common underlying economic mechanisms, we investigate whether (i) interest-rate differentials on five-year government bonds with respect to the United States, (ii) the quadratic variation in currency returns, (iii) currency returns over a trailing window, and (iv) risk reversals can forecast option risk premiums. In the panel regression framework, we allow for robust standard errors along with year fixed effects and currency fixed effects. Our treatment indicates that some of these macroeconomic disparity variables are statistically relevant for forecasting currency option risk premiums.

Focusing on interpretations, we formalize a theory of currency option risk premiums that, to our knowledge, has not been introduced in the context of comparing option risk premiums across currencies. This theory is characterized in terms of the single-name currency risk premiums and the risk premiums associated with currency return moments. Our theory is amenable to addressing questions like those that follow: Why are the put and call risk premiums both negative for some single names? Which sources underlie the variation in currency option risk premiums? Why are the put (call) option risk premiums for the yen positive (highly negative)? Our assessment exercises imply that a model with global risk drivers, non-normalities in the currency return distributions, and differential exposures to uncertainties shows promise in mimicking the multidimensional attributes of the options data across single-name currencies.

How do our theory and findings on option risk premiums connect to other papers in the literature? Imperative to Farhi and Gabaix (2016) is the possibility of rare but extreme disasters. Another theory emphasizes the notion of "the exorbitant privilege" of the United States combined with the safe haven attributes of the U.S. dollar (e.g., Gourinchas and Rey (2007) and Maggiori (2017)). The work of Gopinath, Boz, Casas, Diez, Gourinchas, and Plagborg-Moller (2020) and Gopinath and Stein (2021) proposes a theory of dominant currency based on global trade and banking system configurations.

Our distinction from extant theories is that investors cover positions in both tails of the currency return distribution, and they are averse to both the depreciation of the foreign currency (put option risk premiums can be negative) and the depreciation of the U.S. dollar (call option risk premiums can be negative). Viewed from this standpoint, the negative call option risk premiums can be puzzling if single-name currencies embed positive currency risk premiums.

To our knowledge, our exercises documenting the implications of the U.S. dollar as the king of all currencies for currency option risk premiums do not have direct parallels. At the center of our inquiry is a theory of currency option risk premiums, and we explore consistencies with our empirical findings. Specifically, our treatment considers phenomena related to option risk premiums, and we uncover the return properties of puts, calls, and straddles across single-name currencies and characteristic-sorted currency portfolios.

Our theoretical and empirical angles are motivated by the lack of a coherent view on how investors respond to downside and upside uncertainties in currency markets. Inferring risk premiums from option returns helps emphasize salient facts unavailable from examining currency instruments that do not offer Arrow-Debreu like payoffs (that is, forwards and currency swaps). Models could be enriched if they are informed by the empirical properties of option risk premiums on investment and funding currencies.

2. Daily options data on 15 single-name currencies

Our data consist of *daily* quotes on single-name currency option prices as well as observations on forward and spot exchange rates. By convention, currency option prices are quoted in the form of 10-delta, 25-delta, and at-the-money (ATM) put or call volatilities. Importantly, the positions in currency options and forwards can be *initiated each day* and settle in 30 days.

Table 1 provides the list of single-name currency options, the source for which is a major bank. Our quote convention is such that the *base* currency is the U.S. dollar and the *reference* is the foreign currency. In our daily data, the earliest start date is 1/3/2000, and the end date for all options is 10/31/2019.

Our analysis is based on the following 15 currencies: Australian dollar, Canadian dollar, Czech koruna, Danish krone, euro, Hungarian forint, Japanese yen, South Korean won, New Zealand dollar, Norwegian krone, Polish zloty, South African rand, Swedish krona, Swiss franc, and British pound. Because the currency option contracts settle in 30 days, there are 73,473 expiration cycle observations in our sample.

Our sample includes the G10 currencies, which account for the majority of turnover.[3] We complement this sample by including six non-G10 currencies. Whereas most currency options research relies on data at the monthly frequency, the use of options at the daily frequency, while maintaining a constant maturity of 30 days, is a unique feature of our study.[4]

We employ the following notations:

[3] According to the 2019 survey of turnover in foreign exchange markets (compiled by the Bank for International Settlements), these currencies plus the dollar account for more than 85% of the total global turnover of over-the-counter instruments.

[4] There is a sparsity of studies that exploit currency options data across available strikes and single names. Our paper joins, among others, Bates (1996); Carr and Wu (2007); Bakshi, Carr, and Wu (2008); Burnside, Eichenbaum, Kleshchelski, and Rebelo (2011); Caballero and Doyle (2012); Gavazzoni, Sambalaibat, and Telmer (2013); Jurek (2014); Farhi, Fraiberger, Gabaix, Ranciere, and Verdelhan (2013); Della Corte, Sarno, and Ramadorai (2016); Londono and Zhou (2017); Daniel, Hodrick, and Lu (2017); Della Corte, Kozhan, and Neuberger (2021); and Branger, Herold, and Muck (2021).

τ: Remaining days to maturity of the forward and option contracts, set equal to 30/365.

$S_t^{\mathrm{j|us}}$: Spot price (at day t) of one unit of currency j in terms of the U.S. dollar. Henceforth, a rise in $S_t^{\mathrm{j|us}}$ is associated with the appreciation (depreciation) of the reference (base) currency.

$F_{t,\tau}^{\mathrm{j|us}}$: Forward price of one unit of currency j in terms of the U.S. dollar with settlement in τ days from t.

r_t^{us} (r_t^{j}): Interest-rate on the U.S. dollar (foreign currency) deposit for τ-day horizons (known at day t).

$\triangle_p$ ($\triangle_c$): Delta of a put (call) on the currency (that is, ATM, 25 delta, or 10 delta).

$\sigma_t[\triangle_p]$: Volatility quote of a put on day t, where $\triangle_p$ take values ATM, 25, or 10 (deepest OTM put).

$\sigma_t[\triangle_c]$: Volatility quote of a call on day t, where $\triangle_c$ take values ATM, 25, or 10 (deepest OTM call).

Let K_{ATM}, $K_{\triangle_p}$, and $K_{\triangle_c}$ be the strike prices corresponding to the respective option deltas, and $\mathcal{N}^{-1}[.]$ represent the inverse of the standard normal cumulative distribution. We apply the following conversion formulas (see, for example, Wystup (2006)) to obtain strike prices for the quoted volatilities:

$$K_{\mathrm{ATM}} = F_{t,\tau}^{\mathrm{j|usd}} \exp(\frac{1}{2}\sigma_t^2[\mathrm{ATM}]\,\tau), \tag{1}$$

$$K_{\triangle_p} = F_{t,\tau}^{\mathrm{j|usd}} \exp(\frac{1}{2}\sigma_t^2[\triangle_p]\,\tau + \sigma_t[\triangle_p]\sqrt{\tau}\,\mathcal{N}^{-1}[-\exp(r_t^{\mathrm{j}}\,\tau)\,\triangle_p]), \quad \text{and} \tag{2}$$

$$K_{\triangle_c} = F_{t,\tau}^{\mathrm{j|usd}} \exp(\frac{1}{2}\sigma_t^2[\triangle_c]\,\tau - \sigma_t[\triangle_c]\sqrt{\tau}\,\mathcal{N}^{-1}[\exp(r_t^{\mathrm{j}}\tau)\,\triangle_c]). \tag{3}$$

With the strike prices of the currency options (as in equations (1)–(3)) and the quoted volatilities, we then calculate the corresponding put and call prices using the Garman and Kohlhagen (1983) formula. The put (respectively, call) price with strike price K and remaining maturity τ is denoted as $\mathrm{put}_t^{\mathrm{j|usd}}[K]$ (respectively, $\mathrm{call}_t^{\mathrm{j|usd}}[K]$). We omit the τ dependence on the currency option prices for brevity.[5]

We compute risk reversals as the volatility of a put minus that of call for a fixed delta. Table 1 indicates considerable heterogeneity in risk-neutral currency return distributions, with non-G10 pairs displaying higher volatilities and more pronounced risk reversals. The average risk reversals are negative only for the

[5] Aiding interpretations, the OTM put, say, with strike $K_d < S_t$, provides a payoff if the reference currency (respectively, the U.S. dollar) *depreciates* (respectively, appreciates) beyond the threshold of K_d. In contrast, the OTM call, say, with strike $K_u > S_t$, provides a payoff if the reference currency (respectively, the U.S. dollar) *appreciates* (respectively, depreciates) beyond K_u.

Japanese yen and, to a lesser degree, the Swiss franc, the two traditional funding currencies.

3. Facts about currency option risk premiums

In this section, we document the implications for currency option risk premiums of the critical role of the U.S. dollar in the global financial system. We connect these implications to macroeconomic disparities between the United States and other economies to analyze if, and how, these disparities differentially affect downside versus upside currency option risk premiums.

We address four questions: What are the quantitative features of single-name currency puts, calls, and straddle risk premiums? Are the option risk premiums for investment and funding currencies different? Which economy-pair characteristics describe the heterogeneity in option risk premiums across currencies? Finally, how do option risk premiums change in response to heightened economic uncertainties?

3.1. Put option risk premiums for currencies are overwhelmingly negative

Each day in our sample, we buy a 10-delta (or 25-delta) put on a currency and compute the excess returns from holding this option over the subsequent 30 days, as follows:

$$\mathbf{z}^{\text{put}}_{\{t\to t+\tau\}}[K_{10\triangle_p}] \;=\; \frac{\max(K_{10\triangle_p} - S^{\text{j}|\text{us}}_{t+\tau}, 0)}{\text{put}_t[K_{10\triangle_p}]} \;-\; \exp(r^{\text{us}}_t\,\tau), \tag{4}$$

where $K_{10\triangle_p}$ corresponds to the strike price of a 10 delta put, $S^{\text{j}|\text{us}}_{t+\tau}$ is the settlement price, and $\text{put}_t[K_{10\triangle_p}]$ is the put price. We proxy r^{us}_t by the 30-day U.S. Treasury bill rate.

The $\mathbb{P}$-measure expectation of $\mathbf{z}^{\text{put}}_{\{t\to t+\tau\}}[K_{10\triangle_p}]$ conditional on filtration $\mathcal{F}_t$, that is, $\mathbb{E}^{\mathbb{P}}_t(\mathbf{z}^{\text{put}}_{\{t\to t+\tau\}}[K_{10\triangle_p}])$, defines the currency put option risk premium. If excess returns of puts are aligned with the ex ante expected excess returns of puts and are negative, then market participants are paying a premium to protect against downward movements in the reference currency.

Table 2 shows that, among the G10 currency pairs, the 10 delta put moneyness ranges between 3.5% for the Canadian dollar and 5.1% for the New Zealand dollar. Our rationale for keeping the option delta fixed is to account for differences in currency volatility across single names and in the time-series.

The salient aspect of table 2 (panel A) is that the mean return to holding 10 delta puts is negative for *14 of the 15* pairs. These put risk premiums are statistically significant for six out of the nine G10 pairs, and the evidence is stronger for non-G10 pairs, all of which display negative and significant put risk premiums. We evaluate statistical significance using lower and upper 95% bootstrap confidence intervals for mean put option excess returns.[6] We mark in bold the put risk premiums that are statistically significant.

Inspecting the results from equal-weighted currency portfolios, we find that the put risk premiums are −23.4% (not annualized) for G10 pairs and −24.8% among the 15 pairs. Implying the presence of greater insurance concerns, the put risk premiums are higher for non-G10 pairs (−30.9%).

Akin to 10-delta puts, 25-delta puts (panel B) also manifest negative option risk premiums, but the distinction is that they are less negative. We examine bootstrap confidence intervals for the differences in the adjacent strikes and find that they do not overlap. Moreover, put risk premiums are smaller in magnitude for deeper OTM puts (that is, *more negative* for most currencies or *less positive* for Japan).

Table 2 supports our view that the U.S. dollar is the king of all currencies. Our evidence comes in the form of buying insurance against the depreciation of foreign currencies.

3.2. Call option risk premiums are of variable sign across single-name currency pairs

We buy a 10-delta (or 25-delta) call each day and compute the excess returns over the subsequent 30 days (the holding period), as follows:

$$\mathbf{z}^{\text{call}}_{\{t\to t+\tau\}}[K_{10\triangle_c}] \;=\; \frac{\max(S^{\text{j|us}}_{t+\tau} - K_{10\triangle_c}, 0)}{\text{call}_t[K_{10\triangle_c}]} \;-\; \exp(r^{\text{us}}_t\,\tau), \tag{5}$$

where $K_{10\triangle_c}$ is the strike of a 10 delta call and $\text{call}_t[K_{10\triangle_c}]$ denotes the call price.

Comparing the results in table 3 for call risk premiums with those for put risk premiums in table 2, we

[6]In terms of the reliability of our assessments for the significance of option risk premiums, our evidence is based on 44,408 (respectively, 73,473) option expiration cycles for the G10 (respectively, all 15 currencies).

can emphasize several findings. First, for the farther OTM options (that is, 10 delta), seven (respectively, three) currency pairs have negative (respectively, positive) and significant call option risk premiums. Call option risk premiums are typically higher at 25 delta than at 10 delta, but three currencies with positive and significant call option risk premiums, offer a noticeable contrast. Thus, the heterogeneity in call option risk premiums not only arises from their signs but also from not always decreasing in strike.

Second, focusing on G10 currencies, we find that the Japanese yen (-57.3%), the Canadian dollar (-27.8%), the U.K. pound (-22.5%), the euro (-19.8%), and the Swedish krona (-12.0%) display reliably negative 10 delta call option risk premiums. Our results suggest that negative currency call option risk premiums are concentrated among economies that are heavy exporters to the United States.[7]

One potential driver of negative currency call option risk premiums is then sizable dollar revenue exposures, which is a form of U.S. prominence in global trading arrangements. Accordingly, our evidence is aligned with hedging U.S. dollar depreciations by an economically relevant set of economies.

The magnitude and negative nature of call option risk premiums may also be connected to the use of funding currencies, such as the Japanese yen, in carry trade strategies. If the Japanese yen is sold forward or shorted in the futures market (because it is mostly in contango), then buying calls offers protection against an appreciating yen. In section 3.4, we explore this mechanism by buying currency calls aligned with a dynamically rebalanced set of currencies with relatively low interest-rates.

Our evidence supports that risk premiums for currency calls are, on average, much smaller relative to puts. Fixing delta to 10, we find that the call option risk premium for the 15 currency portfolio is -3.4%, as opposed to -24.8% for puts. The estimate of this difference between put and call option risk premiums is -21.4%, with a lower and upper bootstrap confidence interval of -31% and -12%, respectively.

The takeaway is that markets worry more about downside movements in foreign currencies than about movements to the upside. Broadly speaking, they dislike more the economic states in which the U.S. dollar is appreciating.

[7] According to the IMF Direction of Trade Statistics, for December of 2019, 19.9%, 75.7%, 15.5%, 8.2%, and 8% of the total exports of Japan, Canada, the United Kingdom, the euro area, and Sweden, respectively, are to the United States.

3.3. *Currency volatility risk premiums are not uniformly negative and are near zero for portfolios*

Model-free currency volatility risk premiums can be inferred from the excess return of a currency straddle, calculated as follows:

$$\mathbf{z}^{\text{straddle}}_{\{t\to t+\tau\}} = \frac{\max(S^{\mathrm{j|us}}_{t} - S^{\mathrm{j|us}}_{t+\tau}, 0) \; + \; \max(S^{\mathrm{j|us}}_{t+\tau} - S^{\mathrm{j|us}}_{t}, 0)}{\text{put}_t[S^{\mathrm{j|us}}_t] \; + \; \text{call}_t[S^{\mathrm{j|us}}_t]} \; - \; \exp(r^{\mathrm{us}}_t \tau). \tag{6}$$

We observe from table 4 that the Canadian dollar, the Japanese yen, the Danish krone, the South Korean won, and the South African rand have *negative* and significant straddle excess returns. However, the associated magnitudes are relatively small and range between -2.3% to -5.4%. In contrast, the Australian dollar and the Czech koruna are distinguished by a *positive* and significant volatility risk premium.

The robust finding in table 4 is that single-name currencies elicit small negative, small positive, or indistinguishable from zero volatility risk premiums. Notably, the volatility risk premium diminishes in currency portfolios: It is -0.7% (-0.5%) for G10 (non-G10) pairs, and the average across all 15 pairs is -0.1%; in all cases, the 95% bootstrap confidence intervals bracket zero. Our results suggest that currency volatility does not appear to be a major concern to markets, and this indifference may be a consequence of the U.S. dollar being at the center of the international financial system.

3.4. *Disparities in option risk premiums when currencies are dynamically sorted on* $\log(\frac{F^{\mathrm{j|us}}_t}{S^{\mathrm{j|us}}_t})$

The argument we framed about the U.S. dollar being the king of all currencies is that markets will be more apprehensive about foreign currency depreciations. Therefore, downward movements in the foreign currency would be hedged by buying OTM currency puts. If, as in the traditional carry trade, investors buy investment currencies (those with high $r^{\mathrm{j}}_t - r^{\mathrm{us}}_t$) and possibly cover their downside risk, would this feature exert additional pressure on negative put option risk premiums?

Isomorphically, if investors engage in selling funding currencies (those with low $r^{\mathrm{j}}_t - r^{\mathrm{us}}_t$) and possibly cover their positions by buying OTM currency calls, would it pressure negative call option risk premiums?

To address these questions, we dynamically rank currency pairs by their $\log(\frac{F^{\mathrm{j|us}}_t}{S^{\mathrm{j|us}}_t})$ on day t. The five currencies with the *lowest* $\log(\frac{F_t^{j|us}}{S_t^{j|us}})$ are classified as having the *highest* interest-rate differentials. In contrast, the five currencies with the highest $\log(\frac{F_t^{j|us}}{S_t^{j|us}})$ are classified as having the lowest interest-rate differentials.[8]

Thus, we divide our currency universe into three bins, with the extreme ends constituting the set of investment and funding currencies, respectively. Next, we buy the associated 10 delta puts, 10 delta calls, and straddles. We then compute the equal-weighted excess returns of the option positions over the subsequent 30 days. The three currency sets are dynamically re-balanced each day.

Table 5 presents four noteworthy patterns. First, the carry strategy (panel B of table 5) earns, on average, 3.8%, and the bootstrap confidence intervals do not bracket zero. In essence, our option risk premium patterns are anchored to the empirical observation that the long-leg (respectively, short-leg) of the carry is, on average, profitable (respectively, unprofitable).

