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The information content of currency option-implied volatilities: implications for ex-ante forecasts of global equity correlations

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ABSTRACT
We use existing currency models, global capital flows, international parity, the Taylor rule, and some simplifying assumptions to derive and empirically test a link between the information contained in currency option-implied volatilities and future global equity correlations. Using data from January 1999 to May 2020, we test our hypothesis and find that exchange rate option-implied volatilities — coupled with one-period *ex-post* correlations — more accurately predict subsequent world equity market correlations than other models. Our findings have implications for portfolio diversification, forecasts of overall equity portfolio volatility, and portfolio optimization.

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1. Introduction

Volatility and correlation forecasts are significant components of asset pricing and financial risk management. Prior literature on the measurement, modeling, and forecasting of volatility abounds, with Poon and Granger (2003) and Gonzalez-Perez (2015) providing comprehensive coverage of such studies. However, although volatility and correlations play a joint central role in the behavior of any portfolio, little serious effort has yet been made to link these two concepts. In this paper, we use global capital flows, existing currency models, international parity, the Taylor (1993) rule, and some simplifying assumptions to first derive a justification for the existence of a contemporaneous relation between foreign exchange rate volatilities and equity market correlations. More specifically, we consider two seemingly unrelated concepts - exchange rates and equity correlations - side-by-side and establish the linkage between international equity markets' correlations and the volatility of the exchange rates pertinent to these markets. We then empirically test this relation and show how forward-looking estimates of foreign exchange volatility, as captured by the information contained in currency option-implied volatility, can be used to forecast future correlations among global equity markets.

We acknowledge that currency option-implied volatility is only one of several possible predictors of future realized volatility. However, Jorion (1995) finds that option-implied volatility forecasts, although still biased, tend to generally outperform other time series models. Jorion (1995) goes on to suggest that a linear transformation of the series further improves the forecasts. In our empirical analysis, our choice of currency option-implied volatility as the main estimator of subsequent foreign exchange volatility is both driven by simplicity and by the fact that implied volatilities have long been known to contain valuable information about the future, as demonstrated by the considerable number of articles summarized in Gonzalez-Perez (2015) or Poon and Granger (2003).

The benefits of forecasting future correlations with improved accuracy are noteworthy. Correlations are the driver of diversification and a key measure in any type of portfolio optimization process since they help determine the optimal portfolio weights. Additionally, equity markets correlations and volatilities have been shown

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to be time varying (Longin and Solnik 1995 and 2001), yet the main determinants of these time variations are not fully known and remain an active area of research. Thus, uncovering new insights into the dynamics of the drivers of global equity markets correlations is of great interest. We show that such new findings can be employed to reduce correlation forecast errors. We compare our approach with the 'naïve' forecast often found in practice where future equity correlations among global markets are assumed to be stable and thus simply estimated from the most recent sample period. We also employ Engle's (2002) dynamic conditional correlation model to graphically illustrate the variations in equity market correlations in our sample. Reducing correlation forecast errors should then result in more appropriate portfolio weights and thus in higher Sharpe ratios. Our study greatly expands on the suggestions by Della Corte, Sarno, and Tsiakas (2012) that volatility and correlation timing is possible and clearly beneficial in international asset allocation.

We contribute to the current literature by linking economic fundamentals with correlations among international equity markets. A noteworthy aspect of this endeavor is that the posited link between foreign exchange volatility and equity correlations is built around existing well-established theoretical constructs. In other words, we do not need to introduce a new theoretical currency or economic model. Rather, we employ existing models, make simplifying assumptions, and show derivations that provide a theoretical justification for our empirically documented link between currency volatility and equity correlations. In this regard, we tackle three distinctive challenges. First, we link the monetary side of the economy with its real-side counterpart. Second, we link the monetary side of the economy to currency volatility, as well as the real side of the economy to volatility in the equity markets. Finally, we establish correlations among these two groups of volatilities.

Research relevant to the scope of this paper is seldom attempted. While exchange rates and equity markets are amply covered separately, they are rarely brought together in a joint framework. For instance, Evans' (2011) pioneering work relies exclusively on the dynamics of exchange rate. Equity markets simply do not fall within that area, so they are obviously not addressed. Evans' (2011) comprehensive work on exchange rate dynamics encompasses diverse modeling approaches such as macro models, microstructure models, micro-based macro models, and monetary models. The link between exchange rate volatility and equity correlations presented in our study originates from the assumption of a monetary-based exchange rate model drawn from Evans (2011), or more specifically, a Taylor rule-based model.

On equity markets, there is a significant number of contributions, but for the most part they are shy of exchange rates (e.g. Pukthuanthong and Roll 2009; Veronesi 1999; Cai, Chou, and Li 2009). Regarding the blending of the two together, one of the very few prior related studies that attempts to provide some theoretical explanation for increased equity correlations during economic downturns proposes to use an intertemporal rational expectations model (Veronesi 1999). Therein, uncertainty about the state of the global economy is attributed to higher international equity correlations during economic downturns (e.g. Veronesi 1999; Ribeiro and Veronesi 2002).

Under the assumption that uncertainty about the U.S. economy also implies uncertainty about the global economy, and that equity investors would require to be compensated for this increased risk, there is some theoretical evidence that international equity markets in countries whose economies are sensitive to the global business cycle would decline somewhat in unison during periods of high uncertainty, thus increasing correlation among equity markets. There is ample empirical evidence supporting this phenomenon during the 2008–2009 financial crisis (e.g. Bekaert et al. 2014; Briere, Chapelle, and Szafarz 2012; Samarakoon 2011). However, there are also some differing opinions on the matter. For instance, Forbes and Rigobon (2002) refute the notion of contagion during the 1997 Asian crisis and the U.S. stock market crash of 1987 by showing no increase in unconditional correlation coefficients during these periods. Instead, they argue that correlations are conditional on market volatility and that this 'interdependence' is always present, not only during periods of crises.

On the empirical side, we test our proposed link by examining the relation between option-implied volatility in foreign exchange markets and future international equity market correlations for nine countries and the euro zone-wide Euro STOXX 50 index. Our findings support our posited theory on the existence of a relation between option-implied exchange rate volatility and subsequent correlations among the equity markets. We exploit the dynamics of this relation to provide *ex-ante* forecasts of future correlations. Additionally, we compare the relation between foreign exchange volatility and equity correlations with that of equity volatility and equity correlations. These comparisons yield further insights into the factors that drive international equity correlations. Moreover, we evaluate the economic impact of our proposed model on the potential improvement of risk-adjusted returns in optimized portfolios. The observed performance enhancements are promising and economically significant.

Some intuition into our two seemingly unrelated concepts of correlations and exchange rates is necessary. Several studies such as Roll (1988) and Longin and Solnik (1995) have demonstrated that international markets tend to move together more when equity volatility is high. Longin and Solnik (2001) also find that such correlations are more specifically related to bearish market trends than to volatility directly. However, high volatility and declining markets tend to go hand in hand, as evidenced by a widely observed negative relation between the CBOE VIX (Chicago Board Options Exchange's established indicator of market volatility) and the S&P 500 index. The empirical evidence linking equity volatility – and/or the VIX as its proxy – to equity correlation is therefore compelling, but it lacks solid theoretical support. While volatility in the world's largest equity market and economy is likely to affect most equity markets and economies around the globe (see Parhizgari and Padungsaksawasdi 2021), the strength of its impact is likely to depend on the extent of bilateral trade and economic interdependence. The theory and to some extent the measurement of this impact, however, are inconclusive. For instance, the VIX does not capture any of these dynamics. Given that foreign exchange rates are a major factor in bilateral trade as argued by Forbes and Chinn (2004), we hypothesize that option-implied foreign exchange volatility can better reflect such dynamics between any given two countries and is thus a more effective, or at a minimum complementary, predictor of equity correlations than the VIX.

To the best of our knowledge, there is no consensus in the financial economics literature regarding the link between economic fundamentals and correlations among international equity markets. This is somewhat surprising given that there are several - although segmented - proposed theoretical economic models and empirical studies demonstrating a relation between equity correlations and economic indicators such as business cycles, inflation, and economic output (e.g. Erb, Harvey, and Viskanta 1994; Longin and Solnik 1995; Moskowitz 2003; Forbes and Chinn 2004; Graham, Kiviaho, and Nikkinen 2012; Cai, Chou, and Li 2009). There is also another vein of analyses cutting in the middle or completely departing from the mainstream. This group argues that such relation - if it exists - is either not significant enough or not stable over time (e.g. King, Sentana, and Wadhwani 1994; Ammer and Mei 1996; Kizys and Pierdzioch 2006). Considering these previous studies, the importance and relevance of establishing a rigorous testable theoretical link is therefore evident.