Second, put option risk premiums, while negative for both investment and funding currencies, are more negative for investment currencies. The disparity in put risk premium is -9% per month and is statistically significant. Thus, even though most foreign currencies garner downside hedging interest, our analysis reveals that an incremental negative option risk premium is attached to the investment currencies.

Third, the risk premium differential on 10 delta calls is equally revealing. Specifically, the call option risk premium for the portfolio of funding currencies is -11.1%, and it is statistically more negative than that for investment currencies — in this case, the disparity in risk premiums is 9%. Such an observation ties into our reasoning that negative call option risk premiums arise partly because of investors' desire to cover the appreciation of funding currencies in the short leg of the carry trade.

Fourth, the volatility risk premiums are small and statistically indistinguishable between the investment and funding currencies. The straddle risk premium differential is -0.9% per month, with a bootstrap confidence interval of -2.3% and 0.5%.

[8]See, e.g., Burnside, Eichenbaum, Kleshchelski, and Rebelo (2011); Lustig, Roussanov, and Verdelhan (2011); Menkhoff, Sarno, Schmeling, and Schrimpf (2012); and Bakshi and Panayotov (2013).

3.5. *Intuitively understanding patterns in currency option risk premiums*

Instrumental to our investigation is the primacy of the U.S. dollar and the links to currency option risk premiums and macroeconomic disparities across economies. The United States is endowed with relatively healthier institutions, including a competent central bank and less compromised monetary policies, and offers more protection for investors. These institutional features may be at the root of the stature of the U.S. dollar as the king of all currencies.

The role of the U.S. dollar is multifaceted, which is reflected in the nature of currency option risk premiums. Investors trust that the U.S. dollar will retain its value, in essence, offering safe haven during periods of heightened economic uncertainties. Additionally, the U.S. dollar is used to conduct international trade and financial transactions. The U.S. dollar is a preferred reserve currency.

Global investors appear cautious about potential devaluations in foreign currencies. In comparison with the U.S. dollar, foreign currencies with positive currency risk premiums may be considered riskier (e.g., those entering the long leg of the carry trade). Investors recognize, for example, that during bad times, the foreign currency can depreciate with respect to the U.S. dollar. The workings of flights to quality or safety in currency markets can further exacerbate declines in a foreign currency. Our findings about negative put option risk premiums are compatible with downside protection motives in the currency markets.

Our findings about currency call risk premiums are consistent with the possibility that there is little need to insure against sharp U.S. dollar depreciations, as reflected in call prices. The exception to this behavior could be time-sensitive dollar revenue exposures of economies with exports invoiced in U.S. dollars.

Finally, unlike equities, the leverage effect in currencies is presumably weaker. In other words, a fall in the currency value is *not* accompanied by a substantial rise in volatility that potentially makes options more expensive through the vega. If investors are committed to holding the U.S. dollar, then the risk premiums on currency volatility can be anticipated to be small in magnitude and can be negative or positive.

The reliability of our conclusions about option risk premiums derive their power from currency option excess returns computed over nearly 4,900 option expiration cycles per single-name currency. Additionally, our data interpretations rely on a design that keeps the U.S. dollar as the base currency. Overall, the documented disparities in option risk premiums can be traced to the differential sensitivities of currencies — whether investment or funding — to global economic shocks, and to the preponderance of the U.S. dollar in global financial and trade transactions.

3.6. Panel regressions linking currency option risk premiums to macroeconomic disparities

To investigate how macroeconomic disparities between the United States and other economies quantitatively affect currency option risk premiums, we use a panel regression framework. For example, for put option risk premiums, we estimate the following regression with nonoverlapping monthly observations:

$$\begin{aligned}\underbrace{\mathbf{z}^{\mathrm{put,j}}_{\{t\to t+\tau\}}}_{\text{next 30 days}} \;=\; & \delta_0 + \delta_1 \underbrace{(r_t^{\mathrm{j,5year}} - r_t^{\mathrm{us,5year}})}_{\text{interest-rate differential}} + \delta_2 \underbrace{\mathrm{QV}_t^{\mathrm{fx,j}}}_{\text{quadratic variation}} + \delta_3 \underbrace{\mathrm{MA30}_t^{\mathrm{fx,j}}}_{\text{recent behavior}} \\ & + \delta_4 \underbrace{\mathrm{RR10}_t^{\mathrm{j}}}_{\text{put minus call implied volatility}} + e^{\mathrm{j}}_{\{t,t+\tau\}} \text{ for j} = 1,\ldots,15 \text{ and } t = 1,\ldots,213. \end{aligned} \tag{7}$$

Underscoring distinctions across economies, in table 6, we consider the following disparity variables known at time t: the interest-rate differentials on five-year government bonds ($r_t^{\mathrm{j,5year}} - r_t^{\mathrm{us,5year}}$), the quadratic variation of currency returns ($\mathrm{QV}_t^{\mathrm{fx,j}}$), the currency excess returns over a 30-day trailing window ($\mathrm{MA30}_t^{\mathrm{fx,j}}$), and the 10 delta risk reversals ($\mathrm{RR10}_t^{\mathrm{j}}$). Our choice of variables can be motivated on empirical and/or intuitive grounds. The variable construction is described in the note to table 6.

We consider both currency fixed effects and year fixed effects in the panel regressions. Our rationale for the currency fixed effect is to account for time-invariant currency characteristics (for example, distance and the centrality of the United States). Allowing for year fixed effects internalizes the impact of global risks on the cross-section of option risk premiums. Parameter significance implies a relationship in both the cross-section and time-series.

Pointing to the ability of macroeconomic disparities to explain currency option risk premiums, we emphasize four findings. First, there is a positive association between 10 delta put risk premiums and $r^{\mathrm{j,5year}} - r^{\mathrm{us,5year}}$. Higher interest-rate differentials also forecast the appreciation of these economies' currencies against the U.S. dollar. Second, the dimension of $\mathrm{QV}^{\mathrm{fx,j}}$ is negatively and significantly related to option risk premiums, which suggests that higher currency volatility is related to increasing concerns against currency changes, irrespective of the direction. Third, the negative coefficient on $\mathrm{MA30}^{\mathrm{fx,j}}$ for puts conveys that downside protection concerns are more pronounced for economy pairs with previous currency appreciations against the U.S. dollar. Finally, risk reversals manifest a form of riskiness in the sense of Farhi and Gabaix (2016). Specifically, we assess whether higher $\mathrm{RR10}^{\mathrm{j}}$s forecast higher currency risk premiums and more negative put risk premiums. Although the association of $\mathrm{RR10}^{\mathrm{j}}$ with put and currency risk premiums may be as anticipated, the highest (absolute) t-statistic is 1.66.

Overall, our panel regressions suggest that differences in macroeconomic outcomes, especially the quadratic variation in currency returns, help to quantify subsequent currency option risk premiums.

3.7. Conditional currency option risk premiums and heightened economic uncertainty

The U.S. dollar is conceivably underpinned by sound macroeconomic fundamentals. This view has been molded by, among others, the studies of Gourinchas and Rey (2007); Caballero, Farhi, and Gourinchas (2008); Mendoza, Quadrini, and Rull (2009); and Farhi and Maggiori (2018). These authors have emphasized the safe haven qualities of the U.S. dollar during periods of heightened economic uncertainty.

In our exercise, economic uncertainty is characterized using equity VIX (volatility) states. Specifically, heightened economic uncertainty is measured by realizations of $\mathrm{VIX}_t \geq 40$. For comparison, we divide our daily sample into five VIX bins: (i) $\mathrm{VIX}_t < 11$ (count of 241), (ii) $11 \leq \mathrm{VIX}_t < 17$ (count of 2,270), (iii) $17 \leq \mathrm{VIX}_t < 24$ (count of 1,615), (iv) $24 \leq \mathrm{VIX}_t < 40$ (count of 1,102), and (v) $\mathrm{VIX}_t \geq 40$ (count of 189). The highest VIX states compose 3% of our sample, and these states are often marked by retreating equity markets, the withdrawal of international credit flows, and the global migration to safer assets.

Table 7 shows the currency option risk premiums for each VIX bin. These entries are to be interpreted as partitioned average 30-day excess option returns that are conditional on filtration $\mathcal{F}_t = \mathrm{VIX}_t$. In other words, we take a position in options conditional on $\mathcal{F}_t$ and compute the subsequent excess option returns.

With respect to put option risk premiums, we glean that investors are paying to protect foreign currency devaluations in *every* equity volatility state. Notably, the negative put option risk premiums allied to high volatility states ($\text{VIX}_t \geq 40$) are indistinguishable between investment and funding currencies. While buying puts on currencies can deliver big subsequent payoffs in high volatility states, the cost of protection against the appreciation of the U.S. dollar rises proportionally.

Next, the partitioned average excess returns of 10 delta calls are both positive and negative. Thus, investors do not necessarily pay a premium to protect against the depreciation of the U.S. dollar in every volatility state. The contrast is that the partitioned average excess return of call options is most negative when $\text{VIX}_t \geq 40$. In this state, the negative call risk premium on the funding currencies drives the significant spreads in call risk premiums for investment versus funding currencies. Viewed from the prism of call option risk premiums, our evidence implies distinct susceptibilities for funding currencies.

Reinforcing our earlier result, the global volatility risk premiums — the straddle excess returns averaged across 15 currencies — are insignificantly small in most equity volatility states.

4. A theory of currency option risk premiums anchored to our findings

This section presents a tractable model of currency dynamics and explores its consistency with the empirical properties of currency option risk premiums. Using this framework, we can accommodate differential sensitivity of economies to three candidates for dynamically evolving global risks, namely, those connected to volatility, probability of tail movement, and the size of tail movement.

We are interested in theoretically understanding currency option risk premiums and in highlighting economic mechanisms for the documented empirical patterns. Our question is the following: Can such a model reproduce the properties of option risk premiums across single-name currencies?

4.1. Motivation for the model's elements

Four empirical findings motivate the theoretical model:

1. There are large down and up currency tail movements. As depicted by $\mathbb{1}_{\{\mathbf{z}>0\}}$, 10 delta puts have positive excess returns in 6% to 10% of the option expiration cycles (table 2). Correspondingly, 10 delta calls have positive excess returns in 4% to 11% of the cycles (table 3). A significant number of directional movements are implied by $\mathbb{1}_{\{\mathbf{z}>0\}}$ for currency straddles (table 4).

2. *Option risk premiums have at least three predominant drivers.* Table 8 indicates that three principal components together capture 67%, 59%, and 63% of the variance in the single-name excess returns of 10 delta puts, 10 delta calls, and straddles, respectively.

3. *Currency risk premiums are of variable sign.* Table 9 shows that 12 of the 15 currencies display positive currency risk premiums, and 10 of these 12 pairs are positive and significant. The Japanese yen offers a deviation from this pattern and displays a significantly negative currency risk premium.

4. *Currency option risk premiums are marginally explained by changes in yield differentials and changes in U.S. inflation swap rates.* Table 10 performs regressions with currency option excess returns (10 delta puts and calls, and straddles) as the dependent variable and the following three sets of explanatory variables:

– **SET A**: Principal components extracted from 15 excess currency returns.

– **SET B**: SET A plus principal components extracted from changes in 15 yield differentials. The United States is the base and the yield-to-maturities are anchored to one year.

– **SET C**: SET B plus principal components extracted from changes in zero-coupon U.S. inflation swap rates. We employ swap maturities of 1, 2, 3, 4, and 5 years. Our goal is to explore the extent to which shifts in inflation expectations tied to the dominant currency bear on currency option risk premiums.

The key evidence is that the adjusted R^2's do not change materially when the regressions with SET A are augmented with yield differentials or when additionally augmented with U.S inflation swap rates.

For 10 delta puts, the average adjusted R^2's corresponding to SET A, SET B, and SET C are 27%, 34%, and 37%, respectively. For 10 delta calls, the average adjusted R^2's are 24%, 26%, and 23%, respectively. Our findings indicate that a large fraction of the variation in currency option returns is unspanned.

Overall, this exercise suggests a role for common drivers in the form of volatility and jump uncertainties. The ingredients of volatility and jump risks are incorporated in the ensuing theoretical analysis.

4.2. Mechanism of differential sensitivities to global risks

The dynamics of the domestic pricing kernel (denoted by M_t^{us}) and the foreign pricing kernel (denoted by M_t^{j}) accommodate jumps of random amplitude and stochastic volatility effects, as follows:

$$\frac{dM_t^{\mathrm{us}}}{M_{t-}^{\mathrm{us}}} = -r_t^{\mathrm{us}}\,dt + \beta_{\mathrm{us}}\sqrt{\mathbf{v}_t}\,d\mathbb{W}_t^{\mathbb{P},\mathbf{v}} + \eta_{\mathrm{us}}\sqrt{\mathbf{b}_t}\,d\mathbb{W}_t^{\mathbb{P},\mathbf{b}} + (e^{\alpha_{\mathrm{us}}x}-1)\,d\mathbb{N}_t - \mathbf{b}_t\,\mathbb{E}_t^{\mathbb{P}}(e^{\alpha_{\mathrm{us}}x}-1)dt \tag{8}$$

$$\underbrace{\frac{dM_t^{\mathrm{j}}}{M_{t-}^{\mathrm{j}}}}_{\text{pricing kernel}} = -r_t^{\mathrm{j}}\,dt + \underbrace{\beta_{\mathrm{j}}\sqrt{\mathbf{v}_t}\,d\mathbb{W}_t^{\mathbb{P},\mathbf{v}}}_{\text{volatility contribution}} + \eta_{\mathrm{j}}\sqrt{\mathbf{b}_t}\,d\mathbb{W}_t^{\mathbb{P},\mathbf{b}} + \underbrace{(e^{\alpha_{\mathrm{j}}x}-1)\,d\mathbb{N}_t}_{\text{jump contribution}} - \underbrace{\mathbf{b}_t\,\mathbb{E}_t^{\mathbb{P}}(e^{\alpha_{\mathrm{j}}x}-1)dt}_{\text{compensator}}, \tag{9}$$

where r_t^{us} and r_t^{j} are (deterministic) interest-rates in the United States and the foreign economy, respectively. Furthermore, $\mathbb{W}_t^{\mathbb{P},\mathbf{v}}$ and $\mathbb{W}_t^{\mathbb{P},\mathbf{b}}$ are standard Brownian motions that affect the evolution of the pricing kernels.

Jumps in the pricing kernels are modeled as arriving at random times t_ℓ with jump intensity $\mathbf{b}_t$. The effect of jumps is *asymmetric* with $M_{t_\ell}^{\mathrm{us}} = M_{t_{\ell-}}^{\mathrm{us}}\,e^{\alpha_{\mathrm{us}}x_\ell}$, while $M_{t_\ell}^{\mathrm{j}} = M_{t_{\ell-}}^{\mathrm{j}}\,e^{\alpha_{\mathrm{j}}x_\ell}$. The size of the jump x is an *i.i.d* random variable and is independent of the Poisson process $\mathbb{N}_t$.

All sources of uncertainty (that is, $\mathbb{W}_t^{\mathbb{P},\mathbf{v}}$, $\mathbb{W}_t^{\mathbb{P},\mathbf{b}}$, $\mathbb{N}_t$, x) are uncorrelated. We assume

$$\text{Diffusive (component) variance under } \mathbb{P}: \quad d\mathbf{v}_t = \kappa_{\mathbf{v}}^{\mathbb{P}}\Big(\frac{\theta_{\mathbf{v}}^{\mathbb{P}}}{\kappa_{\mathbf{v}}^{\mathbb{P}}} - \mathbf{v}_t\Big)\,dt + \sigma_{\mathbf{v}}\sqrt{\mathbf{v}_t}\,d\mathbb{W}_t^{\mathbb{P},\mathbf{v}} \tag{10}$$

$$\text{Probability of tail movement under } \mathbb{P}: \quad d\mathbf{b}_t = \kappa_{\mathbf{b}}^{\mathbb{P}}\Big(\frac{\theta_{\mathbf{b}}^{\mathbb{P}}}{\kappa_{\mathbf{b}}^{\mathbb{P}}} - \mathbf{b}_t\Big)\,dt + \sigma_{\mathbf{b}}\sqrt{\mathbf{b}_t}\,d\mathbb{W}_t^{\mathbb{P},\mathbf{b}} \tag{11}$$

$$\text{Poisson jump in the pricing kernels}: \quad d\mathbb{N}_t = \begin{cases} 1 & \text{with probability } \mathbf{b}_t\,dt \\ 0 & \text{with probability } 1-\mathbf{b}_t\,dt \end{cases} \tag{12}$$

$$\text{Size of tail movement}: \ x \sim \text{i.i.d. Normal}(\mu_x, \sigma_x^2). \tag{13}$$

The compensator $\mathbf{b}_t\,\mathbb{E}_t^{\mathbb{P}}(e^{\alpha_{\mathrm{j}}x}-1)\,dt$ ensures that the drift rate of $\frac{dM_t^{\mathrm{j}}}{M_t^{\mathrm{j}}}$ is $-r_t^{\mathrm{j}}$. Notably, the sensitivity of $\log(\frac{M_{t+\tau}^{\mathrm{j}}}{M_{t-}^{\mathrm{j}}})$ to $\int_t^{t+\tau}\sqrt{\mathbf{v}_u}\,d\mathbb{W}_u^{\mathbb{P},\mathbf{v}}$ and $\int_t^{t+\tau}\sqrt{\mathbf{b}_u}\,d\mathbb{W}_u^{\mathbb{P},\mathbf{b}}$ is β_{j} and η_{j}, respectively. Correspondingly, α_{j} is the sensitivity to jump uncertainty $\sum_{\ell=\mathbb{N}_t}^{\mathbb{N}_{t+\tau}} x_\ell$. To quantitatively examine the channels that may affect currency option risk premiums, we consider parameterizations that allow economy j to have exposures to these uncertainties that are different from those for the United States.

The exchange rate is modeled as the ratio of the foreign to the domestic pricing kernel (for example, Backus, Foresi, and Telmer (2001)) and $\frac{F_{t,\tau}^{\mathrm{j|us}}}{S_t^{\mathrm{j|us}}} = \exp(\{r_t^{\mathrm{us}} - r_t^{\mathrm{j}}\}\tau)$. Equations (8)–(9) imply that

$$\begin{aligned}
\log\Big(\frac{S_{t+\tau}^{\mathrm{j|us}}}{S_{t-}^{\mathrm{j|us}}}\Big) \;&=\; (r_t^{\mathrm{us}} - r_t^{\mathrm{j}})\,\tau \;+\; \frac{1}{2}(\beta_{\mathrm{us}}^2 - \beta_{\mathrm{j}}^2)\int_t^{t+\tau} \mathbf{v}_u\, du \\
&+\; \frac{1}{2}\{\eta_{\mathrm{us}}^2 - \eta_{\mathrm{j}}^2 - \mathbb{E}_t^{\mathbb{P}}(e^{\alpha_{\mathrm{j}} x} - 1) + \mathbb{E}_t^{\mathbb{P}}(e^{\alpha_{\mathrm{us}} x} - 1)\}\int_t^{t+\tau} \mathbf{b}_u\, du \qquad (14)\\
&+\; \underbrace{(\beta_{\mathrm{j}} - \beta_{\mathrm{us}})\int_t^{t+\tau}\sqrt{\mathbf{v}_u}\, d\mathbb{W}_u^{\mathbb{P},\mathbf{v}}}_{\text{differential exposure to diffusive volatility}} \;+\; \underbrace{(\eta_{\mathrm{j}} - \eta_{\mathrm{us}})\int_t^{t+\tau}\sqrt{\mathbf{b}_u}\, d\mathbb{W}_u^{\mathbb{P},\mathbf{b}}}_{\text{differential exposure to probability of tail movement}} \;+\; \underbrace{(\alpha_{\mathrm{j}} - \alpha_{\mathrm{us}})\sum_{\ell=\mathbb{N}_t}^{\mathbb{N}_{t+\tau}} x_\ell}_{\text{differential exposure to jump uncertainty}}.
\end{aligned}$$

The currency risk premium implied by the model in (14) is time-varying and can be of either sign. The differentiating element of our approach is the link to a theory of currency option risk premiums.[9]

4.3. *Formulating the currency option risk premiums*

For compactness of expressions, we define the log currency price changes (denoted by z) and currency option moneyness (denoted by k) for strike price K, respectively, as follows:

$$z \;\equiv\; \log\Big(\frac{S_{t+\tau}^{\mathrm{j|us}}}{S_{t-}^{\mathrm{j|us}}}\Big) \in (-\infty,\infty), \qquad \text{and} \qquad k \;\equiv\; \log\Big(\frac{K}{S_t^{\mathrm{j|us}}}\Big) \in (-\infty,\infty). \qquad (15)$$

The case of OTM puts (respectively, calls) corresponds to $k < 0$ (respectively, $k > 0$).

Let $\mathbb{E}_t^{\mathbb{Q}}(\bullet) \equiv \mathbb{E}^{\mathbb{Q}}(\bullet|\mathcal{F}_t)$ be the expectation under the risk-neutral measure $\mathbb{Q}$. For imaginary unit $i = \sqrt{-1}$, we consider the risk premium on the (complex-valued) hypothetical payoff $e^{i\phi z}\{e^k - e^z\}$ as follows:

$$\mathbf{rp}_t[\phi;k] \;\equiv\; \underbrace{\mathbb{E}_t^{\mathbb{P}}(e^{i\phi z}\{e^k - e^z\}) \;-\; \mathbb{E}_t^{\mathbb{Q}}(e^{i\phi z}\{e^k - e^z\})}_{\text{moneyness-dependent risk premium}}, \;\; \text{where } \phi \text{ is some parameter of the contract.} \qquad (16)$$

The risk premium on $e^{i\phi z}\{e^k - e^z\}$ is a fundamental object in our context and relates to moneyness-dependent payoffs on the downside and the upside (details in the Internet Appendix). Our treatment devel-

[9] This model complements the one-currency models in Gabaix (2012) and Wachter (2013) and the two-currency models of Bates (1996); Carr and Wu (2007); Bakshi, Carr, and Wu (2008); Farhi, Fraiberger, Gabaix, Ranciere, and Verdelhan (2013); Jurek and Xu (2014); and Farhi and Gabaix (2016). We emphasize the unequal sensitivity of pricing kernels to bad shocks.

ops the expression for the risk premiums on $e^{i\phi z}\{e^k - e^z\}$, which is tractable for the dynamics in (14).

In what follows, we deduce expressions for the currency option risk premiums. All proofs are in the Internet Appendix. The notation $\mathfrak{Re}[\bullet]$ refers to the real part of the complex-valued function.

Result 1 (Put risk premium ($k<0$)) *The put risk premium, denoted by* $\mu^{\text{put}}_{\{t\to t+\tau\}}[k] \equiv \frac{\mathbb{E}^{\mathbb{P}}_t(\max(e^k - e^z, 0))}{e^{-r^{\text{us}}_t \tau}\mathbb{E}^{\mathbb{Q}}_t(\max(e^k - e^z,0))} - e^{r^{\text{us}}_t \tau}$*, can be expressed as follows:*

$$\mu^{\text{put}}_{\{t\to t+\tau\}}[k] = \underbrace{\frac{e^{r^{\text{us}}_t \tau}}{\mathbb{E}^{\mathbb{Q}}_t(\max(e^k - e^z,0))}}_{>0} \left(\underbrace{-\frac{1}{2}\frac{F^{\text{j|us}}_{t,\tau}}{S^{\text{j|us}}_t}\overbrace{\{\mathbb{E}^{\mathbb{P}}_t(\frac{S^{\text{j|us}}_{t+\tau}}{F^{\text{j|us}}_{t,\tau}})-1\}}^{\text{currency risk premium}}}_{<0 \text{ for a risky currency}} - \frac{1}{\pi}\int_0^\infty \underbrace{\mathfrak{Re}[\frac{e^{-i\phi k}\,\mathbf{rp}_t[\phi;k]}{i\phi}]}_{\substack{\text{impact of moneyness-dependent}\\ \text{risk premium}}} d\phi \right). \tag{17}$$

It can hold that $\frac{1}{\pi}\int_0^\infty \mathfrak{Re}[\frac{e^{-i\phi k}\mathbf{rp}_t[\phi;k]}{i\phi}]d\phi > 0$*, in which case, it would hold that*

$$\text{if } \mathbb{E}^{\mathbb{P}}_t(\frac{S^{\text{j|us}}_{t+\tau}}{F^{\text{j|us}}_{t,\tau}}) - 1 > 0, \quad \text{then the put risk premium is negative.}$$

$$\text{If } \underbrace{\mathbb{E}^{\mathbb{P}}_t(\frac{S^{\text{j|us}}_{t+\tau}}{F^{\text{j|us}}_{t,\tau}}) - 1}_{\text{currency risk premium}} < 0, \quad \text{then the put risk premium } \textit{can} \text{ be } \textit{positive}. \blacksquare$$

Result 1 unravels that a part of the put option risk premium — connected to the conditional currency risk premium — enters with a negative weight of $-\frac{1}{2}\frac{F^{\text{j|us}}_{t,\tau}}{S^{\text{j|us}}_t}$. This contribution is detached from the option moneyness. On the other hand, the contribution of $\int_0^\infty \mathfrak{Re}[\frac{e^{-i\phi k}\mathbf{rp}_t[\phi;k]}{i\phi}]d\phi$ in (17) is moneyness-dependent. Critically, this part encapsulates the risk premiums related to $e^{i\phi z}\{e^k - e^z\}$ for $k<0$.

What is the conceptual role of the U.S. dollar in Result 1? Were the currency risk premium to be positive, investors pay a premium — depending on the economic state — for downside protection on the reference currency (against the U.S. dollar). The intuition is that the stochastic discount factor is high when the U.S. dollar is appreciating, in which case, we impute $\int_0^\infty \mathfrak{Re}[\frac{e^{-i\phi k}\mathbf{rp}_t[\phi;k]}{i\phi}]d\phi$ to be positive for $k<0$. Our model parameterizations suggest this outcome.

Were the currency risk premium to be positive, the sufficient condition for put option risk premiums to be more negative at lower $k<0$ is that $\int_0^\infty \mathfrak{Re}[\frac{e^{-i\phi k}\mathbf{rp}_t[\phi;k]}{i\phi}]\,d\phi$ be higher. Our rationale aligns with aversion to large currency devaluations (or more severe appreciations of the U.S. dollar), which elicits more negative jump risk premiums. This theory conforms with the patterns depicted in table 2. Key to these effects is that the U.S. dollar appreciation corresponds to bad economic states, and the United States is central to the global financial system. By modeling macroeconomic disparities with respect to the United States, we can reconcile the divergence in put option risk premiums associated with the single-name currencies.

Result 2 (Call risk premium ($k>0$)) *The call risk premium* ($\mu^{\text{call}}_{\{t\to t+\tau\}}[k] \equiv \frac{\mathbb{E}_t^{\mathbb{P}}(\max(e^z-e^k,0))}{e^{-r_t^{\text{us}}\tau}\mathbb{E}_t^{\mathbb{Q}}(\max(e^z-e^k,0))} - e^{r_t^{\text{us}}\tau}$) *is*

$$\mu^{\text{call}}_{\{t\to t+\tau\}}[k] \;=\; \frac{e^{r_t^{\text{us}}\tau}}{\mathbb{E}_t^{\mathbb{Q}}(\max(e^z-e^k,0))}\left(\frac{1}{2}\frac{F^{\text{j|us}}_{t,\tau}}{S^{\text{j|us}}_t}\{\mathbb{E}_t^{\mathbb{P}}(\frac{S^{\text{j|us}}_{t+\tau}}{F^{\text{j|us}}_{t,\tau}})-1\} \;+\; \frac{1}{\pi}\int_0^\infty \mathfrak{Re}[\frac{e^{-i\phi k}\{-\mathbf{rp}_t[\phi;k]\}}{i\phi}]\,d\phi\right). \tag{18}$$

The term $\frac{1}{\pi}\int_0^\infty \mathfrak{Re}[\frac{e^{-i\phi k}\{-\mathbf{rp}_t[\phi;k]\}}{i\phi}]\,d\phi$ *can take either sign for* $k>0$. *In which case, it would hold that*

$$\text{if } \mathbb{E}_t^{\mathbb{P}}(\frac{S^{\text{j|us}}_{t+\tau}}{F^{\text{j|us}}_{t,\tau}})-1>0, \quad \text{then} \quad \begin{cases} \text{the call risk premium can be positive or negative for low } k>0 \text{ and} \\ \text{the call risk premium can be } \textit{less} \text{ positive or } \textit{more} \text{ negative for high } k>0. \end{cases}$$

$$\text{If } \mathbb{E}_t^{\mathbb{P}}(\frac{S^{\text{j|us}}_{t+\tau}}{F^{\text{j|us}}_{t,\tau}})-1<0, \quad \text{then} \quad \begin{cases} \text{the call risk premium can be negative for low } k>0 \text{ and} \\ \text{the call risk premium can be } \textit{more} \text{ negative for high } k>0. \quad \blacksquare \end{cases}$$

Result 2 is incisive in its empirical implications. Dissecting theoretical effects from the standpoint of the Japanese yen, we recognize that $\frac{1}{2}\frac{F^{\text{j|us}}_{t,\tau}}{S^{\text{j|us}}_t} > \frac{1}{2}$ (yen is a funding currency) and $\mathbb{E}_t^{\mathbb{P}}(\frac{S^{\text{j|us}}_{t+\tau}}{F^{\text{j|us}}_{t,\tau}})-1<0$. Thus, the mechanism of $\int_0^\infty \mathfrak{Re}[\frac{e^{-i\phi k}\{-\mathbf{rp}_t[\phi;k]\}}{i\phi}]\,d\phi<0$, for $k>0$, is sufficient to produce negative call option risk premiums via the workings of (18). In economic terms, an aversion to positive jumps in the yen is implied in table 3 pertaining to both 25 delta and 10 delta calls.

Our treatment invites explanations for the diversity of patterns in call risk premiums among the risky currencies. If the size of the negative jump risk premiums for currency appreciations were to counteract the positive currency risk premiums, the 10 delta call risk premiums would be negative. Otherwise, the call risk premiums would be positive. The absence of *negative* risk premiums for 25 delta calls coinciding with *positive* risk premiums for 10 delta calls (for a single-name currency) is evidence that favors our theory.

Result 3 (Straddle risk premium (volatility risk premium)) *The straddle risk premium is*

$$\mu^{\text{straddle}}_{\{t\to t+\tau\}}[k] \;=\; \frac{1}{\frac{e^{r_t^{-\text{us}}\tau}}{2\pi}\mathbb{E}_t^{\mathbb{Q}}(\max(1-e^z,0)+\max(e^z-1,0))}\int_0^\infty \mathfrak{Re}[\frac{\mathbb{E}_t^{\mathbb{P}}(e^{i\phi z}\{e^z-1\}) \;-\; \mathbb{E}_t^{\mathbb{Q}}(e^{i\phi z}\{e^z-1\})}{i\phi}]\,d\phi. \quad (19)$$

Although (19) is not amenable to a ready interpretation about the size of the straddle risk premiums, we explore the magnitude of this risk premium using model parameterizations. One may attribute the relatively small straddle risk premiums to the ambivalence about directional currency movements allied to the U.S. dollar currency pairs.

The expressions for option risk premiums in Result 1, 2, and 3 have not yet been assimilated in international finance research. The notion of whether the currency risk premium is positive or negative is fundamental to our theory of currency option risk premiums. Additionally, the moneyness-dependent term $\int_0^\infty \mathfrak{Re}[\frac{e^{-i\phi k}\mathbf{rp}_t[\phi;k]}{i\phi}]\,d\phi$ is relevant to disentangling the nature of option risk premiums across strikes.

4.4. Quantitative implications of Results 1, 2, and 3 and interpretation

How does the model fare in mimicking the observed currency option risk premiums? Working toward this goal, we develop the characteristic functions $\mathbf{C}_t^{\mathbb{P}}[\phi] = \mathbb{E}_t^{\mathbb{P}}(e^{i\phi z})$ and $\mathbf{C}_t^{\mathbb{Q}}[\phi] = \mathbb{E}_t^{\mathbb{Q}}(e^{i\phi z})$ for the currency dynamics in (14). These expressions are displayed in equations (A4) and (A15) of the Appendix.

We focus on G10 currencies for compactness, and Table 11 presents model-based currency option risk premiums. To facilitate comparisons, reported alongside are the actual sample averages.

4.4.1. Modeling macroeconomic disparities and the role of the United States

Elaborating on interpretations, we recognize that the risk premiums — $\mathbf{rp}_t[\phi;k]$ for each k — are a function of component volatility ($\mathbf{v}_t$), probability of tail movement ($\mathbf{b}_t$), and the properties of the jump sizes in the pricing kernels of both economies. Because $\mathbf{v}_t$ and $\mathbf{b}_t$ are latent and the pricing kernels are unobservable, we implement the following steps to construct table 11:

- First, the baseline parameters governing $\mathbf{v}_t$, $\mathbf{b}_t$, and jumps (that is, μ_x and σ_x) are common to all economies. Thus, the base economy pricing kernel properties are the same across economy pairs.

- Second, the parameters of $\mathbf{b}_t$ dynamics are aligned with the price of a crash security (digital) on the S&P 500 equity index (in line with Gabaix (2012) and Wachter (2013)). Our average estimate is 0.057, and we keep $\theta_{\mathbf{b}}^{\mathbb{P}}/\kappa_{\mathbf{b}}^{\mathbb{P}} = 0.057$.

- Third, there is no guidance regarding the parameters of $\mathbf{v}_t$ in the presence of $\mathbf{b}_t$. Our essential criterion is whether the considered parameters provide plausible currency return volatilities. For example, we consider $\sqrt{\theta_{\mathbf{v}}^{\mathbb{P}}/\kappa_{\mathbf{v}}^{\mathbb{P}}} = \sqrt{0.20/1.25} = 40\%$ in the currency dynamics (14).

Our approach is to exploit the device of disparities in a pricing kernel's exposure to global shocks, namely, $\mathbf{v}_t$, $\mathbf{b}_t$, and $\sum_{\ell=\mathbb{N}_t}^{\mathbb{N}_{t+\tau}} x_\ell$. In this regard, we set $\beta_{\mathrm{us}} = 1$, $\eta_{\mathrm{us}} = 1$, and $\alpha_{\mathrm{us}} = 1$ to center the exposures of the United States. More explicitly,

$$\beta_{\mathrm{j}} - \beta_{\mathrm{us}} \neq 0, \;\; \eta_{\mathrm{j}} - \eta_{\mathrm{us}} \neq 0, \;\; \text{and} \;\; \alpha_{\mathrm{j}} - \alpha_{\mathrm{us}} \neq 0, \;\; \text{which generates dispersion in macroeconomic disparities.}$$

The big picture is that our quantifications affect the size of $\int_0^\infty \mathfrak{Re}[\frac{e^{-i\phi k}\mathbf{rp}_t[\phi;k]}{i\phi}]\,d\phi$ for $k<0$, $\int_0^\infty \mathfrak{Re}[\frac{e^{-i\phi k}\{-\mathbf{rp}_t[\phi;k]\}}{i\phi}]\,d\phi$ for $k>0$, and the currency risk premiums. The sources of divergence in currency option risk premiums pave the way for a unified economic analysis across single-name currencies.

Employing the baseline parameters, we numerically search for $(\beta_{\mathrm{j}}, \eta_{\mathrm{j}}, \alpha_{\mathrm{j}})$ to achieve consistency with the following economy-pair features: (i) the currency volatility (table 1), (ii) the currency risk premium (table 9), and (iii) the interest-rate differential (table 1).[10]

We display the baseline parameters in table 11 (panel A). The generated put, call, and straddle risk premiums are a consequence of the forms of the characteristic functions $\mathbf{C}_t^{\mathbb{P}}[\phi]$ and $\mathbf{C}_t^{\mathbb{Q}}[\phi]$.

4.4.2. Assessing the relevance of the model mechanism

Our approach implies that the model can produce heterogeneity in the currency option risk premiums if two restrictions are satisfied. First, economies need to exhibit differential sensitivity to uncertainties with respect to the United States. This condition amounts to global shocks not canceling when determining ex-

[10]Letting the data decide on the heterogeneity to global risks is compatible with, among others, Lustig, Roussanov, and Verdelhan (2011); Farhi and Gabaix (2016); Ready, Roussanov, and Ward (2017); and Colacito, Croce, Gavazzoni, and Ready (2018).

change rate growth. Second, the model needs to exhibit non-normalities in the currency return distributions. This restriction enables plausible properties of $\int_0^\infty \mathfrak{Re}[\frac{e^{-i\phi k}\mathbf{rp}_t[\phi;k]}{i\phi}]\, d\phi$ for $k < 0$ and $\int_0^\infty \mathfrak{Re}[\frac{e^{-i\phi k}\{-\mathbf{rp}_t[\phi;k]\}}{i\phi}]\, d\phi$ for $k > 0$. In the absence of variations in $\mathbf{v}_t$ and $\mathbf{b}_t$, the option risk premiums are constant.