The novelty of our approach and its contribution to the current literature is better appraised through some comparisons with the pioneering studies of Forbes and Chinn (2004), Aslanidis and Casas (2013) and Bodart and Reding (1999). They consider, respectively, bilateral trade and portfolios of equities and currencies as a way to reach correlations. They thus provide, though partially, some isolated segments of the theory we seek to establish. While we find these studies helpful, there are a few other contributions that have not been much encouraging to this cause. For example, contrary to our findings that equity correlations are positively related to implied exchange rate volatility, Bodart and Reding (1999) find that 'an increase in exchange rate volatility is accompanied by a decline in international correlations between bond and, to a lesser extent, stock markets.' Obviously, there are important and clear distinctions between our study and Bodart and Reding's (1999).

Yet, the above example attests to the unsettled positions, both theoretically and empirically, on the topic we have chosen to address. Arguably, the Bodart and Reding (1999) study is mainly on bonds, void of any measures of currency volatilities, and limited to a comparison between countries within and outside the European Union Monetary System. Our study, on the other hand, examines how the equity correlation between a given pair of international equity markets is related to the volatility of the pertinent exchange rate for these two markets. Specifically, our analysis utilizes a daily market-driven measure of implied volatility for exchange rates vis-à-vis subsequent equity market correlations over the subsequent three months. Another study on equity correlations that failed to establish a link to foreign exchange shocks is by Karolyi and Stulz (1996). Analyzing overnight and intraday returns of a portfolio of Japanese ADRs and a matched sample of U.S. stocks, they find no measurable impact on their correlations due to shocks in the Yen/dollar exchange rate.

Considering the above points, it is evident that the breadth and scope of the prior contributions are highly diverse, that a clear consensus is lacking, and that a well-grounded and empirically tested approach to establish the link between currency volatilities and global equity correlations is warranted. This is, as stated earlier, the aim of this paper. The rest of this paper is organized as follows. Section 2 provides a review of theoretical framework,

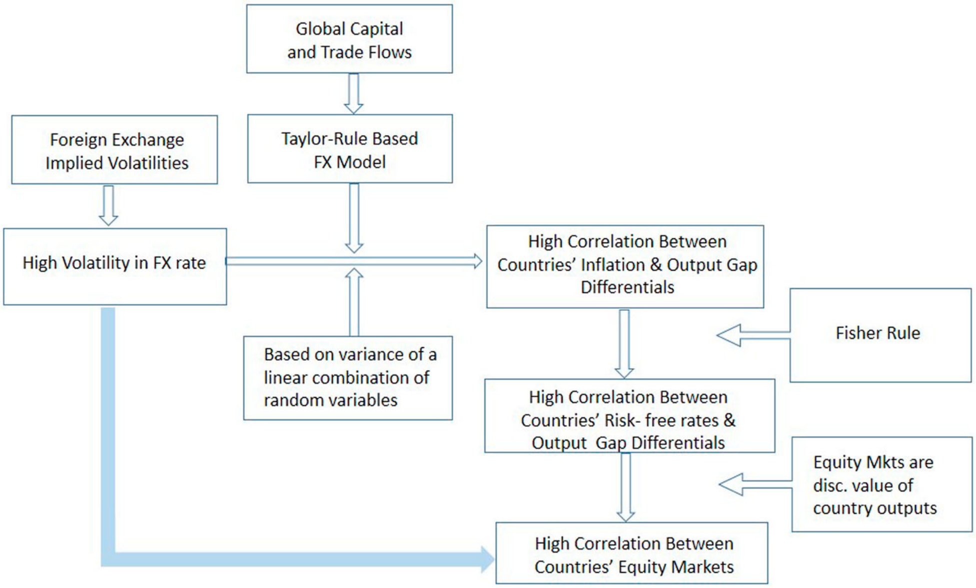

Figure 1. Link between foreign exchange volatility and equity correlation. This flow chart briefly depicts the potential links between foreign exchange rate volatility and equity correlation. It brings together a stochastic model of exchange rates, Taylor-rule-based market expectations of interest rates, and underlying assumptions related to widely accepted parity conditions (i.e. international Fisher rule). It also assumes that broad equity market values should reflect the discounted present value of future aggregate cash payouts and that these payouts are linearly related to each country's output (GDP).

Section 3 describes data, Section 4 discusses our empirical findings, Section 5 offers an application of our model in portfolio management and Section 6 offers concluding remarks.

2. The link between foreign exchange volatility and equity correlations

Given that there is no widely accepted theory linking exchange rate volatility to international equity market correlations, we first consider a few intuition-based relations that draw upon asset-pricing models and parity fundamentals. We then, using existing models and employing some simplifying assumptions, derive a generalized framework underpinned by theory and subsequently test it empirically. In brief, there are several moving parts in our explanations, as summarized in Figure 1. The key components include a stochastic model of exchange rates, Taylor-rule-based market expectations of interest rates, assumptions related to parity conditions, and the assumption that broad equity market values should reflect the discounted present value of future aggregate cash payouts, and that these payouts are linearly related to each country's output.[1]

For simplicity, we start with a two-market (country) two-currency situation. We denote the two countries by 'EUR' and 'US', with 'EUR' representing any country in the Euro zone. Under standard Black–Scholes distributional assumptions, the dollar/euro spot exchange rate follows:

$$S_t = S_0 \exp\{(r_{EUR} - r_{US})t - \sigma^2 t/2 + \sigma W_t\} \tag{1}$$

where S_t is the spot exchange rate at time t expressed in euros per dollar, $S_0$is the spot exchange rate at time *0*, r_{US} and r_{EUR} are the respective dollar-denominated and euro-denominated risk-free rates for the pertinent period from time *0* to time t, σ is the volatility of the exchange rate between time *0* and t, and W_t is a Wiener process. The above expression is the process forming the basis for currency option pricing under Black–Scholes.

On the surface, relation (1) is seemingly unrelated to the real side of the economy, i.e. to equity markets.[2] Upon further scrutiny, we will demonstrate that S_t or its volatility is indeed related to the real side of the global economy and thereby to the correlations among its components. To facilitate the derivations that follow, Figure 1 provides a schematic flowchart showing the steps in our approach from currency volatility to global equity correlations.

Starting with a Taylor-rule based model of real exchange rates and applying the basic concept of variance of a linear combination of random variables, we show that high foreign exchange volatility implies high correlation between the two pertinent countries' inflation and output gap differentials. This in turn implies that there is also a high correlation between these countries' risk-free rates and output gap differentials given the relation between inflation and interest rates based on the Fisher rule. Finally, assuming that broad equity markets are a discounted value of the aggregate countries' cash payouts to investors and that such cash payouts are related to the countries' outputs, we demonstrate that a high correlation between two countries' risk-free rates and output gap differentials also implies high equity market correlations.

The differential interest rate term $(r_{EUR} - r_{US})$ in equation (1) is the key element to our derivations. For spot exchange rate quotes at time t, we assume an equilibrium price based on a micro-based macro model for the dollar-euro spot rate that is a simplified version of the model proposed by Evans and Lyons (2008). The original model, along with several other exchange rate models, are described in detail in Evans (2011). Our simplified version of the model has the form:

$$S_t = \mathbb{E}_t S_{t+1} + (r_{EUR,t} - r_{US,t}) \tag{2}$$

where $\mathbb{E}_t$ denotes the expectation of the market based upon the information available at time t, r_{US} and r_{EUR} are as defined earlier and are now analogous to risk-free short-term dollar and euro rates for a given period. Expanding on equation (2), applying well established currency models and making some simplifying assumptions as detailed in Appendix A, we show that when the correlation between the inflation differential $[\pi_{EUR,t+1} - \pi_{US,t+1}]$ and the log output gaps $[y_{EUR,t} - y_{US,t}]$ is at or very close to 1, the inflation differential is a linear combination of the log output gaps and thus can be expressed as:

$$\pi_{EUR,t+1} - \pi_{US,t+1} = K_{1,t}[y_{EUR,t} - y_{US,t}] + K_{2,t} \tag{3}$$

where $K_{1,t}$ and $K_{2,t}$ are constants, and where $y_{US,t}$ and $y_{EUR,t}$ represent the difference between the log of real output and the log of output potential for the U.S. and the Euro zone, respectively.

Equation (3) also implies that

$$r_{EUR,t} - \mathrm{r}_{US,t} = K_{1,t}[y_{EUR,t} - y_{US,t}] + K_{2,t} \tag{4}$$

since the Fisher Effect holds that an increase (decrease) in the expected inflation rate in a country will cause a proportional increase (decrease) in the interest rate of that country. After a few steps shown in Appendix A Part 4, equation (4) can be expressed as:

$$K_{0,t} \frac{Y_{EUR,t}}{e^{r_{EUR,t}/K_{1,t}}} = \frac{Y_{US,t}}{e^{r_{US,t}/K_{1,t}}} \tag{5}$$

where $Y_{US,t}$ represents the real output for the U.S., $K_{0,t} = exp\left(\frac{K_{2,t}}{K_{1,t}}\right)$, and analogously $Y_{EUR,t}$ represents the real output for the Euro zone. Therefore, in the spot rate volatility maximization state, equation (3) states that the correlation between the inflation differential in the U.S. and the Euro zone and the output gap between the countries is maximized at 1. This also implies that the correlation between the discounted real output of the two countries is also maximized at 1 as shown in equation (5).

Over the long term, equity market efficiency withstands the challenges from return anomalies (see Fama 1998). Intuitively, cash flows generated by publicly listed firms and the discount rate applied to these cash flows by investors are major drivers of long-term equity market returns. It is also intuitive that aggregate equity cash flows in each country, as well as aggregate equity market capitalization, are likely related to GDP in each country. The ratio of stock market capitalization to GDP is viewed by some market practitioners as an informative indicator of overall equity market valuation. Critics argue that this measure ignores profits that firms earn abroad. In an interview with Fortune magazine in 2001, Warren Buffet counters that this 'ratio has certain limitations in telling you what you need to know. Still, it is probably the best single measure of where valuations stand at any given moment.' (Buffett and Loomis 2001). Furthermore, from 1975 to 2017, the ratio of stock market capitalization

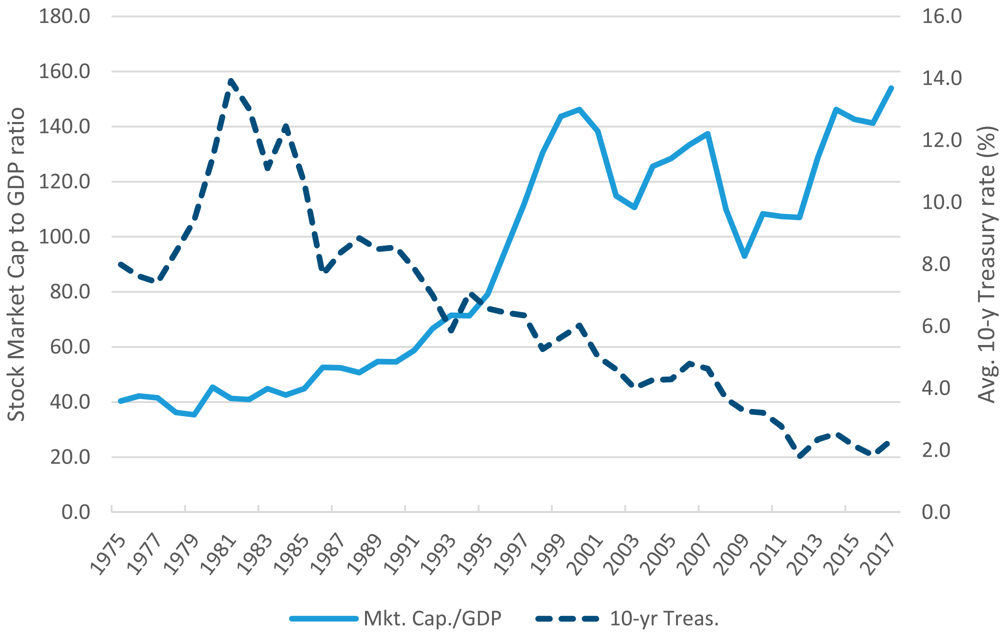

Figure 2. Historical Stock Market Capitalization to GDP ratio for the U.S. versus 10-year Treasury Constant Maturity Rate. This graph depicts the negative historical relation between stock market capitalization to GDP ratio for the United States and average annual 10-year Treasury constant maturity rates. For each graphed data series there are 43 annual data points ranging from 1975 to 2017. The left y-axis contains the annual stock market capitalization to GDP ratios while the right y-axis contains the average 10-year Treasury constant maturity rate. Stock Market Capitalization to GDP vs. 10-year Treasury Rate.

to GDP for the United States has exhibited a strong negative correlation of −0.82 with 10-year Treasury rates. Figure 2 graphically depicts this inverse relation. These empirics are consistent with the U.S. equity market being valued as discounted cash flows that are in turn strongly correlated with GDP. These are also consistent with the model proposed by Dumas, Harvey, and Ruiz (2003) that links changes in national outputs to correlations of stock returns.

Under the risk-neutral probability measure, the broad equity market value for the U.S., denoted as M_{US}, is given by:

$$\mathbb{E}_t M_{US,t} = \int_t^{\infty} e^{-r_{US}(\tau - t)} D_\tau \, d\tau \tag{6}$$

where D_τ represents an aggregate cash payout to investors that is linked to the country's output. The broad equity market value for the Euro zone is defined analogously. If the cash payout to investors in each country is a proportion of the real output of that country, we can then conclude that when the volatility of the spot rate between the two countries approaches a maximum, the correlation between the discounted market values for the two countries should also approach its maximum of 1. Assuming that all (currency, equity, and option) market participants have the same access to information regarding interest rates and the state of the macro economy, the theoretical framework laid out in this section provides a theoretical justification for the hypothesis that implied volatility in currency option prices is positively related to equity market correlations over the life of the option.

In light of our discussion in the preceding two paragraphs, equation (6) sets forth that the real side of a country's economy may be represented by the assets or the equity markets' side of that country. On this basis, the right-hand sides of relations (3) and (4) are thus related to equity markets. The left-hand sides of these two relations reflect inflation rate differential and interest rate differential, respectively. Equation (5) is the final step of these dynamic linkages, with derivations of equation (5) detailed in Appendix A Part 4.

We have shown so far that under some plausible assumptions there is a theoretical justification for equity correlations between two countries to be elevated when the volatility of the exchange rate between the two countries' currencies is high. Assuming that option-implied foreign exchange rate volatility is a good predictor of subsequent observed foreign exchange rate volatility, it should then follow that option-implied exchange rate volatility would be a contributing factor in the forecast of subsequent equity correlations. In addition to the economic indicators mentioned in the theoretical discussion above, the interdependence between option-implied exchange rate volatility and implied correlation of currency pairs (See Beer and Fink 2019) may also contribute to the eventual correlation between dollar-denominated equity markets. At the empirical level, further modifications and fine-tuning of the above relations become necessary; these are discussed in Section 4.

As mentioned earlier, the forecast of correlations is a key ingredient in the calculation of the optimal portfolio's weights. In the case of a global portfolio comprised of broad exposure to equity markets in various countries, we contend that the forecast of future correlations between any country pair would be more accurate if the pertinent option-implied exchange rate volatility were a factor in such forecast. Nonetheless, the theoretical justification we have put forth suggests that this is especially true when the exchange rate volatility is elevated. Taking into consideration previous studies' findings that demonstrate the relation between equity volatility and equity correlations (e.g. Longin and Solnik 2001; Connolly, Stivers, and Sun 2007; Cai, Chou, and Li 2009), our empirical work centers on evaluating the following relation:

$$CorrXY_{t,t+3} = \beta_0 + \beta_1 CorrXY_{t-3,t} + \beta_2 FXIV_t \times FX\_hi_t + \beta_3 Vix_t \times FX\_hi_t + \varepsilon_t \tag{7}$$

where $Corr\ XY_{t,t+3}$ corresponds to the pairwise correlation over the three-month ahead period starting at time t, $Corr\ XY_{t-3,t}$ represents the pairwise correlation over the three-month period preceding time t, $FXIV_t \times FX\ hi_t$ is the interaction between the continuous value of $FXIV_t$ (foreign exchange option-implied volatility at time t) and a dummy variable set to 1 (zero) to indicate a period of high (low) volatility, and $Vix_t \times FX\_hi_t$ is the interaction between the value of the VIX at time t and this same dummy variable. The threshold value used to set this dummy variable is based on historical patterns of volatility levels for the pertinent foreign exchange rate. The interaction of the continuous values of FXIV and VIX with the dummy variable $FX\ hi_t$ in our empirical model is consistent with our theory supported hypothesis that when FXIV is high, there is a positive relation between FXIV and equity correlations.

Empirically evaluating equation (7) is necessary to determine whether the inclusion of exchange rate volatility in the forecast yields any incremental benefits when equity volatility is also used as a factor and/or whether the two factors are jointly significant.

3. Data and sources

Our primary data range from January 1st, 1999 to May 31th, 2020, and include the daily values of eight foreign exchange rates, the S&P 500 index 30-day implied volatility VIX, the one-month, three-months, and one-year at-the-money foreign exchange rate option-implied volatilities, and finally the returns of nine international single-country equity indices and the STOXX index. The sample period's starting date coincides with the introduction of the euro currency. Bloomberg is the source for the daily values of the VIX index as well as the daily values of foreign exchange rates employed in our study.