There are several noteworthy observations from table 11. First, if the currency risk premium is negative (Japan), then the put risk premiums can be positive while the call risk premiums can be negative. By contrast, if the currency premium is positive (New Zealand), then the put risk premiums can be negative while the call risk premiums can be positive. Second, the straddle risk premiums are comparatively smaller. Third, the model is capable of reproducing the patterns of currency option risk premiums with respect to moneyness. Table 11 (panel C), which depicts the average pattern across the G10, reinforces the evidence. We report *absolute errors* in Table 11 (Panel B) to summarize the quantitative model fit.

Overall, the parameterizations produce option risk premiums that are within the bootstrap confidence intervals of the sample counterparts. For example, the model-based call risk premiums are positive, and less so for higher strikes for New Zealand. By contrast, the risk premiums of 10 delta puts and 10 delta calls are both negative for the euro area, whereas the model-based 25 delta call premium is slightly positive (as manifested in the data). In this regard, we note that jump modeling is aimed at coping with distributional non-normalities and helps replicate the patterns by moneyness across single-name puts and calls.

Delineating the correspondence between theory and data on single-name currency calls, six economies (Australia, New Zealand, Norway, Switzerland, Czech Republic, and Hungary) exhibit a pattern in which both OTM call risk premiums are positive. In contrast, four economies (Euro zone, Denmark, Korea, and Poland) show alternative signs: positive risk premiums for 25 delta calls and negative risk premiums for 10 delta calls. Distinct to Canada and South Africa, the 25 delta and 10 delta call risk premiums are noticeably negative. Completing the circle, economy pairs with negative currency risk premiums (Japan, Sweden, and the United Kingdom) display negative call risk premiums for deeper OTM (10 delta) strikes. Our theory appears to conform with options data for G10 economy pairs.

Substantial variation in α_j is detected. This economic mechanism supports differential impacts of pricing kernel jumps on exchange rates (e.g., Anderson, Bollerslev, Diebold, and Vega (2003)). Tracing this insight, $\mathbb{E}_t^{\mathbb{P}}([\alpha_{\mathrm{j}}-\alpha_{\mathrm{us}}]\sum_{\ell=\mathbb{N}_t}^{\mathbb{N}_{t+\tau}} x_\ell) = (\alpha_{\mathrm{j}}-\alpha_{\mathrm{us}})\,\mu_x\,\mathbb{E}_t^{\mathbb{P}}(\int_t^{t+\tau}\mathbf{b}_u du)$, with $\mathbb{E}_t^{\mathbb{P}}(\int_t^{t+\tau}\mathbf{b}_u du) = \frac{\tau\theta_{\mathbf{b}}^{\mathbb{P}}}{\kappa_{\mathbf{b}}^{\mathbb{P}}} + \frac{(1-e^{-\kappa_{\mathbf{b}}^{\mathbb{P}}\tau})}{\kappa_{\mathbf{b}}^{\mathbb{P}}}(\mathbf{b}_t - \frac{\theta_{\mathbf{b}}^{\mathbb{P}}}{\kappa_{\mathbf{b}}^{\mathbb{P}}})$. The interpretation is that (absolute) deviations of α_{j} away from 1.0 can amplify jump risk premiums. Disparities in jump sizes — that vary across the pricing kernels — provide flexibility in calibrating the behavior of option risk premiums in the tails. See Aït-Sahalia and Xiu (2016) for additional formalizations.

Describing empirical realities, our framework incorporates both small and large currency movements, as well as time-varying probability of tail movements and a bivariate depiction of stochastic currency volatility (i.e., $\mathbf{v}_t$ and $\mathbf{b}_t$). We contribute by showing that the considered model can be consistent with the multidimensional aspects of currency markets and risk premiums inferred from single-name currency options, and, crucially, it allows for the semi-analyticity of currency option risk premiums.[11]

Our setup manifests the prominence of the U.S. dollar. Specifically, the combination of sensitivities to global risks yields predominantly positive currency risk premiums, the risk premiums for puts are negative while the risk premiums for calls need not inherit the same sign, and the straddle risk premiums are quantitatively small. Notably, our parameterizations imply negative jump risk premiums for foreign currency devaluations, which suggests aversion to the appreciation of the U.S. dollar.

5. Conclusion

In this paper, we investigate how the supremacy of the U.S. dollar affects the pricing of risks — whether the downside or the upside — in the currency options market. Our empirical work is backed by a tractable model of currency dynamics with global risks as the drivers.

We consider daily quotes of currency options that expire in a fixed time span of 30 days, and the reliability of our conclusions is gauged by way of option returns constructed over 73,473 option expiration cycles. The options data consist of 15 single-name currencies that elicit high trading interests and constitute

[11] While our focus has been on the performance of a model for currency option risk premiums, this model can be extended to allow for additive jumps in $\mathbf{v}_t$ or $\mathbf{b}_t$, or to consider alternative characterizations of jumps in the pricing kernels. Our evaluation shows that a model that relies on economies having different exposures to global risks — and supports non-normalities in currency returns — has value in producing features of currency option risk premiums.

the vast majority of international trading arrangements. Our design of employing the U.S. dollar as the base currency facilitates unifications connected to the supremacy of the U.S. dollar.

Our empirical exercises substantiate the following findings. The risk premiums on single-name currency put options are predominantly negative, in essence, implying that markets are keen to insure the devaluations of the foreign currency. We find that 10 delta (deeper out-of-the-money) put risk premiums are typically more negative than their 25 delta counterparts.

Our analyses identify considerable heterogeneity in the sign of the call option risk premiums. Crucially, these call risk premiums are, on average, statistically smaller than those of puts. Our evidence suggests that insurance concerns against U.S. dollar depreciations vary along the dimension of trade imbalances (more negative for economies with higher dollar revenue exposures), currency volatility, and interest-rate differentials (reflecting their membership to the set of funding or investment currencies).

The average excess returns of straddles are small in magnitude. Moreover, the average excess returns of a portfolio of currency straddles — the global currency volatility risk premium — is statistically insignificant. Thus, our evidence indicates that currency volatility concerns do not appear to be sizable.

We use interest-rate differentials as a characteristic to dynamically sort currencies. The option positions are held over the next 30 days. Our approach shows that put risk premiums are reliably more negative for a portfolio of investment currencies in comparison to funding currencies. Additionally, call risk premiums are reliably more negative for a portfolio of funding currencies in relation to investment currencies. We find no distinction between the volatility risk premiums of investment and funding currencies.

The currency option risk premiums are state-dependent and vary with VIX volatility states. There are material shifts in these risk premiums around periods of high uncertainty, with higher option risk premiums for investment currencies than for funding currencies.

Our panel regressions show that economic disparity variables such as (i) yield differentials on five-year government bonds, (ii) quadratic variations in currency returns, and (iii) prior currency returns can help to forecast subsequent currency option returns.

We feature model compatibility exercises to show that currency option risk premiums are linked to both the sign and magnitude of the currency risk premiums, as well as to moneyness-dependent risk premiums.

In what way could our empirical findings help to sharpen models of international finance? First, they impose hurdles on models that can be consistent with the data on currency option returns. Second, they point to the relevance of heterogeneity in risk exposures related to volatility, probability of tail movements, and jumps for currency option risk premiums.

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Table 1
Daily data on currency option quotes with option expiration maintained at 30 days

The exchange rates are expressed in U.S. dollars per unit of foreign currency; that is, the U.S. dollar is the base currency and the foreign currency is the reference. The quoted convention implies that an increase (decrease) in the exchange rate is consistent with the appreciation (depreciation) of the foreign currency. The option and forward quotes are available each day for expiration in the next 30 days. The matched daily data on the spot exchange rate, forward rate, and currency options come from a major bank. We also report the average quoted at-the-money (ATM) option volatility (%, annualized), the average risk reversal of 10 delta currency options (%, annualized), and the average risk reversal of 25 delta currency options (%, annualized). These risk reversals are defined as follows:

- *10 delta risk reversal*: quoted volatility of a 10 delta put minus 10 delta call.
- *25 delta risk reversal*: quoted volatility of a 25 delta put minus 25 delta call.

"Volat." is the realized monthly volatility (annualized), and $r^{\mathrm{j}} - r_t^{\mathrm{us}}$ is the interest-rate differential on 30 day deposits (annualized). Our sample contains the G10 currency pairs (the 10 largest and most liquid currencies) plus 6 additional non-G10 currency pairs.

	Base	Foreign economy j	Currency Symbol	Start date	End date	No. of options cycles	$r^{\mathrm{j}} - r_t^{\mathrm{us}}$ (%)	ATM volatility (%)	Risk reversals 10 delta (%)	Risk reversals 25 delta (%)	Volat. (%)
		Panel A: G10 economy pairs									
1	USD	Australia	AUD	1/3/2000	10/31/2019	4953	2.2	11.2	1.9	1.1	11.5
2	USD	Canada	CAD	1/3/2000	10/31/2019	4951	0.2	8.5	0.7	0.4	8.9
3	USD	Euro area	EUR	8/29/2000	10/31/2019	4790	-0.5	9.6	0.6	0.3	9.1
4	USD	Japan	JPY	1/3/2000	10/31/2019	4955	-2.1	10.0	-1.8	-1.0	9.7
5	USD	New Zealand	NZD	1/3/2000	10/31/2019	4954	2.6	12.2	2.0	1.1	12.4
6	USD	Norway	NOK	1/3/2000	10/31/2019	4946	0.9	11.4	1.1	0.6	11.6
7	USD	Sweden	SEK	1/3/2000	10/31/2019	4953	-0.3	11.3	1.0	0.6	11.2
8	USD	Switzerland	CHF	1/3/2000	10/31/2019	4953	-1.6	9.9	-0.0	-0.0	9.9
9	USD	United Kingdom	GBP	1/3/2000	10/31/2019	4953	0.5	9.0	0.9	0.5	9.1
		Panel B: Non-G10 economy pairs									
10	USD	Czech Republic	CZK	1/3/2000	10/31/2019	4950	-0.4	11.3	1.5	0.8	11.1
11	USD	Denmark	DKK	1/3/2000	10/31/2019	4956	-0.5	9.7	0.8	0.5	9.1
12	USD	Hungary	HUF	6/9/2000	10/31/2019	4818	3.6	12.9	3.3	1.8	13.2
13	USD	Korea	KRW	1/2/2002	10/31/2019	4459	0.8	9.7	2.6	1.4	8.7
14	USD	Poland	PLN	1/3/2000	10/31/2019	4936	3.2	12.8	2.4	1.3	12.5
15	USD	South Africa	ZAR	1/4/2000	10/31/2019	4946	6.4	16.5	5.1	2.8	16.6
		Panel C: Summary across economy pairs									
		All 15 currencies				73473	1.0	11.1	1.5	0.8	11.0
		G10 currencies				44408	0.3	10.4	0.7	0.4	10.4
		Non-G10 currencies				29065	2.0	12.2	2.6	1.4	11.9

Table 2

Risk premiums of currency put options

The base currency is the U.S. dollar, and the foreign currency is the reference. *Each day*, we compute the excess returns of 10 delta put over the next 30 days (the holding period of the option is denoted by τ), as follows:

$$\mathbf{z}^{\text{put}}_{\{t\to t+\tau\}}[K_{10\Delta_p}] \equiv \frac{\max(K_{10\Delta_p} - S^{\text{j|us}}_{t+\tau}, 0)}{\text{put}_t[K_{10\Delta_p}]} - \exp(r^{\text{us}}_t \tau), \quad \text{and analogously for 25 delta put,}$$

where $K_{10\Delta_p}$ is the strike price of a 10 delta put, $S^{\text{j|us}}_{t+\tau}$ is the price of the foreign currency, $\text{put}_t[K_{10\Delta_p}]$ is the put option price, and r^{us}_t is the 30-day U.S. Treasury bill rate (annualized). The table reports the sample mean, standard deviation (SD), and the 95% bootstrap confidence intervals. We use block bootstrap with 1,000 simulations. $\mathbb{1}_{\{\mathbf{z}>0\}}$ represents the proportion of excess returns that are positive. The sample period is 1/3/2000 to 10/31/2019, although data for the euro area and Hungary start in August and June 2000, respectively (see table 1). We also report the excess returns of currency portfolios, which are computed by equally weighting excess returns of 10-delta (and 25-delta) puts over each t to $t+\tau$, considering all 15 currencies, G10 currencies, and non-G10 currencies. The entries in bold indicate statistical significance of the mean excess returns according to the bootstrap confidence intervals. The reported put moneyness (in %) is calculated as, for example for 10 delta puts, $\log(\frac{K_{10\Delta_p}}{S^{\text{j|us}}_t}) < 0$.

	Foreign economy (base is U.S.)	Panel A: 10 delta puts (farther OTM) 30 days Mean	SD	Bootstrap Lower	Upper	Max.	$\mathbb{1}_{\{\mathbf{z}>0\}}$ (%)	$\log(\frac{K_{10\Delta_p}}{S^{\text{j\|us}}_t})$ (%)	Panel B: 25 delta puts (nearer OTM) 30 days Mean	SD	Bootstrap Lower	Upper	Max.	$\mathbb{1}_{\{\mathbf{z}>0\}}$ (%)	$\log(\frac{K_{25\Delta_p}}{S^{\text{j\|us}}_t})$ (%)
1	Australia	-0.074	4.8	-0.18	0.04	64	7	-4.7	-0.064	2.7	-0.12	0.00	26	18	-2.3
2	Canada	**-0.431**	3.8	-0.52	-0.34	85	6	-3.5	**-0.219**	2.2	-0.27	-0.16	31	18	-1.7
3	Euro area	**-0.305**	3.5	-0.38	-0.22	48	6	-3.9	**-0.184**	2.2	-0.24	-0.13	19	17	-1.9
4	Japan	0.043	4.6	-0.06	0.15	58	10	-3.7	**0.102**	2.6	0.04	0.16	22	22	-1.9
5	New Zealand	**-0.252**	3.8	-0.35	-0.16	66	7	-5.1	**-0.142**	2.3	-0.20	-0.09	26	17	-2.5
6	Norway	**-0.273**	3.6	-0.36	-0.19	62	7	-4.6	**-0.118**	2.2	-0.17	-0.07	24	19	-2.3
7	Sweden	**-0.267**	3.2	-0.34	-0.19	61	9	-4.6	-0.041	2.2	-0.09	0.01	24	21	-2.2
8	Switzerland	**-0.359**	3.0	-0.43	-0.29	34	7	-3.9	**-0.152**	2.1	-0.20	-0.11	15	20	-1.9
9	United Kingdom	-0.043	4.5	-0.15	0.06	58	7	-3.7	-0.022	2.6	-0.08	0.04	23	18	-1.8
10	Czech Republic	**-0.245**	3.9	-0.33	-0.15	51	6	-4.8	**-0.127**	2.4	-0.18	-0.07	20	18	-2.3
11	Denmark	**-0.321**	3.4	-0.40	-0.24	49	6	-4.0	**-0.164**	2.2	-0.21	-0.11	19	18	-1.9
12	Hungary	**-0.275**	3.9	-0.37	-0.19	63	6	-5.9	**-0.141**	2.5	-0.20	-0.08	26	17	-2.7
13	Korea	**-0.365**	3.4	-0.44	-0.28	50	5	-4.4	**-0.219**	2.4	-0.28	-0.16	25	15	-2.0
14	Poland	**-0.288**	3.9	-0.38	-0.21	59	6	-5.6	**-0.192**	2.4	-0.25	-0.14	23	16	-2.6
15	South Africa	**-0.315**	4.0	-0.41	-0.22	74	6	-7.6	**-0.132**	2.4	-0.19	-0.08	30	18	-3.5
	Summary (equal-weighted) across economy pairs														
	All 15 currencies	**-0.248**	2.6	-0.31	-0.19	58	16	-4.6	**-0.137**	1.6	-0.18	-0.10	23	25	-2.2
	G10 currencies	**-0.234**	2.5	-0.29	-0.17	58	17	-4.2	**-0.118**	1.6	-0.16	-0.08	23	26	-2.0
	Non-G10 currencies	**-0.309**	2.8	-0.37	-0.24	74	13	-5.4	**-0.176**	1.8	-0.22	-0.13	30	23	-2.5

Table 3
Risk premiums of currency call options

The base currency is the U.S. dollar, and the foreign currency is the reference. *Each day*, we compute the excess returns of 10 delta call over the next 30 days (the holding period of the option is denoted by τ), as follows:

$$\mathbf{z}^{\text{call}}_{\{t\to t+\tau\}}[K_{10\Delta_c}] \;=\; \frac{\max(S^{\text{j|us}}_{t+\tau} - K_{10\Delta_c}, 0)}{\text{call}_t[K_{10\Delta_c}]} \;-\; \exp(r^{\text{us}}_t \tau), \quad \text{and analogously for 25 delta call,}$$

where $K_{10\Delta_c}$ is the strike price of a 10 delta call, $S^{\text{j|us}}_{t+\tau}$ is the price of the foreign currency, $\text{call}_t[K_{10\Delta_c}]$ is the call option price, and r^{us}_t is the 30-day U.S. Treasury bill rate (annualized). The table reports the sample mean, standard deviation (SD), and the 95% bootstrap confidence intervals. We use block bootstrap with 1,000 simulations. $\mathbb{1}_{\{\mathbf{z}>0\}}$ represents the proportion of excess returns that are positive. The sample period is 1/3/2000 to 10/31/2019, although data for the euro area and Hungary start in August and June 2000, respectively (see table 1). We also report the excess returns of currency portfolios, which are computed by equally weighting excess returns of 10-delta (and 25-delta) calls over each t to $t+\tau$, considering all 15 currencies, G10 currencies, and non-G10 currencies. The entries in bold indicate statistical significance of the mean excess returns according to the bootstrap confidence intervals. The reported call moneyness (in %) is calculated as, for example for 10 delta calls, $\log(\frac{K_{10\Delta_c}}{S^{\text{j|us}}_t}) > 0$.

		Panel A: 25 delta calls (nearer OTM)							**Panel B: 10 delta calls** (farther OTM)						
	Foreign economy (base is U.S.)	30 days Mean	30 days SD	Bootstrap Lower	Bootstrap Upper	Max.	$\mathbb{1}_{\{\mathbf{z}>0\}}$ (%)	$\log(\frac{K_{25\Delta_c}}{S^{\text{j\|us}}_t})$ (%)	30 days Mean	30 days SD	Bootstrap Lower	Bootstrap Upper	Max.	$\mathbb{1}_{\{\mathbf{z}>0\}}$ (%)	$\log(\frac{K_{10\Delta_c}}{S^{\text{j\|us}}_t})$ (%)
1	Australia	**0.166**	2.6	0.11	0.23	14	24	2.2	0.077	4.1	-0.02	0.18	34	10	4.2
2	Canada	**-0.121**	2.3	-0.18	-0.07	18	19	1.7	**-0.278**	3.4	-0.36	-0.19	43	7	3.3
3	Euro area	0.008	2.4	-0.05	0.07	15	20	1.9	**-0.198**	3.5	-0.28	-0.11	34	8	3.8
4	Japan	**-0.278**	2.1	-0.33	-0.23	17	15	2.1	**-0.573**	2.5	-0.63	-0.51	34	4	4.5
5	New Zealand	0.181	2.5	0.12	0.25	17	24	2.4	0.005	3.8	-0.08	0.10	39	10	4.6
6	Norway	**0.085**	2.8	0.02	0.15	18	20	2.3	**0.184**	4.8	0.07	0.31	42	8	4.4
7	Sweden	-0.029	2.5	-0.09	0.03	17	19	2.3	**-0.120**	3.8	-0.20	-0.03	40	8	4.3
8	Switzerland	**0.116**	2.9	0.05	0.18	28	20	2.0	**0.142**	5.1	0.02	0.27	76	9	4.0
9	United Kingdom	-0.059	2.4	-0.11	0.00	21	20	1.8	**-0.225**	3.8	-0.31	-0.13	51	7	3.5
10	Czech Republic	**0.278**	2.9	0.21	0.35	22	23	2.3	**0.367**	5.1	0.24	0.50	61	11	4.3
11	Denmark	0.011	2.5	-0.04	0.07	16	20	1.9	**-0.130**	3.7	-0.22	-0.04	36	8	3.8
12	Hungary	**0.196**	2.8	0.13	0.26	18	22	2.5	**0.165**	4.4	0.06	0.27	42	10	4.8
13	Korea	0.039	2.9	-0.03	0.12	39	21	1.9	-0.060	5.4	-0.20	0.07	96	7	3.6
14	Poland	**0.170**	2.6	0.11	0.23	20	23	2.5	-0.017	4.1	-0.12	0.08	51	9	4.9
15	South Africa	**-0.139**	2.1	-0.19	-0.09	18	20	3.2	**-0.424**	2.9	-0.49	-0.36	44	7	6.0
	Summary (equal-weighted) across economy pairs														
	All 15 currencies	**0.079**	1.8	0.03	0.12	21	29	2.2	-0.034	2.5	-0.10	0.03	51	20	4.2
	G10 currencies	0.034	1.8	-0.01	0.08	21	29	2.1	**-0.081**	2.5	-0.14	-0.02	51	19	4.0
	Non-G10 currencies	**0.107**	2.0	0.06	0.16	18	29	2.4	-0.021	2.8	-0.09	0.05	44	18	4.6

Table 4
Risk premiums of currency straddles

The base currency is the U.S. dollar, and the foreign currency is the reference. *Each day*, we compute the excess returns of currency straddle over the next 30 days, as follows:

$$\mathbf{z}^{\text{straddle}}_{\{t\to t+\tau\}} = \frac{\max(S^{\mathrm{j|us}}_t - S^{\mathrm{j|us}}_{t+\tau}, 0) \ + \ \max(S^{\mathrm{j|us}}_{t+\tau} - S^{\mathrm{j|us}}_t, 0)}{\mathrm{put}_t[S^{\mathrm{j|us}}_t] \ + \ \mathrm{call}_t[S^{\mathrm{j|us}}_t]} \ - \ \exp(r^{\mathrm{us}}_t \tau),$$

where $S^{\mathrm{j|us}}_{t+\tau}$ is the price of the foreign currency, $\mathrm{put}_t[S^{\mathrm{j|us}}_t]$ is the price of the ATM put option, $\mathrm{call}_t[S^{\mathrm{j|us}}_t]$ is the price of the ATM call option, and r^{us}_t is the 30-day U.S. Treasury bill rate (annualized). The table reports the sample mean, standard deviation (SD), and the 95% bootstrap confidence intervals. We use block bootstrap with 1,000 simulations. $\mathbb{1}_{\{\mathbf{z}>0\}}$ represents the proportion of excess returns that are positive. The sample period is 1/3/2000 to 10/31/2019, although data for the euro area and Hungary start in August and June 2000, respectively (see table 1). We also report the excess returns of currency portfolios, which are computed by equally weighting excess returns of straddles over each t to $t+\tau$, considering all 15 currencies, G10 currencies, and non-G10 currencies. The entries in bold indicate statistical significance of the mean excess returns according to the bootstrap confidence intervals.

	Foreign economy (base is U.S.)	30 days Mean	30 days SD	Bootstrap Lower	Bootstrap Upper	Max.	$\mathbb{1}_{\{\mathbf{z}>0\}}$ (%)
1	Australia	**0.034**	0.83	0.011	0.056	5	43
2	Canada	**-0.054**	0.75	-0.075	-0.034	6	39
3	Euro area	-0.022	0.77	-0.044	0.000	4	40
4	Japan	**-0.029**	0.79	-0.050	-0.008	4	39
5	New Zealand	0.018	0.78	-0.003	0.040	5	43
6	Norway	-0.009	0.81	-0.031	0.013	5	40
7	Sweden	-0.005	0.76	-0.026	0.016	5	42
8	Switzerland	0.007	0.81	-0.015	0.030	5	41
9	United Kingdom	-0.003	0.82	-0.026	0.020	5	41
10	Czech Republic	**0.054**	0.85	0.030	0.077	4	43
11	Denmark	**-0.025**	0.77	-0.046	-0.004	4	40
12	Hungary	0.002	0.84	-0.022	0.026	6	40
13	Korea	**-0.039**	0.86	-0.065	-0.014	7	38
14	Poland	-0.002	0.82	-0.025	0.022	5	41
15	South Africa	**-0.023**	0.79	-0.045	-0.002	7	41
	Summary (equal-weighted) across economy pairs						
All 15 currencies		-0.001	0.52	-0.017	0.015	4	38
G10 currencies		-0.007	0.51	-0.022	0.007	4	39
Non-G10 currencies		-0.005	0.59	-0.023	0.013	4	39

Table 5

Currency option risk premiums when currencies are dynamically sorted on $\log(\frac{F_{t,\tau}^{j|us}}{S_t^{j|us}})$

The base currency is the U.S. dollar. *Each day*, we assign currencies to the following three bins:

- Five economies with the *lowest* $F_{t,\tau}^{j|us}/S_t^{j|us}$ (investment currencies, i.e., those with the highest $r^j - r^{us}$)
- Five economies with medium $F_{t,\tau}^{j|us}/S_t^{j|us}$
- Five economies with the *highest* $F_{t,\tau}^{j|us}/S_t^{j|us}$ (funding currencies, i.e., those with the lowest $r^j - r^{us}$).

Then, we compute the equal-weighted excess return of currency options (panel A) and currency excess returns (panel B). Reported are the sample mean, the standard deviation (SD), and the 95% bootstrap confidence intervals. We use block bootstrap with 1,000 simulations. The sample period is 8/3/2000 to 10/31/2019. $\mathbb{1}_{\{\mathbf{z}>0\}}$ represents the proportion of excess returns that are positive. The entries in bold indicate statistical significance of the mean excess returns according to the bootstrap confidence intervals. We report the returns of the carry strategy as annualized percentages.

			30 days		Bootstrap			
			Mean	SD	Lower	Upper	Max.	$\mathbb{1}_{\{\mathbf{z}>0\}}$ (%)
	Panel A: Currency option risk premiums (sorting currencies on $\frac{F_{t,\tau}^{j\|us}}{S_t^{j\|us}}$ (low to high))							
10 delta puts	*Investment currencies*	High $r^j - r^{us}$	**-0.298**	3.0	-0.373	-0.223	56	13
		Medium $r^j - r^{us}$	**-0.238**	3.0	-0.317	-0.164	55	14
	Funding currencies	Low $r^j - r^{us}$	**-0.208**	2.6	-0.271	-0.142	29	15
		High minus Low	$\boxed{\mathbf{-0.090}}$	2.4	-0.151	-0.028	29	13
10 delta calls	*Investment currencies*	High $r^j - r^{us}$	-0.022	2.5	-0.087	0.040	19	19
		Medium $r^j - r^{us}$	0.032	3.1	-0.046	0.107	28	17
	Funding currencies	Low $r^j - r^{us}$	**-0.111**	2.9	-0.183	-0.042	31	15
		High minus Low	$\boxed{\mathbf{0.090}}$	2.5	0.030	0.153	16	20
Straddles	*Investment currencies*	High $r^j - r^{us}$	-0.006	0.56	-0.019	0.008	6	40
		Medium $r^j - r^{us}$	-0.001	0.59	-0.016	0.014	4	39
	Funding currencies	Low $r^j - r^{us}$	0.003	0.61	-0.010	0.018	3	41
		High minus Low	$\boxed{-0.009}$	0.54	-0.023	0.005	2	50

			Annualized (%)		Bootstrap			
			Mean	SD	Lower	Upper	Max.	$\mathbb{1}_{\{\mathbf{z}>0\}}$ (%)
	Panel B: Currency risk premiums (sorting currencies on $\frac{F_{t,\tau}^{j\|us}}{S_t^{j\|us}}$ (low to high), annualized, percentage)							
Currency	*Investment currencies*	High $r^j - r^{us}$	**4.6**	11.3	3.7	5.6	14	55
		Medium $r^j - r^{us}$	**1.8**	8.8	1.1	2.5	11	53
	Funding currencies	Low $r^j - r^{us}$	**0.8**	8.4	0.0	1.5	8	50
		High minus Low (carry strategy)	$\boxed{\mathbf{3.8}}$	7.4	3.2	4.5	9	61

Table 6

Panel regressions: Macroeconomic disparities and option risk premiums

This table reports panel regressions in which the dependent variable is the excess return of (i) 10 delta puts, (ii) 10 delta calls, (iii) straddles, or (iv) currencies. We construct (economy-pair specific) macroeconomic disparity variables (all known at t) as follows:

- $r_t^{\mathrm{j,5year}} - r_t^{\mathrm{us,5year}}$: Interest-rate differential on a five-year government bond (source: Federal Reserve Board).
- $\mathrm{QV}_t^{\mathrm{fx,j}}$ (return quadratic variation of currency j): Sum of daily squared percentage changes in the spot exchange rates over the previous month.
- $\mathrm{MA30}_t^{\mathrm{fx,j}}$: Currency excess returns over the 30-day trailing window.
- $\mathrm{RR10}_t^{\mathrm{j}}$ (Risk reversal of 10 delta options): Extracted as quoted volatility of a 10 delta put minus the 10 delta call.

The following panel regressions are performed at the end of each month:

$$\underbrace{\mathbf{z}^{j}_{\{t\to t+\tau\}}}_{\substack{\text{next 30 days} \\ \text{(puts, calls, straddles)}}} = \delta_0 + \delta_1\,(r_t^{\mathrm{j,5year}} - r_t^{\mathrm{us,5year}}) + \delta_2\,\mathrm{QV}_t^{\mathrm{fx,j}} + \delta_3\,\mathrm{MA30}_t^{\mathrm{fx,j}} + \delta_4\,\mathrm{RR10}_t^{\mathrm{j}} + e^{\mathrm{j}}_{\{t\to t+\tau\}} \text{ for } j = 1,\ldots,15 \text{ and } t = 1,\ldots,213.$$

Reported t-statistics (in square brackets) are based on robust standard errors that are clustered by currency. The markings ***, **, and * represent statistical significance at the 99%, 95%, and 90% confidence levels, respectively. There are 3,195 currency monthly observations (15 currencies and 213 months (over 02/2002 to 10/2019); some variables on Korea were not available until 02/2002). The constant is included in the panel regressions but not reported. We allow for currency fixed effects and year fixed effects.

	10 delta put risk premiums		10 delta call risk premiums		Straddle risk premiums		Currency risk premiums	
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Currency fixed effects	*No*	Yes	*No*	Yes	*No*	Yes	*No*	Yes
$r^{\mathrm{j,5year}} - r^{\mathrm{us,5year}}$	**0.05*** **	-0.04	-0.00	0.01	0.00	**-0.04** **	**1.18*** **	**2.88** **
	[3.13]	[-0.65]	[-0.13]	[0.12]	[0.94]	[-2.56]	[6.72]	[2.39]
$\mathrm{QV}^{\mathrm{fx,j}} \times 100$	**-5.78** **	**-6.09** **	**-3.72*** **	**-3.83*** **	**-1.38*** **	**-1.55*** **	**-31.31***	-32.91
	[-2.83]	[-2.66]	[-3.34]	[-3.84]	[-3.88]	[-4.13]	[-1.92]	[-1.74]
$\mathrm{MA30}^{\mathrm{fx,j}}$	**-3.10** **	**-3.08** **	-1.25	-1.61	0.28	0.24	**-79.61*** **	**-81.53*** **
	[-2.51]	[-2.54]	[-0.65]	[-0.86]	[0.70]	[0.61]	[-4.34]	[-4.43]
$\mathrm{RR10}^{\mathrm{j}}$	-5.43	-6.02	**5.78***	4.66	0.73	0.23	-11.92	10.56
	[-1.66]	[-1.33]	[1.88]	[1.41]	[0.76]	[0.24]	[-0.27]	[0.17]
R^2 (%)	6	6	5	6	3	3	8	8
Within R^2 (%)	0.51	0.54	0.05	0.03	0.40	0.71	0.66	0.71

Table 7

Option risk premiums and *equity* volatility states: Currencies dynamically sorted on $\log(\frac{F_{t,\tau}^{j|us}}{S_t^{j|us}})$

The base currency is the U.S. dollar. Each day, we assign currencies to the following three bins:

- – Five economies with the *lowest* $F_{t,\tau}^{j|us}/S_t^{j|us}$ (investment currencies, that is, those with the highest $r^j - r^{us}$)
- – Five economies with medium $F_{t,\tau}^{j|us}/S_t^{j|us}$
- – Five economies with the *highest* $F_{t,\tau}^{j|us}/S_t^{j|us}$ (funding currencies, that is, those with the lowest $r^j - r^{us}$).

We initiate positions depending on VIX states and compute excess returns over the next 30 days on the options position. For brevity, we only report excess returns for investment and funding currencies. Reported are the partitioned sample mean across the VIX volatility states and the 95% bootstrap confidence intervals. We use block bootstrap with 1,000 simulations. The sample period is 8/3/2000 to 10/31/2019. The entries in bold indicate statistical significance of the mean excess returns according to the bootstrap confidence intervals. Shown are the (equal-weighted) excess returns of currency options (panels A, B, and C) and currency excess returns (panel D).

	$VIX_t < 11$ 241 (4%)			$11 \leq VIX_t < 17$ 2270 (42%)			$17 \leq VIX_t < 24$ 1615 (30%)			$24 \leq VIX_t < 40$ 1102 (20%)			$VIX_t \geq 40$ 189 (3%)		
		Bootstrap			Bootstrap			Bootstrap			Bootstrap			Bootstrap	
	Mean	Lower	Upper	Mean	Lower	Upper	Mean	Lower	Upper	Mean	Lower	Upper	Mean	Lower	Upper
	Panel A: 10 delta put option risk premiums														
All 15 currencies	$\boxed{\mathbf{-0.84}}$	-0.88	-0.79	$\boxed{\mathbf{-0.23}}$	-0.30	-0.16	$\boxed{\mathbf{-0.23}}$	-0.34	-0.11	$\boxed{-0.09}$	-0.36	0.18	$\boxed{\mathbf{-0.50}}$	-0.73	-0.21
Investment currencies	**-0.84**	-0.91	-0.77	**-0.29**	-0.38	-0.19	**-0.36**	-0.47	-0.25	0.02	-0.28	0.36	**-0.51**	-0.78	-0.15
Funding currencies	**-0.83**	-0.89	-0.76	**-0.16**	-0.25	-0.07	**-0.16**	-0.28	-0.05	-0.14	-0.35	0.07	**-0.59**	-0.74	-0.42
Investment minus Funding	-0.02	-0.10	0.07	**-0.13**	-0.22	-0.03	**-0.20**	-0.30	-0.10	**0.17**	0.00	0.34	0.08	-0.20	0.37
	Panel B: 10 delta call option risk premiums														
All 15 currencies	$\boxed{\mathbf{0.96}}$	0.58	1.37	$\boxed{\mathbf{-0.31}}$	-0.38	-0.23	$\boxed{\mathbf{0.15}}$	0.01	0.27	$\boxed{\mathbf{0.23}}$	0.06	0.42	$\boxed{\mathbf{-0.37}}$	-0.53	-0.21
Investment currencies	**0.63**	0.32	0.96	**-0.37**	-0.43	-0.30	**0.22**	0.08	0.37	**0.38**	0.21	0.55	0.05	-0.26	0.39
Funding currencies	**0.89**	0.42	1.39	**-0.35**	-0.44	-0.25	0.05	-0.08	0.19	0.09	-0.08	0.28	**-0.60**	-0.73	-0.45
Investment minus Funding	-0.26	-0.64	0.10	-0.02	-0.09	0.05	**0.17**	0.04	0.31	**0.29**	0.11	0.46	**0.65**	0.33	0.96
	Panel C: Straddle risk premiums														
All 15 currencies	$\boxed{\mathbf{0.13}}$	0.07	0.19	$\boxed{\mathbf{-0.02}}$	-0.04	0.00	$\boxed{0.00}$	-0.03	0.03	$\boxed{0.02}$	-0.02	0.06	$\boxed{-0.02}$	-0.08	0.04
Investment currencies	0.04	-0.02	0.08	**-0.02**	-0.04	-0.01	-0.02	-0.04	0.01	0.05	0.00	0.10	0.03	-0.04	0.11
Funding currencies	**0.22**	0.14	0.30	**-0.03**	-0.05	-0.01	**0.03**	0.00	0.06	0.00	-0.04	0.04	**-0.10**	-0.15	-0.06
Investment minus Funding	**-0.19**	-0.25	-0.13	0.00	-0.02	0.02	**-0.05**	-0.07	-0.02	**0.05**	0.01	0.08	**0.13**	0.07	0.19
	Panel D: Currency risk premiums (annualized, percentage)														
All 15 currencies	$\boxed{\mathbf{11.2}}$	8.9	13.4	$\boxed{\mathbf{-1.60}}$	-2.4	-0.8	$\boxed{\mathbf{4.0}}$	2.7	5.5	$\boxed{\mathbf{9.3}}$	6.8	11.8	$\boxed{1.0}$	-7.0	9.1
Investment currencies	**12.2**	9.5	14.9	-0.8	-1.9	0.2	**7.2**	5.5	9.0	**13.8**	10.4	16.9	6.7	-5.4	17.4
Funding currencies	**12.3**	9.8	14.8	**-2.1**	-3.1	-1.3	**1.5**	0.1	2.8	**5.4**	3.4	7.6	-1.8	-8.4	4.3
Investment minus Funding (carry strategy)	-0.1	-1.8	1.7	**1.3**	0.5	2.1	**5.8**	4.6	7.0	**8.4**	6.4	10.4	**8.6**	2.2	14.4

Table 8
Principal components of excess returns of 10-delta puts, 10-delta calls, straddles, and currencies

Reported in this table is the fraction of the variance explained by each of the principal components (panel A). We use all 15 single-name currencies and their options. Specifically, we employ the time series of (i) excess returns of 10 delta puts, (ii) excess returns of 10 delta calls, (iii) excess returns of straddles, and (iv) excess returns of currencies. Panel B reports the loading of each economy pair on the first principal component.