The option-implied volatilities reflecting the market's expected future volatility of the respective currencies from the present (time t) to maturity for the eight exchange rates are also obtained directly from Bloomberg. Bloomberg provides daily values for option-implied foreign exchange volatilities at various maturities based on option prices and quotes. We employ options with three months to maturity. The foreign currencies used in our study are the Euro, the British Pound, the Japanese Yen, the Swiss Franc, the Canadian Dollar, the Australian Dollar, the Norwegian Krone, the Swedish Krone, and the New Zealand Dollar. To compute correlations among international equity markets in a common currency, we employ the Datastream U.S. dollar denominated daily values for the equity indices included in our study. In total, we examine the returns and pairwise correlations of 11 equity indices. The data for our study are at the daily frequency so we account for trade time synchronization when time zones differences are greater than six hours. For correlations between Asian (or Australian continent) (Japan, Australia and New Zealand) and non-Asian markets, the Asian (or Australian continent) market is lagged

Table 1. Summary statistics of the data.

	Obs	Mean	Max	Min	Std dev.	Skewness	Kurtosis
Panel A: Daily returns in foreign exchange rates. Mean and Std dev. are annualized.							
Canadian Dollar	5,585	−0.0071	0.033	−0.040	0.104	0.103	3.067
Australian Dollar	5,585	0.0054	0.083	−0.073	0.149	−0.363	9.501
British Pound	5,585	−0.0195	0.030	−0.084	0.110	−0.746	10.402
Euro	5,585	−0.0041	0.035	−0.025	0.116	0.047	1.599
Swiss Franc	5,585	−0.0232	0.091	−0.194	0.133	−3.553	113.252
Japanese Yen	5,585	−0.0035	0.055	−0.038	0.120	−0.040	4.060
Norwegian Krone	5,585	0.0165	0.073	−0.050	0.144	0.320	4.454
Swedish Krona	5,585	0.0104	0.042	−0.050	0.140	0.059	2.614
New Zealand Dollar	5,585	0.0103	0.043	−0.067	0.151	−0.311	2.837
Panel B: Daily values of annualized implied one-month ahead volatilities (in pct)							
Canadian Dollar	5,560	8.4115	26.945	3.643	3.093	2.275	7.930
Australian Dollar	5,586	11.1459	44.530	5.065	4.085	2.728	12.913
British Pound	5,586	8.9577	29.623	4.335	2.995	2.653	10.427
Euro	5,586	9.6564	28.885	3.773	3.099	1.266	3.745
Swiss Franc	5,586	9.8258	28.375	4.018	2.856	0.912	2.600
Japanese Yen	5,586	10.1338	38.420	3.923	3.199	1.670	6.241
Norwegian Krone	5,560	11.3468	36.190	5.698	3.435	1.909	6.109
Swedish Krona	5,586	11.2437	31.453	6.075	3.435	1.877	5.022
New Zealand Dollar	5,586	12.1416	40.348	5.553	3.854	2.031	7.330
Panel C: Daily values of S&P500's 30-day implied volatility – CBOE's VIX							
VIX	5,385	19.9782	82.690	9.140	8.832	2.197	7.728
Panel D: Rolling daily one-month realized volatility in FX rate returns – classical method.							
Canadian Dollar	5,565	9.5493	41.101	3.384	4.315	2.356	9.834
Australian Dollar	5,565	13.2681	86.038	4.657	6.761	4.517	34.157
British Pound	5,565	10.2116	43.814	3.012	4.112	3.154	16.544
Euro	5,565	10.9207	30.098	3.201	3.823	0.873	1.541
Swiss Franc	5,565	11.7881	85.750	3.306	6.380	6.348	63.493
Japanese Yen	5,565	11.1973	38.140	3.793	4.448	1.473	4.424
Norwegian Krone	5,565	13.3321	53.394	4.297	5.411	2.561	11.164
Swedish Krona	5,565	13.1517	41.159	4.047	5.033	2.082	6.356
New Zealand Dollar	5,565	14.0955	56.429	5.444	5.531	2.252	9.595
Panel E: Rolling daily one-month realized volatility in FX rate returns – Garman-Klass.							
Canadian Dollar	5,565	9.2406	33.325	3.851	3.757	2.021	6.762
Australian Dollar	5,565	12.8931	63.880	5.907	5.671	3.510	19.742
British Pound	5,565	9.9336	36.853	3.852	3.781	2.960	12.123
Euro	5,565	10.5807	29.312	3.621	3.448	1.141	2.943
Swiss Franc	5,565	11.2439	37.841	3.987	3.639	1.659	7.225
Japanese Yen	5,565	10.8219	33.864	3.885	3.627	1.409	4.302
Norwegian Krone	5,565	13.4004	56.700	5.822	5.057	3.118	15.528
Swedish Krona	5,565	13.0690	38.126	6.325	4.583	2.279	7.095
New Zealand Dollar	5,565	14.2063	52.349	6.576	5.161	2.435	9.867

This table reports summary statistics on daily percentage returns in foreign exchange rates, annualized implied one-month ahead volatilities, rolling daily values of one-month-ahead volatilities calculated under the classical method found in equation (14), and rolling daily values of one-month-ahead volatilities calculated under the Garman-Klass estimator described in equation (15).

one day to account for time zone differences. The German equity market and the STOXX index in our sample are markets where the Euro is the official currency. The other seven equity markets correspond to markets wherein each of the other foreign currencies in our sample is the official currency. The U.S. is the benchmark market in our sample used for the correlations' calculations. Specifically, we use the main equity index in the United States (S&P 500), Canada (S&P/TSX composite), United Kingdom (FTSE 100), Australia (S&P/ASX 300), Germany (DAX 30), Switzerland (SMI), Japan (NIKKEI 225), New Zealand (NZX 50), Sweden (OMX 30) and Norway (OBX) as proxies for the broad equity markets in these countries. We also obtain historical 10-year U.S. Treasury rates and stock market capitalization to GDP ratios from the Federal Reserve Bank of St. Louis.

Summary statistics of the data are provided in Table 1. The details of computations on currency volatilities are in section 4.1.

4. Empirical applications and results

At the empirical level, applications of relations (2) through (6) in conjunction with relation (1) require some computations and substitutions and include the following steps:

1. Identifying currency volatility measures
2. Providing some preliminary empirics on contemporaneous relations between the major variables
3. Linking implied volatility with a forecast of the one-period ahead realized volatility
4. Measuring equity correlations
5. Linking currency volatilities of steps 1 and 3 with equity correlations of step 4 via an autoregressive error correction model[3] (See Appendix B for details).

Obviously, steps 1 through 5 above do not automatically correspond to the relations expressed in (2) through (6). This 'seemingly unrelated' reference will be clarified as we move through each step and as we identify and assign various components to their underlying variables in relations (2) through (6).

4.1. Identification of currency volatility measures

As implied volatility measures, we consider Bloomberg's exchange rate option-implied volatility for one month, three months, and one year. Realized exchange rate volatility is calculated via two approaches: variance of exchange rates over a given period (classical method), and by applying the Garman and Klass (1980) methodology. The former is given by:

$$\widehat{\sigma_{S_t}}^2 = \frac{1}{N-1}\sum_{t=1}^{N}(FX\_RET_t - \overline{FX\_RET})^2 \tag{8}$$

where FX_RET_t represents the daily change in the foreign exchange rate on day t calculated using first differences, and $\overline{FX\_RET}$ is the mean foreign exchange daily change over the measured period. The standard deviation is simply the square root of the calculated variance. We then annualize the daily standard deviation by multiplying it by the square root of 365. We perform this calculation for each of the eight foreign exchange rates used in our study and over each day in our data sample, measuring realized volatility over one-, three-, and twelve-months ahead rolling periods.

In the second method, following Garman and Klass (1980), we use open, close, high, and low daily values to measure volatility of ΔS_t. It is shown that this measure is about eight times more efficient than a simpler measure that uses close-to-close daily values.[4] Specifically, we employ the reduced-form estimator that yields virtually the same level of efficiency as the full-form estimator. The difference is that the reduced-form estimator specification has marginally different coefficients and excludes cross-product terms. Under this methodology, we calculate realized volatility levels as the average of the daily volatilities during the period, with the volatility on a given day t being:

$$\hat{\sigma}_{S_t}^2 = \frac{1}{2}[\ln(High) - \ln(Low)]^2 - [2\ln 2 - 1][\ln(Open) - \ln(Close)]^2 \tag{9}$$

where *High, Low, Open*, and *Close* represent the daily high, low, open, and close of foreign exchange rates. We perform this calculation for each of the eight foreign exchange rates and for each day in our sample, measuring realized volatility over rolling periods of one-, three-, and twelve-months ahead. Table 1 reports the summary statistics for the currencies' volatility levels and the VIX.