	Excess returns of			
Principal Components	10 delta puts	10 delta calls	Straddles	Currencies
Panel A: Percentage of the variance explained				
1	49	41	45	63
2	59	51	55	72
3	67	59	63	78
4	73	66	68	82
5	78	71	73	85
6	82	76	78	88
7	85	81	82	91
8	89	85	86	93
9	92	89	90	95
10	94	92	92	96
11	96	95	95	98
12	98	97	97	99
13	99	98	99	99
14	100	100	100	100
15	100	100	100	100

	Excess returns of			
	10 delta puts	10 delta calls	Straddles	Currencies
Panel B: Loadings on the first principal component				
Australia	0.27	0.26	0.24	0.27
Canada	0.33	0.36	0.35	0.30
Euro area	0.23	0.18	0.18	0.22
Japan	0.26	0.32	0.29	0.28
New Zealand	0.33	0.36	0.35	0.30
Norway	0.19	0.08	0.14	0.20
Sweden	0.20	0.20	0.26	0.25
Switzerland	0.30	0.32	0.30	0.29
United Kingdom	0.29	0.32	0.31	0.29
Czech Republic	0.04	0.13	0.11	0.09
Denmark	0.17	0.10	0.17	0.23
Hungary	0.20	0.13	0.18	0.25
Korea	0.32	0.26	0.30	0.29
Poland	0.31	0.34	0.31	0.30
South Africa	0.26	0.24	0.23	0.24

Table 9

Single-name currency risk premiums (constant horizon of 30 days)

The base currency is the U.S. dollar, and the foreign currency is the reference. On each day t, we compute the currency excess returns of individual names over t to $t+\tau$, as follows:

$$z^{\text{currency}}_{\{t\to t+\tau\}} \equiv \frac{S^{\text{j|us}}_{t+\tau}}{F^{\text{j|us}}_{t,\tau}} - 1, \quad \text{with} \quad \mathbb{E}^{\mathbb{P}}_t(z^{\text{currency}}_{\{t\to t+\tau\}}) \text{ defining the currency risk premium,}$$

where $F^{\text{j|us}}_{t,\tau}$ denotes the time-t forward rate for delivery in 30 days and $S^{\text{j|us}}_{t+\tau}$ the exchange rate recorded in 30 days from day t. The table reports annualized sample mean, standard deviation (SD), and the 95% bootstrap confidence intervals on the mean excess returns. We use block bootstrap with 1,000 simulations. We also report the skewness (Skew.) and excess kurtosis (Kurt.), both for 30-day returns. $\mathbb{1}_{\{\mathbf{z}>0\}}$ represents the proportion of currency excess returns that are positive. The final two columns show the maximum and minimum realizations. The sample period is 1/3/2000 to 10/31/2019, although data for the euro area and Hungary start in August and June 2000, respectively (see table 1). We also report the excess returns of currency portfolios, which are computed by equally-weighting currency excess returns, considering all 15 currencies, G10 currencies, and non-G10 currencies. The entries in bold indicate statistical significance of the mean currency excess returns according to the bootstrap confidence intervals.

		Annualized (%)							Realization over 30 days	
				Bootstrap						
	Foreign economy (base is U.S.)	Mean	SD	Lower	Upper	$\mathbb{1}_{\{\mathbf{z}>0\}}$ (%)	Skew.	Kurt.	Max.	Min.
1	Australia	**3.1**	12.3	1.9	4.4	53	-0.6	6.6	13	-27
2	Canada	**1.0**	8.5	0.2	1.9	51	-0.5	8.0	10	-20
3	Euro area	**1.2**	9.8	0.2	2.2	50	0.1	4.4	15	-15
4	Japan	**-1.7**	9.7	-2.7	-0.8	47	0.1	3.7	14	-10
5	New Zealand	**4.5**	12.9	3.2	5.8	55	-0.1	4.5	17	-21
6	Norway	0.9	11.3	-0.2	2.0	51	-0.2	4.4	11	-20
7	Sweden	-0.4	11.4	-1.4	0.7	49	0.1	4.2	16	-19
8	Switzerland	**1.2**	10.6	0.2	2.2	50	0.2	5.1	17	-18
9	United Kingdom	-0.5	9.3	-1.3	0.4	51	-0.6	5.6	11	-16
10	Czech Republic	**2.5**	12.4	1.3	3.7	51	-0.1	4.4	20	-18
11	Denmark	0.3	9.9	-0.6	1.3	49	0.1	4.3	15	-15
12	Hungary	**4.1**	14.0	2.7	5.5	54	-0.4	5.7	17	-25
13	Korea	**2.0**	10.4	0.9	3.0	55	-0.6	10.6	20	-23
14	Poland	**4.4**	13.5	3.2	5.7	56	-0.7	6.0	16	-26
15	South Africa	**3.1**	16.5	1.5	4.8	52	-0.4	4.9	18	-28
		Summary (equal-weighted (where relevant)) across economy pairs								
All 15 currencies		**2.5**	9.0	1.6	3.4	53	-0.4	5.5	10	-17
G10 currencies		**1.7**	8.2	0.9	2.4	51	-0.1	4.4	9	-15
Non-G10 currencies		**3.2**	10.7	2.1	4.3	54	-0.6	6.6	14	-21

Table 10

Link of currency option excess returns to yield differentials and U.S. inflation swap rates

We construct three different time-series for this exercise:

- Monthly excess currency returns of 15 economy pairs.
- Yield differentials between the one-year government bond of an economy versus the United States.
- Zero-coupon U.S. inflation swap rates with a maturity of 1-, 2-, 3-, 4-, and 5-year.

We extract principal components for (i) excess currency returns (15 series), (ii) changes in the yield differentials (15 series), and (iii) changes in the U.S. inflation swap rates (five series). Reported are the results from the following empirical specification (full and restricted):

$$\underbrace{\text{Excess return of options}_{\{t\to t+\tau\}}[k]}_{\text{(10 delta put, 10 delta call, or straddle)}} = \overline{\theta} + \sum_{j=1}^{15} \theta_{\text{j, returns}} \underbrace{\text{PC}^{\lfloor \text{j,returns} \rfloor}_{\{t\to t+\tau\}}}_{\text{currency excess returns}} + \sum_{j=1}^{15} \theta_{\text{j, yields}} \underbrace{\text{PC}^{\lfloor \text{j,change in yield differentials} \rfloor}_{\{t\to t+\tau\}}}_{\text{one-year bonds}} + \sum_{j=1}^{5} \theta_{\text{j, inflation}} \underbrace{\text{PC}^{\lfloor \text{j,change in inflation swaps} \rfloor}_{\{t\to t+\tau\}}}_{\text{U.S. inflation swap rates}} + \underbrace{e_{\{t\to t+\tau\}}}_{\text{residual}}.$$

For compactness, we report three adjusted R^2:

– $\overline{R}^2_{\text{A}}$ is the adjusted R^2 using the 15 PC's of currency returns.

– $\overline{R}^2_{\text{B}}$ is the adjusted R^2 using the 15 PC's of currency returns plus 15 PC's of yield differentials.

– $\overline{R}^2_{\text{C}}$ is the adjusted R^2 using the 15 PC's of currency returns plus 15 PC's of yield differentials plus 5 PC's of changes in zero-coupon inflation swap rates.

The base currency is the U.S. dollar, and the foreign currency is the reference.

	10 delta puts			10 delta calls			Straddles		
	$\overline{R}^2_{\text{A}}$	$\overline{R}^2_{\text{B}}$	$\overline{R}^2_{\text{C}}$	$\overline{R}^2_{\text{A}}$	$\overline{R}^2_{\text{B}}$	$\overline{R}^2_{\text{C}}$	$\overline{R}^2_{\text{A}}$	$\overline{R}^2_{\text{B}}$	$\overline{R}^2_{\text{C}}$
Australia	20	21	23	28	31	37	1	5	12
Canada	40	53	57	19	16	16	0	1	5
Euro area	25	36	39	33	34	30	10	16	15
Japan	29	40	42	27	32	23	9	15	15
New Zealand	29	40	42	26	30	23	9	15	15
Norway	40	60	61	21	26	16	10	16	20
Sweden	23	23	22	15	14	15	9	12	11
Switzerland	23	30	30	5	17	20	2	9	7
UK	18	24	27	25	24	27	2	6	7
Czech Republic	31	39	40	30	30	22	3	7	8
Denmark	28	36	37	15	17	16	4	8	7
Hungary	25	35	40	17	19	14	6	7	16
Korea	24	28	30	25	25	17	2	12	10
Poland	24	32	36	44	52	59	12	18	16
South Africa	23	23	25	27	24	17	4	4	2
Average (all 15 currencies)	27	34	37	24	26	23	5	10	11

Table 11

Quantitative implications of Results 1, 2, and 3 utilizing currency dynamics in equation (14)

Presented in this table are the findings from implementing Results 1, 2, and 3. We employ the dynamics of exchange rate growth in (14). This model allows for differential sensitivity of an economy to global risks, namely, diffusive volatility, diffusive probability of tail movement, and size of tail movement. The associated characteristic functions, $\mathbf{C}_t^{\mathbb{P}}[\phi]$ and $\mathbf{C}_t^{\mathbb{Q}}[\phi]$, are presented in equations (A4) and (A15) of the appendix. Our implementations parameterize the evolution of global risk variables as follows (with the U.S. dollar as the base currency):

Panel A: Parameterizations of the global variables that affect the pricing kernels

			Variance component $\mathbf{v}_t$			Probability of tail movement $\mathbf{b}_t$			Size of tail movement		State variables	
β_{us}	η_{us}	α_{us}	$\sqrt{\frac{\theta_{\mathbf{v}}^{\mathbb{P}}}{\kappa_{\mathbf{v}}^{\mathbb{P}}}}$	$\kappa_{\mathbf{v}}^{\mathbb{P}}$	$\sigma_{\mathbf{v}}$	$\frac{\theta_{\mathbf{b}}^{\mathbb{P}}}{\kappa_{\mathbf{b}}^{\mathbb{P}}}$	$\kappa_{\mathbf{b}}^{\mathbb{P}}$	$\sigma_{\mathbf{b}}$	μ_x	σ_x	$\mathbf{v}_t$	$\mathbf{b}_t$
1.0	1.0	1.0	0.40	1.25	0.40	0.057	1.05	0.25	0.1	0.1	0.20	0.06

Our parameterizations are in line with the counterparts in the literature on equity options and disasters. The currency volatility and currency risk premiums depend on the state variables $\mathbf{v}_t$ and $\mathbf{b}_t$. The reported absolute error represents the average absolute difference between the model and the data estimates of the (five) currency option premiums differentiated by strikes.

Panel B: Single-name G10 currencies

		Heterogeneity			Currency option risk premiums (monthly)					Annualized (%)			
		β_j	η_j	α_j	10 delta put	25 delta put	Straddle	25 delta call	10 delta call	Currency premium	Currency volatility	$r^j - r^{us}$	Absolute Error
	Key pattern: Puts are mildly negative and calls are most positive near strike and declining												
Australia	**Model**	1.0	0.6	1.8	-0.175	-0.137	-0.015	0.095	0.050	3.0	11.6		14%
	Data				**-0.074**	**-0.064**	**0.034**	**0.166**	**0.077**	**3.1**	**11.5**	2.2	
	Key pattern: All option returns are negative, and 10 delta puts and 10 delta calls are both highly negative												
Canada	**Model**	1.1	0.8	-0.7	-0.152	-0.090	-0.028	-0.043	-0.069	0.23	8.9		14%
	Data				**-0.431**	**-0.219**	**-0.054**	**-0.121**	**-0.278**	**1.0**	**8.9**	0.2	
	Key pattern: 10 delta puts and 10 delta calls are both highly negative												
Eurozone	**Model**	0.8	1.1	1.9	-0.213	-0.161	-0.020	0.053	-0.054	2.2	9.2		6%
	Data				**-0.305**	**-0.184**	**-0.022**	**0.008**	**-0.198**	**1.2**	**9.1**	-0.5	
	Key pattern: Puts are positive and less positive at lower strike and calls are highly negative at higher strikes												
Japan	**Model**	1.1	1.3	0.1	0.083	0.156	-0.019	-0.201	-0.257	-3.8	9.8		10%
	Data				**0.043**	**0.102**	**-0.029**	**-0.278**	**-0.573**	**-1.7**	**9.7**	-2.1	
	Key pattern: Puts are highly negative and calls are positive and less positive at higher strikes												
New Zealand	**Model**	0.7	1.0	1.9	-0.245	-0.193	-0.020	0.140	0.075	4.6	12.4		4%
	Data				**-0.252**	**-0.142**	**0.018**	**0.181**	**0.005**	**4.5**	**12.4**	2.6	
	Key pattern: Puts are highly negative while calls are highly positive												
Norway	**Model**	1.0	0.6	0.1	-0.187	-0.148	0.010	0.131	0.171	3.3	11.6		7%
	Data				**-0.273**	**-0.118**	**-0.009**	**0.085**	**0.184**	**0.9**	**11.6**	0.9	
	Key pattern: Puts and calls are both negative												
Sweden	**Model**	0.9	1.3	-0.9	-0.146	-0.052	-0.024	-0.070	-0.094	-0.5	11.1		5%
	Data				**-0.267**	**-0.041**	**-0.005**	**-0.029**	**-0.120**	**-0.4**	**11.2**	-0.3	
	Key pattern: Puts are highly negative and calls are positive												
Switzerland	**Model**	0.8	1.1	-0.5	-0.205	-0.173	-0.014	0.109	0.123	2.6	9.9		4%
	Data				**-0.359**	**-0.152**	**0.007**	**0.116**	**0.142**	**1.2**	**9.9**	-1.6	
	Key pattern: Puts are mildly negative and 10 delta call is highly negative												
United Kingdom	**Model**	0.9	1.3	0.8	-0.050	-0.007	-0.018	-0.068	-0.095	-0.7	9.4		4%
	Data				**-0.043**	**-0.022**	**-0.003**	**-0.059**	**-0.225**	**-0.5**	**9.1**	0.5	

Panel C: Averaged across all G10 currencies

		10 delta put	25 delta put	Straddle	25 delta call	10 delta call	Currency premium	Currency volatility
G10	**Model**	-0.143	-0.089	-0.016	0.016	-0.034	1.0	10.4
	Data	**-0.234**	**-0.118**	**-0.007**	**0.034**	**-0.084**	**1.7**	**10.4**

Appendix: Risk premiums on $e^{i\phi z}\{e^k - e^z\}$

In the context of Table 11, we are interested in the following calculation:

$$\mathbf{rp}_t[\phi;k] = \overbrace{\mathbb{E}_t^{\mathbb{P}}(e^{i\phi z}\{e^k - e^z\}) - \mathbb{E}_t^{\mathbb{Q}}(e^{i\phi z}\{e^k - e^z\})}^{\text{risk premium on } e^{i\phi z}\{e^k - e^z\}}, \qquad \text{for} \qquad z \equiv \log(\frac{S_{t+\tau}}{S_{t-}}). \tag{A1}$$

$$= (e^k \mathbf{C}_t^{\mathbb{P}}[\phi] - \mathbf{C}_t^{\mathbb{P}}[\phi - i]) - (e^k \mathbf{C}_t^{\mathbb{Q}}[\phi] - \mathbf{C}_t^{\mathbb{Q}}[\phi - i]), \tag{A2}$$

where the characteristic functions of currency returns are defined as follows:

$$\mathbf{C}_t^{\mathbb{P}}[\phi] \equiv \mathbb{E}_t^{\mathbb{P}}(e^{i\phi \log(\frac{S_{t+\tau}}{S_{t-}})}) \qquad \text{and} \qquad \mathbf{C}_t^{\mathbb{Q}}[\phi] \equiv \mathbb{E}_t^{\mathbb{Q}}(e^{i\phi \log(\frac{S_{t+\tau}}{S_{t-}})}), \tag{A3}$$

for the exchange rate dynamics in equation (14).

Characteristic function of $\log(\frac{S_{t+\tau}}{S_{t-}})$ **under** $\mathbb{P}$**:** We can show that (proof available from the authors)

$$\mathbf{C}_t^{\mathbb{P}}[\phi] = \mathbb{E}_t^{\mathbb{P}}(e^{i\phi \log(\frac{S_{t+\tau}}{S_{t-}})}) = \exp(i\phi\{r_t^{\text{us}} - r_t^{\text{j}}\}\tau - \mathfrak{a}^{\mathbb{P}}[\tau;\phi] - \mathfrak{b}^{\mathbb{P}}[\tau;\phi]\mathbf{v}_t - \mathfrak{e}^{\mathbb{P}}[\tau;\phi] - \mathfrak{f}^{\mathbb{P}}[\tau;\phi]\mathbf{b}_t), \tag{A4}$$

where

$$\mathfrak{b}^{\mathbb{P}}[\tau;\phi] = \frac{2c_{\mathbf{v}}^{\mathbb{P}}\{1 - e^{-\tau\delta_{\mathbf{v}}^{\mathbb{P}}}\}}{\{2\delta_{\mathbf{v}}^{\mathbb{P}} - (b_{\mathbf{v}}^{\mathbb{P}} + \delta_{\mathbf{v}}^{\mathbb{P}})\{1 - e^{-\tau\delta_{\mathbf{v}}^{\mathbb{P}}}\}\}} \quad \text{where} \quad \delta_{\mathbf{v}}^{\mathbb{P}} \equiv \sqrt{\{b_{\mathbf{v}}^{\mathbb{P}}\}^2 - 4a_{\mathbf{v}}c_{\mathbf{v}}^{\mathbb{P}}} \quad \text{and} \tag{A5}$$

$$\mathfrak{a}^{\mathbb{P}}[\tau;\phi] = -\frac{(\delta_{\mathbf{v}}^{\mathbb{P}} + b_{\mathbf{v}}^{\mathbb{P}})}{2a_{\mathbf{v}}}\theta_{\mathbf{v}}^{\mathbb{P}}\tau - \frac{\theta_{\mathbf{v}}^{\mathbb{P}}}{a_{\mathbf{v}}}\log\left(\frac{2\delta_{\mathbf{v}}^{\mathbb{P}} - (b_{\mathbf{v}}^{\mathbb{P}} + \delta_{\mathbf{v}}^{\mathbb{P}})\{1 - e^{-\tau\delta_{\mathbf{v}}^{\mathbb{P}}}\}}{2\delta_{\mathbf{v}}^{\mathbb{P}}}\right), \tag{A6}$$

with

$$a_{\mathbf{v}} \equiv -\frac{1}{2}\sigma_{\mathbf{v}}^2, \tag{A7}$$

$$b_{\mathbf{v}}^{\mathbb{P}} \equiv -\kappa_{\mathbf{v}}^{\mathbb{P}} + \sigma_{\mathbf{v}} i\phi(\beta_{\text{j}} - \beta_{\text{us}}), \text{ and} \tag{A8}$$

$$c_{\mathbf{v}}^{\mathbb{P}} \equiv -\frac{1}{2}(i\phi)(i\phi - 1)\{\beta_{\text{j}} - \beta_{\text{us}}\}^2 - i\phi\{\beta_{\text{us}}^2 - \beta_{\text{us}}\beta_{\text{j}}\}. \tag{A9}$$

Additionally,

$$\mathfrak{f}^{\mathbb{P}}[\tau;\phi] = \frac{2\,c_{\mathbf{b}}^{\mathbb{P}}\{1-e^{-\tau\delta_{\mathbf{b}}^{\mathbb{P}}}\}}{\{2\,\delta_{\mathbf{b}}^{\mathbb{P}} - (b_{\mathbf{b}}^{\mathbb{P}}+\delta_{\mathbf{b}}^{\mathbb{P}})\{1-e^{-\tau\delta_{\mathbf{b}}^{\mathbb{P}}}\}\}} \quad \text{where} \quad \delta_{\mathbf{b}}^{\mathbb{P}} \equiv \sqrt{\{b_{\mathbf{b}}^{\mathbb{P}}\}^2 - 4a_{\mathbf{b}}c_{\mathbf{b}}^{\mathbb{P}}}, \tag{A10}$$

and

$$\mathfrak{e}^{\mathbb{P}}[\tau;\phi] \;=\; -\frac{(\delta_{\mathbf{b}}^{\mathbb{P}}+b_{\mathbf{b}}^{\mathbb{P}})}{2a_{\mathbf{b}}}\theta_{\mathbf{b}}^{\mathbb{P}}\tau - \frac{\theta_{\mathbf{b}}^{\mathbb{P}}}{a_{\mathbf{b}}}\log\left(\frac{2\delta_{\mathbf{b}}^{\mathbb{P}} - (b_{\mathbf{b}}^{\mathbb{P}}+\delta_{\mathbf{b}}^{\mathbb{P}})\{1-e^{-\tau\delta_{\mathbf{b}}^{\mathbb{P}}}\}}{2\delta_{\mathbf{b}}^{\mathbb{P}}}\right). \tag{A11}$$

Completing the solution, we set

$$a_{\mathbf{b}} \;\equiv\; -\frac{1}{2}\sigma_{\mathbf{b}}^2, \tag{A12}$$

$$b_{\mathbf{b}}^{\mathbb{P}} \;\equiv\; -\kappa_{\mathbf{b}}^{\mathbb{P}} + \sigma_{\mathbf{b}} i\phi(\eta_{\mathrm{j}} - \eta_{\mathrm{us}}), \text{ and} \tag{A13}$$

$$\begin{aligned} c_{\mathbf{b}}^{\mathbb{P}} \;\equiv\; & -\frac{1}{2}(i\phi)(i\phi-1)\{\eta_{\mathrm{j}}-\eta_{\mathrm{us}}\}^2 - \{\exp(i\phi\{\alpha_{\mathrm{j}}-\alpha_{\mathrm{us}}\}\mu_x + \frac{1}{2}\{i\phi(\alpha_{\mathrm{j}}-\alpha_{\mathrm{us}})\}^2\sigma_x^2) - 1\} \\ & - i\phi[\{\exp(\alpha_{\mathrm{us}}\mu_x + \frac{1}{2}\alpha_{\mathrm{us}}^2\sigma_x^2) - 1\} - \{\exp(\alpha_{\mathrm{j}}\mu_x + \frac{1}{2}\alpha_{\mathrm{j}}^2\sigma_x^2) - 1\} + \eta_{\mathrm{us}}^2 - \eta_{\mathrm{us}}\eta_{\mathrm{j}}]. \end{aligned} \tag{A14}$$

Characteristic function of $\log(\frac{S_{t+\tau}}{S_{t-}})$ **under** $\mathbb{Q}$**:** Next, we can show that

$$\mathbf{C}_t^{\mathbb{Q}}[\phi] = \mathbb{E}_t^{\mathbb{Q}}(e^{i\phi\log(\frac{S_{t+\tau}}{S_{t-}})}) = \exp(i\phi\{r_t^{\mathrm{us}} - r_t^{\mathrm{j}}\}\tau - \mathfrak{a}^{\mathbb{Q}}[\tau;\phi] - \mathfrak{b}^{\mathbb{Q}}[\tau;\phi]\mathbf{v}_t - \mathfrak{e}^{\mathbb{Q}}[\tau;\phi] - \mathfrak{f}^{\mathbb{Q}}[\tau;\phi]\mathbf{b}_t), \tag{A15}$$

where, as before, $a_{\mathbf{v}} = -\frac{1}{2}\sigma_{\mathbf{v}}^2$,

$$\mathfrak{b}^{\mathbb{Q}}[\tau;\phi] \;=\; \frac{2\,c_{\mathbf{v}}^{\mathbb{Q}}\{1-e^{-\tau\delta_{\mathbf{v}}^{\mathbb{Q}}}\}}{\{2\,\delta_{\mathbf{v}}^{\mathbb{Q}} - (b_{\mathbf{v}}^{\mathbb{Q}}+\delta_{\mathbf{v}}^{\mathbb{Q}})\{1-e^{-\tau\delta_{\mathbf{v}}^{\mathbb{Q}}}\}\}} \quad \text{where} \quad \delta_{\mathbf{v}}^{\mathbb{Q}} \equiv \sqrt{\{b_{\mathbf{v}}^{\mathbb{Q}}\}^2 - 4\,a_{\mathbf{v}}\,c_{\mathbf{v}}^{\mathbb{Q}}} \text{ and} \tag{A16}$$

$$\mathfrak{a}^{\mathbb{Q}}[\tau;\phi] \;=\; -\frac{(\delta_{\mathbf{v}}^{\mathbb{Q}}+b_{\mathbf{v}}^{\mathbb{Q}})}{2\,a_{\mathbf{v}}}\theta_{\mathbf{v}}^{\mathbb{Q}}\,\tau - \frac{\theta_{\mathbf{v}}^{\mathbb{Q}}}{a_{\mathbf{v}}}\log\left(\frac{2\,\delta_{\mathbf{v}}^{\mathbb{Q}} - (b_{\mathbf{v}}^{\mathbb{Q}}+\delta_{\mathbf{v}}^{\mathbb{Q}})\{1-e^{-\tau\delta_{\mathbf{v}}^{\mathbb{Q}}}\}}{2\,\delta_{\mathbf{v}}^{\mathbb{Q}}}\right). \tag{A17}$$

We determine:

$$b_{\mathbf{v}}^{\mathbb{Q}} = -\kappa_{\mathbf{v}}^{\mathbb{P}} + \sigma_{\mathbf{v}}\, i\,\phi\,(\beta_{\mathrm{j}} - \beta_{\mathrm{us}}) + \sigma_{\mathbf{v}}\beta_{\mathrm{us}} \quad \text{and} \tag{A18}$$

$$c_{\mathbf{v}}^{\mathbb{Q}} = -\frac{1}{2}(i\phi)(i\phi-1)\beta_{\mathrm{j}}^2 - \frac{1}{2}\{-i(\phi+i)\}\{-i(\phi+i)-1\}\beta_{\mathrm{us}}^2 - (i\phi)\{-i(\phi+i)\}\beta_{\mathrm{j}}\beta_{\mathrm{us}}. \tag{A19}$$

Additionally,

$$\mathfrak{f}^{\mathbb{Q}}[\tau;\phi] = \frac{2\,c_{\mathbf{b}}^{\mathbb{Q}}\{1-e^{-\tau\delta_{\mathbf{b}}^{\mathbb{Q}}}\}}{\{2\,\delta_{\mathbf{b}}^{\mathbb{Q}} - (b_{\mathbf{b}}^{\mathbb{Q}} + \delta_{\mathbf{b}}^{\mathbb{Q}})\{1-e^{-\tau\delta_{\mathbf{b}}^{\mathbb{Q}}}\}\}} \quad \text{where} \quad \delta_{\mathbf{b}}^{\mathbb{Q}} \equiv \sqrt{[b_{\mathbf{b}}^{\mathbb{Q}}]^2 - 4\,a_{\mathbf{b}}\,c_{\mathbf{b}}^{\mathbb{Q}}}, \text{ and} \tag{A20}$$

$$\mathfrak{e}^{\mathbb{Q}}[\tau;\phi] = -\frac{(\delta_{\mathbf{b}}^{\mathbb{P}} + b_{\mathbf{b}}^{\mathbb{Q}})}{2a_{\mathbf{b}}}\theta_{\mathbf{b}}^{\mathbb{Q}}\,\tau - \frac{\theta_{\mathbf{b}}^{\mathbb{Q}}}{a_{\mathbf{b}}}\log\left(\frac{2\,\delta_{\mathbf{b}}^{\mathbb{Q}} - (b_{\mathbf{b}}^{\mathbb{Q}} + \delta_{\mathbf{b}}^{\mathbb{Q}})\{1-e^{-\tau\delta_{\mathbf{b}}^{\mathbb{Q}}}\}}{2\,\delta_{\mathbf{b}}^{\mathbb{Q}}}\right), \tag{A21}$$

and we set, as before, $a_{\mathbf{b}} = -\frac{1}{2}\sigma_{\mathbf{b}}^2$,

$$b_{\mathbf{b}}^{\mathbb{Q}} = -\kappa_{\mathbf{b}}^{\mathbb{P}} + \sigma_{\mathbf{b}} i\phi\{\eta_{\mathrm{j}} - \eta_{\mathrm{us}}\} + \sigma_{\mathbf{b}}\eta_{\mathrm{us}} \text{ and} \tag{A22}$$

$$\begin{aligned} c_{\mathbf{b}}^{\mathbb{Q}} = & -\frac{1}{2}(i\phi)(i\phi-1)\eta_{\mathrm{j}}^2 + \frac{1}{2}(i\{\phi+i\})(-i\{\phi+i\}-1)\eta_{\mathrm{us}}^2 + (i\phi)(i\{\phi+i\})\eta_{\mathrm{j}}\eta_{\mathrm{us}} \\ & -(e^{\{i\phi\alpha_{\mathrm{j}} - i\{\phi+i\}\alpha_{\mathrm{us}}\}\mu_x + \frac{1}{2}\{i\phi\alpha_{\mathrm{j}} - i\{\phi+i\}\alpha_{\mathrm{us}}\}^2\sigma_x^2} - 1) \\ & + i\phi(e^{\alpha_{\mathrm{j}}\mu_x + \frac{1}{2}\alpha_{\mathrm{j}}^2\sigma_x^2} - 1) - i\{\phi+i\}(e^{\alpha_{\mathrm{us}}\mu_x + \frac{1}{2}\alpha_{\mathrm{us}}^2\sigma_x^2} - 1). \end{aligned} \tag{A23}$$

We have the analytical expressions corresponding to $\mathbb{E}_t^{\mathbb{P}}(e^{i\phi\log(\frac{S_{t+\tau}}{S_{t-}})})$ and $\mathbb{E}_t^{\mathbb{Q}}(e^{i\phi\log(\frac{S_{t+\tau}}{S_{t-}})})$. ■

King U.S. Dollar, Global Risks, and Currency Option Risk Premiums

Internet Appendix: Not Intended for Publication

Abstract

We provide the steps of the proof of the expression for the put option risk premium and call option risk premium in Section I and Section II, respectively. Section III has the proof of the expression for the straddle risk premium. Section IV elaborates on the sign of $\int_0^\infty \mathfrak{Re}[\frac{\mathbb{E}_t^{\mathbb{P}}(e^{-i\phi(k-z)}\{e^k-e^z\})-\mathbb{E}_t^{\mathbb{Q}}(e^{-i\phi(k-z)}\{e^k-e^z\})}{i\phi}]d\phi$ across option strikes.

I. Proof of the risk premium of the currency put in Result 1

The strike price for the OTM put is $K < S_t^{\mathrm{j|us}}$. Recall that $z \equiv \log(\frac{S_{t+\tau}^{\mathrm{j|us}}}{S_{t-}^{\mathrm{j|us}}})$ and $k \equiv \log(\frac{K}{S_t^{\mathrm{j|us}}}) < 0$.

Let $p[z]$ and $q[z]$ denote the physical density (i.e., for $\mathbb{P}$) and the risk-neutral density (i.e., for $\mathbb{Q}$) corresponding to uncertainty z. It follows that,

$$\underbrace{\mathbb{E}_t^{\mathbb{P}}(\frac{S_{t+\tau}^{\mathrm{j|us}}}{S_t^{\mathrm{j|us}}})}_{\text{time-varying}} = \int_{-\infty}^{\infty} e^z\, p[z]\, dz \qquad \text{and} \qquad \underbrace{\mathbb{E}_t^{\mathbb{Q}}(\frac{S_{t+\tau}^{\mathrm{j|us}}}{S_t^{\mathrm{j|us}}})}_{\text{time-varying}} = \int_{-\infty}^{\infty} e^z\, q[z]\, dz = \frac{F_{t,\tau}^{\mathrm{j|us}}}{S_t^{\mathrm{j|us}}}. \tag{I1}$$

Consider the risk premium of the put, $\mu_{\{t\to t+\tau\}}^{\text{put}}[k] \equiv e^{r_t^{\mathrm{us}}\tau}(\frac{\mathbb{E}_t^{\mathbb{P}}(\max(e^k - e^z, 0))}{\mathbb{E}_t^{\mathbb{Q}}(\max(e^k - e^z, 0))} - 1)$. Now

$$\begin{aligned}\mathbb{E}_t^{\mathbb{P}}(\max(e^k - e^z, 0)) &= e^k \underbrace{\int_{-\infty}^{k} p[z]\, dz}_{\equiv\, \mathrm{Prob}^{\mathbb{P}}[z<k]} - \left(\int_{-\infty}^{\infty} e^z p[z]\, dz\right) \underbrace{\int_{-\infty}^{k} \frac{e^z p[z]}{\left(\int_{-\infty}^{\infty} e^z p[z]\, dz\right)}\, dz}_{\equiv\, \mathrm{Prob}^{\mathbb{P}^*}[z<k]}, &\text{(I2)}\\ &= e^k\, \mathrm{Prob}^{\mathbb{P}}[z<k] - \mathbb{E}_t^{\mathbb{P}}(e^z)\, \mathrm{Prob}^{\mathbb{P}^*}[z<k]. &\text{(I3)}\end{aligned}$$

The measure $\mathbb{P}^*$ is defined by the Radon-Nikodym derivative $\frac{d\mathbb{P}^*}{d\mathbb{P}} = \frac{e^z p[z]}{\int_{-\infty}^{\infty} e^z p[z] dz}$. If one were to define the measure $\mathbb{Q}^*$ as $\frac{d\mathbb{Q}^*}{d\mathbb{Q}} = \frac{e^z q[z]}{\int_{-\infty}^{\infty} e^z q[z] dz}$, then the analogue under the risk-neutral probability measure is

$$\begin{aligned}\mathbb{E}_t^{\mathbb{Q}}(\max(e^k - e^z, 0)) &= e^k \underbrace{\int_{-\infty}^{k} q[z]\, dz}_{\mathrm{Prob}^{\mathbb{Q}}[z<k]} - \left(\int_{-\infty}^{\infty} e^z q[z]\, dz\right) \int_{-\infty}^{k} \frac{e^z q[z]}{\left(\int_{-\infty}^{\infty} e^z q[z]\, dz\right)}\, dz, &\text{(I4)}\\ &= e^k\, \mathrm{Prob}^{\mathbb{Q}}[z<k] - \frac{F_{t,\tau}^{\mathrm{j|us}}}{S_t^{\mathrm{j|us}}}\, \mathrm{Prob}^{\mathbb{Q}^*}[z<k]. &\text{(I5)}\end{aligned}$$

By Stuart and Ord (1987, Chapter 4), the form of the four probabilities are

$$\mathrm{Prob}^{\mathbb{P}}[z<k] = \frac{1}{2} - \frac{1}{\pi}\int_0^{\infty} \mathfrak{Re}[\frac{e^{-i\phi k}\mathbb{E}_t^{\mathbb{P}}(e^{i\phi z})}{i\phi}]d\phi, \qquad \mathrm{Prob}^{\mathbb{P}*}[z<k] = \frac{1}{2} - \frac{1}{\pi}\int_0^{\infty} \mathfrak{Re}[\frac{e^{-i\phi k}\frac{\mathbb{E}_t^{\mathbb{P}}(e^{i\phi z+z})}{\mathbb{E}_t^{\mathbb{P}}(e^z)}}{i\phi}]d\phi, \tag{I6}$$

$$\mathrm{Prob}^{\mathbb{Q}}[z<k] = \frac{1}{2} - \frac{1}{\pi}\int_0^{\infty} \mathfrak{Re}[\frac{e^{-i\phi k}\mathbb{E}_t^{\mathbb{Q}}(e^{i\phi z})}{i\phi}]d\phi, \quad \text{and} \quad \mathrm{Prob}^{\mathbb{Q}*}[z<k] = \frac{1}{2} - \frac{1}{\pi}\int_0^{\infty} \mathfrak{Re}[\frac{e^{-i\phi k}\frac{\mathbb{E}_t^{\mathbb{Q}}(e^{i\phi z+z})}{\mathbb{E}_t^{\mathbb{Q}}(e^z)}}{i\phi}]d\phi. \tag{I7}$$