4.2. Preliminary empirics: contemporaneous relation between currency volatility and equity correlation

While our ultimate goal is to examine the relation between forward-looking option-implied foreign exchange volatility and subsequent (i.e. future) equity correlation, we first examine a simple theoretical position on the 'contemporaneous' link between realized foreign exchange volatility and equity correlations. For consistency, we evaluate a specification similar to relation (7), except that option-implied foreign exchange volatility and the VIX are now replaced with contemporaneous realized volatility. As in relation (7), the most recently observed three-month correlation around t -period is employed. Specifically, we estimate:

$$CorrXY_{t,t+3} = \beta_0 + \beta_1 CorrXY_{t-3,t} + \beta_2 RelVol_t + \varepsilon_t \tag{10}$$

where $Corr\ XY_{t,t+3}$ corresponds to the pairwise correlation over the three-month ahead period starting at time t, $Corr\ XY_{t-3,t}$ represents the pairwise correlation over the three-month period preceding time t, and $Rel\ Vol_t$ is the pertinent contemporaneous 'realized' foreign exchange volatility over the t to $t+3$ period.

We compute two measures of FX volatility: classical and Garman-Klass. We estimate relation (10) a total of 20 times, using three-month correlations between the U.S. S&P 500 and ten other equity indices (nine countries plus STOXX), and the above two FX volatility measures. The equity correlations are measured between daily S&P 500 returns and U.S. dollar returns on other indices. In the first ten estimations, foreign exchange volatility is the contemporaneous realized foreign exchange volatility, measured according to the classical method, during the same three-month period over which the dependent variable correlation is measured. The results of these ten estimations are reported in Panel A of Table 2. In the second ten estimations, reported in Panel B of Table 2, the currency volatility is being measured according to the Garman-Klass method.

In Panel A, the coefficients for $RelVol_t$ are statistically significant for all currency/country pairs, except for the CFH/Swiss market, JPY/Nikkei and EUR/STOXX pairs. In Panel B, where the realized volatility is measured according to Garman-Klass, the coefficient for AUD/ASX 200 is also not statistically significant. These statistically significant empirical results confirm the relation between contemporaneous realized foreign exchange volatility and equity correlations posited under the theoretical framework laid out in Section 2 for more than half of the currency/equity index pairs in our sample. Note that the simple check evaluated is an unconditional relation while the theoretical framework calls for the relation when the foreign exchange implied volatility is high.

4.3. Linking FX option-implied volatility to a forecast of a one-period ahead FX realized volatility

Using the above computed measures of realized volatility, we examine the efficacy of Bloomberg's option-implied foreign exchange rate volatility measures[5] as a forecast of actual currency volatilities. We adopt two approaches and expand this analysis to evaluate the forecasts for one-, three-, and twelve-month horizons using both afore-calculated volatility measures.

In a first approach, we compute Pearson correlation coefficients for each option-implied volatility and subsequent realized volatility pair. The results are reported in Table 3. The correlation coefficients are higher for shorter horizon forecasts and for the Garman-Klass volatility measures. These observations are consistent with the fact that options on major currencies and of shorter maturities tend to exhibit greater liquidity.

In a second approach, we regress each of the two computed realized volatilities for each currency on its option-implied volatility to examine how much of the variation in the realized volatilities is explained by the option-implied volatility. Given that the scales and the underlying computational methods of these volatilities are not the same, and following Jorion's (1995) suggestion,[6] we standardize the volatility series into Z-scores with mean zero and standard deviation of one. We report the results of the regressions in Panels A and B of Table 4. With no exceptions, all the intercepts are not statistically different from zero, confirming our expectation; additionally, all the estimated volatility coefficients are highly statistically significant (all at the one percent or below), though they are not necessarily equal to one. While these results suggest that option-implied volatility is by no means a perfect forecast of subsequent realized volatility, the large R-squared values and the highly statistically significant coefficients of the FX option-implied volatility variables in 'all' cases, coupled with the fact that most of the estimates are not too far away from 1, suggest that FX option-implied volatility explains a lot of the variations in subsequent FX realized volatility measures.

Table 2. Test of the contemporaneous relation between international equity market correlations and two measures of realized foreign exchange volatilities (1 of 2).

Currency/Country Index	Intercept	Lag CorrXY	Foreign exchange Vol	Adj. Rsq	Obs.
Panel A: Contemporaneous realized foreign exchange volatility measured using the classical method					
EUR/Ger	0.2285***	0.4804***	8.6532*	0.2525	254
	(5.77)	(8.95)	(1.88)		
GBP/UK	0.1582***	0.5261***	13.4359***	0.3214	254
	(4.57)	(10.21)	(2.96)		
CHF/Swz	0.2449***	0.4362***	−2.4938	0.1896	254
	(7.45)	(7.54)	(−0.77)		
CAD/Can	0.2655***	0.5000***	10.3439***	0.2705	253
	(6.62)	(9.06)	(2.60)		
AUD/Aus	0.3610***	0.0860	6.0665**	0.0270	254
	(10.30)	(1.26)	(2.00)		
JPY/Jap	0.3164***	0.2789***	−1.2348	0.0801	254
	(7.96)	(4.60)	(−0.27)		
EUR/STOXX	0.2615***	0.4743***	2.7661	0.2318	254
	(6.26)	(8.65)	(0.59)		
SEK/Swe	0.1449***	0.4935***	12.6340***	0.3034	254
	(4.18)	(9.49)	(3.33)		
NOK/Nor	0.0398	0.5682***	16.9115***	0.4083	253
	(1.24)	(11.55)	(4.30)		
NZD/Nzd	0.0822**	0.1475***	26.1140***	0.2227	231
	(2.56)	(2.26)	(5.98)		
Panel B: Contemporaneous realized foreign exchange volatility measured using the Garman-Klass method					
EUR/Ger	0.2113***	0.4783***	12.3408***	0.2603	254
	(5.31)	(8.96)	(2.48)		
GBP/UK	0.1656***	0.5214***	13.1050***	0.3183	254
	(4.86)	(10.06)	(2.75)		
CHF/Swz	0.2131***	0.4387***	2.5560	0.2506	254
	(4.97)	(7.58)	(0.44)		
CAD/Can.	0.2771***	0.5035***	7.9814**	0.2598	253
	(6.70)	(9.06)	(1.76)		
AUS/Aus.	0.3693***	0.0983	4.3177	0.0167	254
	(9.98)	(1.44)	(1.16)		
JPY/Jap	0.3029***	0.2809***	0.9469	0.0799	254
	(5.85)	(2.85)	(2.94)		
EUR/STOXX	0.2418***	0.4762***	6.2749	0.2355	254
	(5.76)	(8.72)	(1.24)		
SEK/Swe	0.1430***	0.4882***	13.5580***	0.3041	254
	(4.10)	(9.36)	(3.37)		
NOK/Nor	0.0289	0.5574***	19.2601***	0.4131	253
	(0.88)	(11.30)	(4.55)		
NZD/Nzd	0.0768**	0.1511**	26.9467***	0.2168	231
	(2.31)	(2.31)	(5.82)		

This Table reports regressions results of three-month correlations between the U.S. S&P 500 and ten other equity indices nine countries plus STOXX0. Correlations are measured between daily S&P 500 returns and U.S. dollar returns for other indices. The variable *Lag CorrXY* is the most recent three-month correlation up until observation day. *Foreign exchange Vol* is the contemporaneous realized foreign exchange volatility during the same three-month period over which the dependent variable correlation is measured. Panel A contains the results for all currency/country pairs where the realized volatility is measured according to the classical method. Panel B contains the results with the currency volatility measured according to the Garman-Klass method. The numbers reported below the coefficient estimates are *t-statistics*. The asterisks *, **, and *** indicate statistical significance at the 10%, 5%, and 1% level, respectively. The full sample period includes monthly observations from Jan 1, 1999 to May 30, 2020. For some currencies, such as the New Zealand dollar, foreign exchange rate option-implied volatility is not available for the entire sample period.

4.4. Measuring equity correlations

This sub-section focuses on the correlation between the real sides of two economies. First, we have already shown that the real side of a country's economy may be represented by the assets or the equity markets' side of that country (see Section 2, relation (6) and related discussion). Second, to address the notion that correlations increase in times of higher volatility, we designate September 2008 to August 2009 as the most notable period

Table 3. Pearson correlation between foreign exchange option-implied volatilities and subsequent FX realized volatilities.