Aided by these expressions, we obtain the following:

$$\underbrace{\mu^{\text{put}}_{\{t\to t+\tau\}}[k]}_{\text{time-varying}} = \frac{e^{r^{\text{us}}_t\tau}}{\mathbb{E}^{\mathbb{Q}}_t(\max(e^k - e^z,0))}\underbrace{\{\mathbb{E}^{\mathbb{P}}_t(\max(e^k - e^z,0)) - \mathbb{E}^{\mathbb{Q}}_t(\max(e^k - e^z,0))\}}_{\equiv \mathbb{A}_t}. \tag{I8}$$

Using (I6) and (I7) and simplifying the real part of the complex-valued functions, we determine that

$$\mathbb{A}_t = e^k\{\text{Prob}^{\mathbb{P}}[z<k] - \text{Prob}^{\mathbb{Q}}[z<k]\} - \mathbb{E}^{\mathbb{P}}_t(e^z)\{\text{Prob}^{\mathbb{P}^*}[z<k] - \frac{F^{\text{j|us}}_{t,\tau}}{S^{\text{j|us}}_t}\text{Prob}^{\mathbb{Q}^*}[z<k]\}, \tag{I9}$$

$$= \underbrace{-\frac{1}{2}(\mathbb{E}^{\mathbb{P}}_t(e^z) - \frac{F^{\text{j|us}}_{t,\tau}}{S^{\text{j|us}}_t})}_{\substack{<\,0 \text{ for a risky currency} \\ \text{(time-varying)}}} - \frac{1}{\pi}\int_0^\infty \mathfrak{Re}[\frac{\mathbb{E}^{\mathbb{P}}_t(e^{-i\phi(k-z)}\{e^k - e^z\}) - \mathbb{E}^{\mathbb{Q}}_t(e^{-i\phi(k-z)}\{e^k - e^z\})}{i\phi}]d\phi. \tag{I10}$$

Table 11 uncovers that $\frac{1}{\pi}\int_0^\infty \mathfrak{Re}[\frac{\mathbb{E}^{\mathbb{P}}_t(e^{-i\phi(k-z)}\{e^k-e^z\}) - \mathbb{E}^{\mathbb{Q}}_t(e^{-i\phi(k-z)}\{e^k-e^z\})}{i\phi}]d\phi$ is positive under a variety of parameterizations across economy pairs. The economic states $z<k<0$ correspond to sizable U.S. dollar appreciations, which are associated with a high stochastic discount factor. We consider further elaborations in Section IV. ■

II. Proof of the risk premium of the currency call in Result 2

With $\mu^{\text{call}}_{\{t\to t+\tau\}}[k] \equiv e^{r^{\text{us}}_t\tau}(\frac{\mathbb{E}^{\mathbb{P}}_t(\max(e^z-e^k,0))}{\mathbb{E}^{\mathbb{Q}}_t(\max(e^z-e^k,0))} - 1)$ and $k>0$ for OTM calls, we obtain the following:

$$\mathbb{E}^{\mathbb{P}}_t(\max(e^z - e^k,0)) = \left(\int_{-\infty}^{\infty} e^z p[z]\,dz\right)\underbrace{\int_k^\infty \frac{e^z p[z]}{\left(\int_{-\infty}^{\infty} e^z p[z]\,dz\right)}dz}_{\text{Prob}^{\mathbb{P}^*}[z>k]} - e^k \underbrace{\int_k^\infty p[z]\,dz}_{\text{Prob}^{\mathbb{P}}[z>k]} \tag{I11}$$

$$= \mathbb{E}^{\mathbb{P}}_t(e^z)\,\text{Prob}^{\mathbb{P}^*}[z>k] - e^k\,\text{Prob}^{\mathbb{P}}[z>k]. \tag{I12}$$

Additionally, it holds that

$$\mathbb{E}^{\mathbb{Q}}_t(\max(e^z - e^k,0)) = \left(\int_{-\infty}^{\infty} e^z q[z]\,dz\right)\int_k^\infty \frac{e^z q[z]}{\left(\int_{-\infty}^{\infty} e^z q[z]\,dz\right)}dz - e^k \underbrace{\int_k^\infty q[z]\,dz}_{\text{Prob}^{\mathbb{Q}}[z>k]} \tag{I13}$$

$$= \frac{F^{\text{j|us}}_{t,\tau}}{S^{\text{j|us}}_t}\,\text{Prob}^{\mathbb{Q}^*}[z>k] - e^k\,\text{Prob}^{\mathbb{Q}}[z>k]. \tag{I14}$$

The form of the four probabilities are

$$\text{Prob}^{\mathbb{P}*}[z > k] = \frac{1}{2} + \frac{1}{\pi}\int_0^{\infty} \mathfrak{Re}[\frac{e^{-i\phi k}\frac{\mathbb{E}_t^{\mathbb{P}}(e^{i\phi z + z})}{\mathbb{E}_t^{\mathbb{P}}(e^z)}}{i\phi}]d\phi, \quad \text{Prob}^{\mathbb{P}}[z > k] = \frac{1}{2} + \frac{1}{\pi}\int_0^{\infty} \mathfrak{Re}[\frac{e^{-i\phi k}\mathbb{E}_t^{\mathbb{P}}(e^{i\phi z})}{i\phi}]d\phi, \quad \text{(I15)}$$

$$\text{Prob}^{\mathbb{Q}*}[z > k] = \frac{1}{2} + \frac{1}{\pi}\int_0^{\infty} \mathfrak{Re}[\frac{e^{-i\phi k}\frac{\mathbb{E}_t^{\mathbb{Q}}(e^{i\phi z + z})}{\mathbb{E}_t^{\mathbb{Q}}(e^z)}}{i\phi}]d\phi, \quad \text{Prob}^{\mathbb{Q}}[z > k] = \frac{1}{2} + \frac{1}{\pi}\int_0^{\infty} \mathfrak{Re}[\frac{e^{-i\phi k}\mathbb{E}_t^{\mathbb{Q}}(e^{i\phi z})}{i\phi}]d\phi. \text{ (I16)}$$

Hence, we determine the following:

$$\underbrace{\mu^{\text{call}}_{\{t \to t+\tau\}}[k]}_{\text{time-varying}} = \frac{e^{r_t^{\text{us}}\tau}}{\mathbb{E}_t^{\mathbb{Q}}(\max(e^z - e^k, 0))} \underbrace{\{\mathbb{E}_t^{\mathbb{P}}(\max(e^z - e^k, 0)) - \mathbb{E}_t^{\mathbb{Q}}(\max(e^z - e^k, 0))\}}_{\equiv \mathbb{A}_t^{\text{up}}}, \quad \text{(I17)}$$

$$\text{where } \mathbb{A}_t^{\text{up}} = \mathbb{E}_t^{\mathbb{P}}(e^z)\,\text{Prob}^{\mathbb{P}^*}[z > k] - \frac{F_{t,\tau}^{\text{j|us}}}{S_t^{\text{j|us}}}\text{Prob}^{\mathbb{Q}^*}[z > k] - e^k(\text{Prob}^{\mathbb{P}}[z > k] - \text{Prob}^{\mathbb{Q}}[z > k])\} \quad \text{(I18)}$$

$$= \underbrace{\frac{1}{2}(\mathbb{E}_t^{\mathbb{P}}(e^z) - \frac{F_{t,\tau}^{\text{j|us}}}{S_t^{\text{j|us}}})}_{\substack{> 0 \text{ for a risky currency} \\ (\text{time}-\text{varying})}} + \frac{1}{\pi}\int_0^{\infty} \mathfrak{Re}[(\frac{\mathbb{E}_t^{\mathbb{P}}(e^{-i\phi(k-z)}\{e^z - e^k\}) - \mathbb{E}_t^{\mathbb{Q}}(e^{-i\phi(k-z)}\{e^z - e^k\})}{i\phi})]d\phi. \text{ (I19)}$$

To clarify the quantitative effects imputed from table 11, we note that the states $z > k > 0$ map to U.S. dollar depreciations.

Economically, $\int_0^{\infty} \mathfrak{Re}[(\frac{\mathbb{E}_t^{\mathbb{P}}(e^{-i\phi(k-z)}\{e^z - e^k\}) - \mathbb{E}_t^{\mathbb{Q}}(e^{-i\phi(k-z)}\{e^z - e^k\})}{i\phi})]d\phi$ can accommodate either sign for $k > 0$. If there were to be aversion to sizable dollar depreciations, then for some high $k > 0$, the stochastic discount factor can be increasing in z. Accordingly, $\int_0^{\infty} \mathfrak{Re}[(\frac{\mathbb{E}_t^{\mathbb{P}}(e^{-i\phi(k-z)}\{e^z - e^k\}) - \mathbb{E}_t^{\mathbb{Q}}(e^{-i\phi(k-z)}\{e^z - e^k\})}{i\phi})]d\phi$ is negative. Otherwise, dollar depreciations align with prosperous times and $\int_0^{\infty} \mathfrak{Re}[(\frac{\mathbb{E}_t^{\mathbb{P}}(e^{-i\phi(k-z)}\{e^z - e^k\}) - \mathbb{E}_t^{\mathbb{Q}}(e^{-i\phi(k-z)}\{e^z - e^k\})}{i\phi})]d\phi$ is positive. ■

III. Proof of the risk premium of the currency straddle in Result 3

Consider the straddle risk premium

$$\mu^{\text{straddle}}_{\{t \to t+\tau\}}[K]\Big|_{K = S_t^{\text{j|us}}} \equiv e^{r_t^{\text{us}}\tau}(\frac{\mathbb{E}_t^{\mathbb{P}}(\max(K - S_{t+\tau}^{\text{j|us}}, 0) + \max(S_{t+\tau}^{\text{j|us}} - K, 0))}{\mathbb{E}_t^{\mathbb{Q}}(\max(K - S_{t+\tau}^{\text{j|us}}, 0) + \max(S_{t+\tau}^{\text{j|us}} - K, 0))} - 1) \quad \text{(I20)}$$

$$= \frac{\mathbb{E}_t^{\mathbb{P}}(\max(1 - e^z, 0) + \max(e^z - 1, 0)) - \mathbb{E}_t^{\mathbb{Q}}(\max(1 - e^z, 0) + \max(e^z - 1, 0))}{e^{-r_t^{\text{us}}\tau}\mathbb{E}_t^{\mathbb{Q}}(\max(1 - e^z, 0) + \max(e^z - 1, 0))}. \quad \text{(I21)}$$

The next step essentially combines the $\mathbb{P}$ and $\mathbb{Q}$ measure payoffs when $k = 0$. Then,

$$\text{Numerator of (I21)} = \frac{2}{\pi}\int_0^\infty \mathfrak{Re}[\frac{\mathbb{E}_t^{\mathbb{Q}}(e^{i\phi z})}{i\phi}]d\phi - \frac{2}{\pi}\int_0^\infty \mathfrak{Re}[\frac{\mathbb{E}_t^{\mathbb{P}}(e^{i\phi z})}{i\phi}]d\phi \tag{I22}$$

$$+ \frac{2}{\pi}\int_0^\infty \mathfrak{Re}[\frac{\mathbb{E}_t^{\mathbb{P}}(e^{i\phi z+z})}{i\phi}]d\phi - \frac{2}{\pi}\int_0^\infty \mathfrak{Re}[\frac{\mathbb{E}_t^{\mathbb{Q}}(e^{i\phi z+z})}{i\phi}]d\phi. \tag{I23}$$

Rearranging yields (19) of Result 3. ∎

IV. Sign of $\int_0^\infty \mathfrak{Re}[\frac{\mathbb{E}_t^{\mathbb{P}}(e^{-i\phi(k-z)}\{e^k-e^z\})-\mathbb{E}_t^{\mathbb{Q}}(e^{-i\phi(k-z)}\{e^k-e^z\})}{i\phi}]d\phi$ across option strikes

In what follows, we fix $S_t = 1$. Hence, for $k = \log(\frac{K}{S_t}) < 1$ and $z = \log(\frac{S_{t+\tau}}{S_{t-}})$, we obtain that

$$e^k = K < 1, \qquad e^z = S_{t+\tau} \equiv S, \qquad \text{and} \qquad k - z = \log(\frac{K}{S}). \tag{I24}$$

There is only uncertainty about the random variable S.

We are interested in the effects of aversion to foreign currency depreciations (U.S. dollar appreciations). This aversion coincides with low exchange rate $S < 1$. Incorporating such effects, one may consider,

$$\underbrace{\frac{q[S]}{p[S]}}_{\text{Radon Nikodym derivative}} = \underbrace{m[S]}_{\text{unit mean stochastic discount factor}} \text{ is monotonically declining in the remaining uncertainty } S. \tag{I25}$$

An often utilized form is $m[S] = S^{-\gamma}$, for some constant γ, and we normalize the mean of $m[S] = 1$.

Next, using the Euler formula that $e^{-i\phi x} = \cos[\phi x] - i\sin[\phi x]$, it follows that

$$Y[\phi] \equiv \frac{e^{-i\phi(k-z)}\{e^k - e^z\}}{i\phi} \tag{I26}$$

$$= \frac{\{\cos[\phi\log(\frac{K}{S})] - i\sin[\phi\log(\frac{K}{S})]\}\{K-S\}}{i\phi} \tag{I27}$$

$$= \frac{\{-i\cos[\phi\log(\frac{K}{S})] - \sin[\phi\log(\frac{K}{S})]\}\{K-S\}}{\phi} \tag{I28}$$

$$= \{-\frac{1}{\phi}\sin[\phi\log(\frac{K}{S})] - i\frac{1}{\phi}\cos[\phi\log(\frac{K}{S})]\}\{K-S\}. \tag{I29}$$

We consider the sign of the following term:

$$\Delta = \int_0^\infty \mathfrak{Re}[\frac{\mathbb{E}_t^{\mathbb{P}}(e^{-i\phi(k-z)}\{e^k - e^z\}) - \mathbb{E}_t^{\mathbb{Q}}(e^{-i\phi(k-z)}\{e^k - e^z\})}{i\phi}]d\phi. \tag{I30}$$

$$= \int_0^\infty \mathfrak{Re}[\mathbb{E}_t^{\mathbb{P}}(Y[\phi]) - \mathbb{E}_t^{\mathbb{Q}}(Y[\phi])]\,d\phi, \tag{I31}$$

$$\text{where } \mathbb{E}_t^{\mathbb{P}}(Y[\phi]) - \mathbb{E}_t^{\mathbb{Q}}(Y[\phi]) = \mathbb{E}_t^{\mathbb{P}}(\{-\frac{1}{\phi}\sin[\phi\log(\frac{K}{S})]\}\{K-S\}) - \mathbb{E}_t^{\mathbb{Q}}(\{-\frac{1}{\phi}\sin[\phi\log(\frac{K}{S})]\}\{K-S\})$$
$$+ \mathbb{E}_t^{\mathbb{P}}(\{-i\frac{1}{\phi}\cos[\phi\log(\frac{K}{S})]\}\{K-S\}) - \mathbb{E}_t^{\mathbb{Q}}(\{-i\frac{1}{\phi}\cos[\phi\log(\frac{K}{S})]\}\{K-S\}).$$

Set $\mathbb{h}[S;\phi] = -\frac{1}{\phi}\sin[\phi\log(\frac{K}{S})]\{K-S\}$ and $\mathbb{g}[S] = \frac{1}{\frac{q[S]}{p[S]}}$. Then the real part of $\{\mathbb{E}_t^{\mathbb{P}}(Y[\phi]) - \mathbb{E}_t^{\mathbb{Q}}(Y[\phi])\}$ is

$$\mathfrak{Re}[\mathbb{E}_t^{\mathbb{P}}(Y[\phi]) - \mathbb{E}_t^{\mathbb{Q}}(Y[\phi])] = \mathbb{E}_t^{\mathbb{P}}(\{-\frac{1}{\phi}\sin[\phi\log(\frac{K}{S})]\}\{K-S\}) - \mathbb{E}_t^{\mathbb{Q}}(\{-\frac{1}{\phi}\sin[\phi\log(\frac{K}{S})]\}\{K-S\})$$
$$= \mathrm{cov}_t^{\mathbb{Q}}(\mathbb{g}[S], \mathbb{h}[S;\phi]). \tag{I32}$$

We note that $\mathbb{E}_t^{\mathbb{P}}(\mathbb{h}[S;\phi]) - \mathbb{E}_t^{\mathbb{Q}}(\mathbb{h}[S;\phi]) = \mathrm{cov}_t^{\mathbb{Q}}(\frac{1}{\frac{q[S]}{p[S]}}, \mathbb{h}[S;\phi])$. Consequently, in line with (I30)–(I31), we determine $\Delta = \int_0^\infty \mathrm{cov}_t^{\mathbb{Q}}(\mathbb{g}[S], \mathbb{h}[S;\phi])\,d\phi$. In light of $\frac{q[S]}{p[S]}$ being monotonically declining in S, we have

$$\frac{d(\frac{1}{\frac{q[S]}{p[S]}})}{dS} \text{ is positive in } S \text{ for } S < K < 1 \quad \text{(aversion to dollar appreciation)}. \tag{I33}$$

Thus, $\mathbb{g}[S]$ is an increasing function.

Analogously, taking the derivative of $\mathbb{h}[S;\phi]$ with respect to S,

$$\frac{d(-\frac{1}{\phi}\sin[\phi\log(\frac{K}{S})]\{K-S\})}{dS} = \frac{\sin\left(\phi\log\left(\frac{K}{S}\right)\right)}{\phi} + \frac{(K-S)\cos\left(\phi\log\left(\frac{K}{S}\right)\right)}{S} \text{ can have positive segments}$$
$$\text{over a large range of } \phi \text{ for } S < K < 1. \tag{I34}$$

If $\mathbb{h}[S;\phi]$ were to be an increasing function, we anticipate the sign of $\mathrm{cov}_t^{\mathbb{Q}}(\mathbb{g}[S], \mathbb{h}[S;\phi])$ to be nonnegative (from such sources as Schmidt (2014)).

In our parameterizations of SDFs in Table 11, $\int_0^\infty \mathrm{cov}_t^{\mathbb{Q}}(\frac{1}{\frac{q[S]}{p[S]}}, -\frac{1}{\phi}\sin[\phi\log(\frac{K}{S})]\{K-S\})\,d\phi$ is positive. ■