	Classical Method			Garman-Klass Method		
	1-mo	3-mo	1-year	1-mo	3-mo	1-year
Canadian Dollar	0.798***	0.712***	0.626***	0.871***	0.783***	0.642***
Australian Dollar	0.756***	0.587***	0.364***	0.819***	0.674***	0.432***
British Pound	0.748***	0.681***	0.368***	0.841***	0.760***	0.479***
Euro	0.799***	0.763***	0.499***	0.864***	0.799***	0.544***
Swiss Franc	0.504***	0.467***	0.197***	0.763***	0.755***	0.493***
Japanese Yen	0.656***	0.558***	0.279***	0.763***	0.684***	0.376***
Swedish Krona	0.788***	0.754***	0.550***	0.855***	0.780***	0.581***
Norwegian Krone	0.713***	0.620***	0.433***	0.763***	0.676***	0.493***
New Zealand Dollar	0.767***	0.673***	0.451***	0.804***	0.691***	0.461***

This table contains the Pearson correlation coefficients between Bloomberg foreign exchange rate implied volatilities and the subsequent FX realized volatilities. Results are tabulated for one-month, three-month, and one-year option-implied foreign exchange volatilities. The pertinent FX realized volatilities are calculated using both the classical and the Glass-Karman methodologies. All Pearson correlation coefficients are statistically significant at the 1% confidence level ($= ***$).

of high volatility and focus on it as a separate period. Then, we calculate unconditional correlations among the 11 equity markets for both the full sample and the shorter period of crisis. The results are reported in Table 5. A number of fine issues arise when contemporaneous and lagged data across the globe are employed (see, for example, Jaffe and Westerfield 1985 and Sandoval 2014). For instance, Australia is about two hours ahead of Japan during the northern hemisphere summer. During the winter, Australia is ahead an *additional* two hours because the northern hemisphere falls back an hour in October, while Australia springs ahead an hour. Therefore, there are some changes in the overlapping and opening hours of the U.S. S&P 500 markets and the Australian and New Zealand equity markets.[7]

Economic ties appear to be an important factor in determining the correlation among equity markets. For example, Panel A in Table 5 shows that the U.K.'s equity market correlation coefficient with other European markets range from 0.74–0.87 versus 0.23–0.66 for non-European markets in our sample universe. Another notable fact is the across-the-board significant increase in correlations during the 2008–2009 crisis period. For instance, over the entire sample period the correlation coefficients for Japan's equity market with any other market in our sample universe range from 0.27–0.49. During the crisis period (Panel B) the corresponding range is from 0.42–0.66. Correlation coefficients among the European equity markets during the crisis period reported in Panel B of Table 5 rise to as high as 0.97 reflecting their strong economic ties.

To better illustrate how correlations among equity markets in our sample universe vary through time, we also use Engle's (2002) dynamic conditional correlation (DCC) model. A graphical representation of changes in correlation over time for three select country equity market pairs (US-Germany, US-UK, and US-Japan) are displayed in Figure 3.

Additionally, considering the monetary components of relations (3) and (5), we categorize the equity markets based on the volatility of the currency markets. Focusing on the historical option-implied foreign exchange volatilities of three major currencies (Euro, British Pound, and Swiss Franc), we divide the equity sample into three sub-periods of low, medium, and high implied foreign exchange volatility. Equity market correlations are then calculated separately for each of these three sub-periods and are summarized in Table 6, Panel A. Corresponding currency option-implied volatility variations are included in Panel B of this Table. The average volatility for the Euro in each category is similar to that of the Swiss Franc and generally higher than the volatility of the British Pound.

The DCCs reported in Figure 3 provide a more continuous graphical representation of the variations in correlations reported in Panel A of Table 6. For Panel B of Table 6, we provide Figure 4 that graphically depicts FX option-implied volatilities over time for Euro, British Pound, and Swiss Franc. Taking Swiss Franc as an example, it is not surprising to observe similarities between this currency volatility and the other two currencies. This attests to the economic interdependence between Switzerland and the Euro zone. In fact, the Swiss National Bank pegged the Swiss Franc for a period of about three years. The surprise abolishment of this peg on January

Table 4. Test of the relation between three-month foreign-exchange option-implied volatility and subsequent FX realized volatility (1 of 2).

Currency	Intercept	FX Implied Volatility	Adj. Rsq	Obs
Panel A: Regression of realized volatility (classical method) on FX implied volatility				
CAD:	0.0033	0.7131***	0.507	5,495
	(0.34810)	(72.20)		
AUD:	−904E-18	0.5665***	0.344	5,521
	(−83E-15)	(53.80)		
GBP:	−297E-17	0.6812***	0.464	5,521
	(−302E-15)	(69.12)		
EUR:	1.52E-14	0.7635***	0.583	5,521
	(1.75E-12)	(87.83)		
CHF:	5.6E-15	0.4674***	0.218	5,521
	(4.71E-13)	(39.27)		
JPY:	9.37E-15	0.5584***	0.312	5,521
	(8.39E-13)	(50.00)		
SEK:	−256E-17	0.7540***	0.569	5,521
	(−29E-14)	(85.28)		
NOK:	0.004082	0.6181***	0.381	5,493
	(0.384246)	(58.19)		
NZD:	−157E-17	0.6726***	0.452	5,521
	(−157E-15)	(67.52)		
Panel B: Regression of realized volatility (Garman-Klass) on FX implied volatility				
CAD:	0.004288	0.7835***	0.613	5,495
	(0.510912)	(93.34)		
AUD:	−399E-17	0.6742***	0.455	5,521
	(−401E-15)	(67.82)		
GBP:	2.26E-17	0.7601***	0.578	5,521
	(2.59E-15)	(86.91)		
EUR:	1.32E-15	0.7987***	0.638	5,521
	(1.63E-13)	(96.62)		
CHF:	4.93E-15	0.7547***	0.570	5,521
	(5.59E-13)	(85.46)		
JPY:	−212E-17	0.6844***	0.468	5,521
	(−216E-15)	(69.73)		
SEK:	2.55E-15	0.7799***	0.608	5,521
	(3.03E-13)	(95.56)		
NOK:	0.000221	0.6781***	0.457	5,493
	(0.022147)	(68.05)		
NZD:	6.14E-15	0.6914***	0.478	5,521
	(6.32E-13)	(71.09)		

This Table reports the results of regressions to evaluate the validity of option-implied volatility to forecast subsequent three-month realized volatility in foreign exchange markets. Panel A is based on FX realized volatility calculated according to the classical method. Panel B is based on Garman-Klass volatility measure. The numbers reported below the coefficient estimates are *t-statistics*. The asterisks *, **, and *** indicate statistical significance at the 10%, 5%, and 1% level, respectively. The full sample period includes monthly observations from Jan 1, 1999 to May 30, 2020.

15, 2015, resulted in a temporary spike in the Swiss Franc option-implied volatility, clearly visible on the graph in Figure 4.

4.5. Linking currency option-implied volatilities to equity correlations

This step brings together and sets side by side the components that are so far separately computed by linking currency volatilities of steps 1 and 3 (see top of this section) with equity correlations of step 4 via an autoregressive error correction model. Expressed differently, the implied measures of, or the substitutes for, the underlying concepts of both sides of relations (3), or (4) or (5), are now ready for further empirical analysis.

As discussed at the end of Section 2, using monthly data we estimate relation (7), repeated here for convenience, and relabeled relation (11). Each period t refers to a one-month period, thus the dependent variable in

Table 5. International equity markets correlations (entire and volatile periods).

	US	CAN	SWZ	GER	UK	STOX	NOR	SWE	JAP	AUS	NZD
Panel A – Unconditional correlations over the full-sample period											
US	1.00										
CAN	0.70	1.00									
SWZ	0.45	0.56	1.00								
GER	0.57	0.62	0.79	1.00							
UK	0.52	0.66	0.79	0.82	1.00						
STOX	0.55	0.64	0.82	0.95	0.87	1.00					
NOR	0.42	0.63	0.67	0.69	0.74	0.74	1.00				
SWE	0.49	0.61	0.75	0.81	0.79	0.85	0.74	1.00			
JAP	0.43	0.36	0.29	0.36	0.33	0.36	0.27	0.32	1.00		
AUS	0.46	0.37	0.24	0.29	0.26	0.28	0.22	0.25	0.49	1.00	
NZD	0.44	0.35	0.21	0.25	0.23	0.24	0.19	0.22	0.38	0.72	1.00
Panel B – Correlations during the high foreign-exchange rate volatility period of September 2008 to August 2009											
	US	CAN	SWZ	GER	UK	STOX	NOR	SWE	JAP	AUS	NZD
US	1.00										
CAN	0.75	1.00									
SWZ	0.51	0.68	1.00								
GER	0.62	0.72	0.85	1.00							
UK	0.56	0.74	0.87	0.88	1.00						
STOX	0.59	0.74	0.90	0.97	0.94	1.00					
NOR	0.52	0.74	0.79	0.85	0.86	0.87	1.00				
SWE	0.54	0.69	0.82	0.89	0.85	0.91	0.86	1.00			
JAP	0.63	0.54	0.52	0.54	0.52	0.53	0.42	0.47	1.00		
AUS	0.62	0.42	0.27	0.31	0.26	0.27	0.24	0.26	0.66	1.00	
NZD	0.68	0.47	0.28	0.35	0.29	0.31	0.26	0.29	0.60	0.86	1.00

This table reports the unconditional correlations between various international equity markets using U.S. dollar daily returns over the full sample period ranging from January 1999 to May 2020 and over the shorter crisis period ranging from September 2008 to August 2009. For correlations between Asian (Japan, Australia, and New Zealand) and non-Asian markets, the Asian market is lagged one day to account for time zone differences.

relation (11) represents the correlation of variables X and Y over three months starting at time t. The other variables are as described in Section 2. Based on historical ranges for foreign exchange implied volatility discussed in section 4.4, $FXIV_t \times FX\_hi_t$ in the evaluation of relation (11) is computed as the interaction of $FXIV_t$ (foreign exchange option-implied volatility at time t) and a dummy set to 1 when the foreign exchange implied volatility is greater than its historical median rounded to the nearest 0.5% and set to 0 otherwise. Similarly, the $Vix_t \times FX_hi_t$variable is also computed as the interaction of the VIX value with this same dummy variable.

The autoregressive error correction methodology we employ is a modified OLS by which the autocorrelation of the errors is accounted for via an autoregressive model (See appendix B)[8]: This is the same as relation (7), merely replicated below for convenience:

$$CorrXY_{t,t+3} = \beta_0 + \beta_1 CorrXY_{t-3,t} + \beta_2 FXIV_t \times FX\_hi_t + \beta_3 Vix_t \times FX\_hi_t + \varepsilon_t \tag{11}$$

Specifically, we estimate two variations of equation (11): the model as depicted in relation (11), and an estimation with $FXIV \times Vix_t \times FX_hi_t$as an interaction variable replacing the two independent variables $FXIV_t \times FX\_hi_t$ and $Vix_t \times FX\_hi_t$. Namely, we also estimate the following equation:

$$CorrXY_{t,t+3} = \beta_0 + \beta_1 CorrXY_{t-3,t} + \beta_2 FXIV_t \times Vix_t \times FX\_hi_t + \varepsilon_t \tag{12}$$

The reason for creating this interaction variable is to capture the combined option-implied volatility level for both foreign exchange rates and the U.S. equity market via the VIX measure. A priori, we would expect the two variables $FXIV_t \times FX\_hi_t$ and $Vix_t \times FX\_hi_t$.in relation (11) to be highly correlated, leading us to focus mostly on their joint versus individual statistical significance.

The evaluation of relation (11) requires, in addition to vectors of recently observed equity correlations, construction of two vectors to capture the 'intensity' of the market, i.e. when the FXIV for each country pair is above its historical median. This is captured by a dummy variable and is labeled as FX_hi_t in relation (11). This dummy

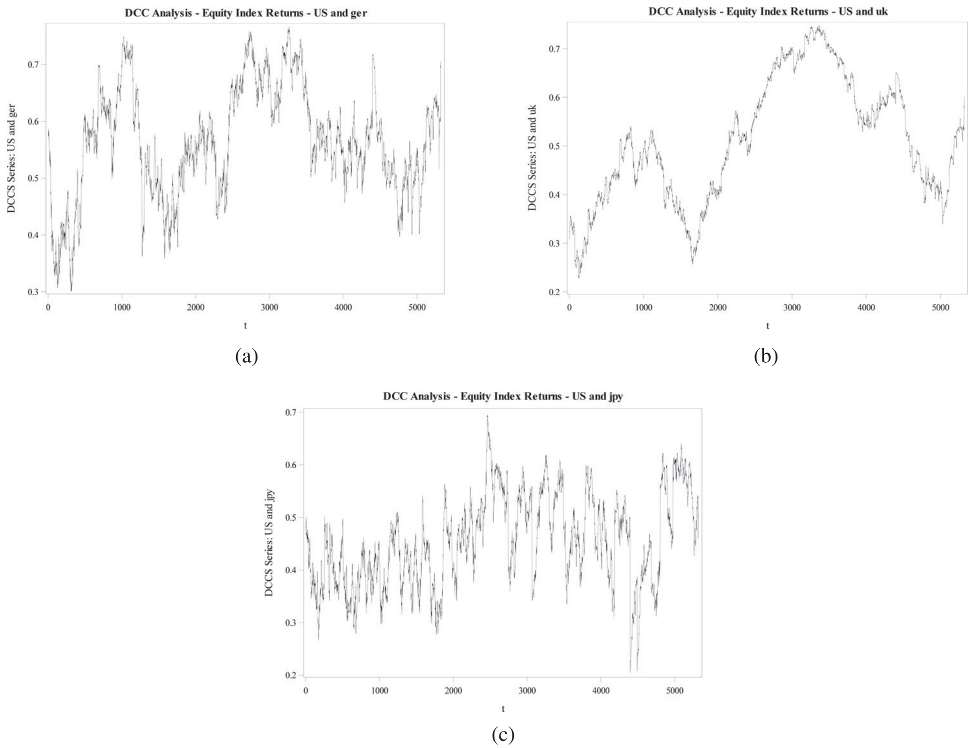

Figure 3. DCC analysis of three select equity market pairs.

variable is set to interact with the *actual* amounts of both FXIV and VIX. Thus all variables, except the FX_hi_t in relation (11) are in continuous actual values. This specification is consistent with the notion that when FXIV is elevated, its value, along with that of the VIX, yield significant insights into subsequent equity correlations. When FXIV is low, the most recently observed equity correlation may override the effect of low FXIV and yield sufficient insight into subsequent equity correlations.

Since the two interaction variables in relation (11) indicate intense (= high volatility) market conditions, multicollinearity between them is induced by design and is likely to be present. If so, it could be argued that one of them should be dropped from the relation. Since FXIV is the variable of interest in this paper, obviously it cannot be dropped. VIX on the other hand can be dropped, but there is a loss of information if it is excluded. VIX, by all measures, is a powerful and highly established explanatory variable of the equity exchanges. It captures considerably more effects than a focused variable such as FXIV.[9] So, if VIX is dropped, there is a significant loss in the predictability of the equity markets. We, therefore, have opted to include both variables while accounting differently for the unwanted multicollinearity between them. We posit that it is imperative to focus on the joint significance of these two variables, rather than on the significance and/or sign of the coefficient for each of them. This practice takes care of the competition between these two variables, and thereby the multicollinearity between them. We also calculate the forecast errors for each estimation versus a naïve model for estimating equity correlation based solely on the most recently observed correlation, a common practice in portfolio management. See Panel C in Table 7. Since global equity market correlations tend to be somewhat stable, such naïve model can yield adequately accurate estimates. The goal is to verify whether our proposed model measurably improves upon this forecast accuracy.

In all the above experiments, the foreign exchange option-implied volatility is for the three-month horizon. As noted earlier in Section 4.3, we consider one-month, three-month, and twelve-month option-implied volatilities in our analysis. Although foreign exchange option-implied volatility is a more accurate predictor of actual volatility for shorter maturity options, calculation of cross-country one-month correlations using daily data is

Table 6. Country pair equity correlations and foreign exchange implied volatilities during periods of low, medium, and high volatility levels.

Panel A: Equity market correlations during periods of high, medium, and low FX volatility

	Country Pair Broad Equity Market Correlation		
	GER-US	UK-US	SWI-US
FX Implied Volatility Level			
Low	0.49	0.44	0.40
Medium	0.51	0.47	0.37
High	0.59	0.62	0.42

Panel B: Average FX implied volatility during periods of high, medium, and low FX volatility

	Avg. Foreign Exchange Volatility		
	EUR-USD	GBP-USD	CHF-USD
FX Implied Volatility Level			
Low	7.85	8.07	8.15
Medium	10.49	8.94	10.95
High	13.74	11.98	13.03

This table reports the averages of three-month foreign exchange implied volatilities for three pairs of European currencies (equity and FX). The sample period is from January 1999 through May 2020. Low implied foreign exchange volatility level includes sub-periods of Feb 2005 – Nov 2007 and Sept 2012 – Feb 2020. High implied foreign exchange volatility level includes sup-periods of Aug 2000 – Sept 2001, Sept 2008 – Aug 2009, May 2010 – Jan 2012, and Mar-2020 – Apr 2020. All other sub-periods are considered to display medium levels of implied foreign exchange volatility. EUR, USD, GBP, and CHF refer to Euro, US dollar, British Pound, and Swiss Franc, respectively.

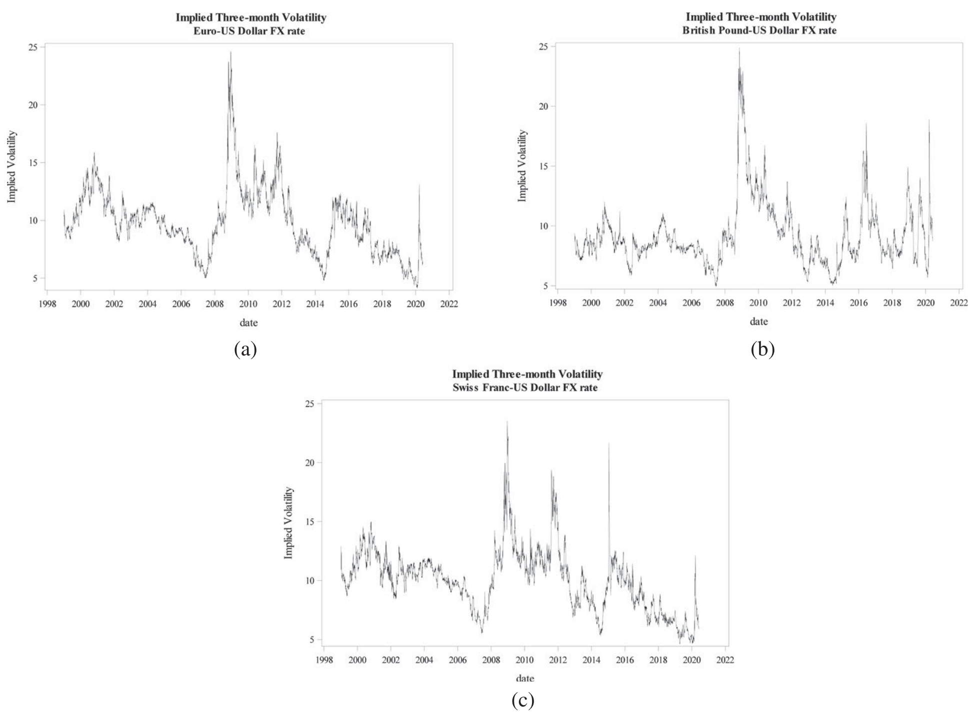

Figure 4. Three-month implied volatility of European currencies.

not always practical within our data set due to the low number of observations.[10] Thus, we use the next shorter horizon (three months) in our regression analysis. We recognize that there is a slight horizon mismatch with the VIX volatility measure as it captures the option-implied volatility of the S&P500 over the next thirty days, not the next three months. Although our scope and measurements pertain to a 3-month horizon, the benefit of

Table 7. Test of the relation between future equity market correlations and foreign exchange option-implied volatilities.

	EUR/		GBP/	CHF/	CAD/	AUD/	JPY/	SEK/	NOK/	NZD/
	GER	STOXX	UK	SWZ	CAN	AUS	JAP	SWE	NOR	NZD
Panel A: Model: $CorrXY_{t,t+3} = \beta_0 + \beta_1 CorrXY_{t-3,t} + \beta_2 FXIV_t \times FX\_hi_t + \beta_3 Vix_t \times FX\_hi_t + \varepsilon_t$										
Intercept	0.2812***	0.2733***	0.2257***	0.2275***	0.3520***	0.0619***	0.3231**	0.2197***	0.1486***	0.0166
	(9.71)	(9.30)	(8.72)	(8.60)	(9.61)	(4.28)	(11.19)	(8.71)	(7.38)	(1.11)
$Corr\ XY_{t-3,t}$	0.4305***	0.4549***	0.5027***	0.4187***	0.4609***	0.5124***	0.2364**	0.4754***	0.5422***	0.5050***
	(7.89)	(8.36)	(9.43)	(7.24)	(8.23)	(8.70)	(3.81)	(8.74)	(10.06)	(8.98)
$FXIV_t \times FX\_hi_t$	−0.0037	−0.0051	0.00014	−0.0076*	−0.020***	0.0106***	−0.0099**	0.0037	0.0083	0.0026
	(−0.88)	(−1.17)	(0.03)	(−1.68)	(−3.90)	(2.16)	(−2.27)	(0.84)	(1.50)	(0.58)
$Vix_t \times FX\_hi_t$	0.0040	0.0039*	0.0018	0.0046**	0.0093***	−0.0040**	0.0057***	−0.00015	−0.0025	0.0025
	(1.96)	(1.87)	(0.88)	(2.16)	(3.87)	(−1.47)	(2.66)	(−0.06)	(−0.81)	(0.98)
R-square	0.2809	0.2528	0.3172	0.2059	0.2946	0.3289	0.1078	0.2921	0.3834	0.4128
Obs./DFE	247	247	247	247	246	247	247	247	246	223
Joint test of significance for: *FX high*$_t$ and *Vix high*$_t$										
Joint Test	6.71***	3.66**	3.58**	2.85*	7.71***	4.43**	3.88**	3.47**	3.86**	10.61***
F-test/Probf	0.0015	0.0272	0.0293	0.0599	0.0006	0.0129	0.022	0.0326	0.0224	< .0001
Med. $FXIV_t$	10	10	9.0	10	7.5	10.5	10.5	11	12	11.5
	EUR/	GBP/	CHF/	CAD/	AUD/	JPY/	SEK/	NOK/	NZD/	
	GER	STOXX	UK	SWZ	CAN	AUS	JAP	SWE	NOR	NZD
Panel B: Model: $CorrXY_{t,t+3} = \beta_0 + \beta_1 CorrXY_{t-3,t} + \beta_2 FXIV_t \times Vix_t \times FX\_hi_t + \varepsilon_t$										
Intercept	0.2813***	0.2738***	0.2280***	0.2203***	0.3152***	0.0696***	0.3040***	0.2231***	0.1500***	0.0262*
	(9.70)	(9.37)	(8.1)	(8.71)	(8.77)	(5.07)	(11.21)	(8.96)	(7.46)	(1.94)
$Corr\ XY_{t-3,t}$	0.4384***	0.4538***	0.5069***	0.4257***	0.4901***	0.5385	0.2663***	0.4772***	0.5445***	0.5195***
	(8.01)	(8.32)	(9.57)	(7.34)	(8.64)	(9.39)	(4.41)	(8.91)	(10.45)	(9.59)
$FXIV_{t\_t}$	0.0132***	0.0098**	0.0116**	0.0085	0.0074	0.0093**	0.0087*	0.0109***	0.0115***	0.0210***
$\times Vix_t \times FX\_hi_t$	(3.11)	(2.34)	(2.52)	(1.62)	(1.56)	(2.23)	(1.92)	(2.71)	(2.48)	(4.75)
R-square	0.2704	0.2473	0.3149	0.1962	0.2577	0.3185	0.0933	0.2932	0.3795	0.4158
Obs./DFE	248	248	248	248	247	248	248	248	247	224
Panel C: Difference of average absolute value of residuals in basis points: Naïve model MINUS models A and B										
vs. Panel A	18.409	16.488	13.909	23.059	9.737	15.493	26.044	20.134	11.917	18.467
vs. Panel B	16.752	16.029	13.211	22.702	7.905	15.047	25.271	19.803	10.604	17.215

This Table reports regressions results of three-month correlations between the S&P 500 index and nine other country equity indices plus the STOXX index. Correlations are measured between daily S&P 500 returns and other index returns in the U.S. dollar. The variable $Corr\ XY_{t-3,t}$ is the most recent three-month correlation up until the observation day. $FXIV_t \times FX\_hi_t$ is the interaction of the actual value of the 3-month option-implied foreign exchange volatility ($FXIV_t$) with a dummy variable set to 1 when foreign exchange volatility is above its historical median and set to 0 otherwise. $Vix_t \times FX\_hi_t$ is the interaction of the VIX_t with the same dummy variable. Panel A contains the results for the full model. Panel B contains the results for a model using the interaction of three regressors as one variable to account for multicollinearity. Panel C contains the difference of the average absolute value of residuals between the naïve model (estimated as the most recently observed correlation) and models A and B. The numbers below the coefficient estimates are t-statistics. The asterisks *, **, and *** indicate statistical significance at the 10%, 5%, and 1% level, respectively. The full sample period includes monthly observations from Jan 1, 1999 to May 31, 2020.

Note: Coefficient *for* $FXIV_t \times Vix_t \times FX\_hi_t$ for CHF/SWZ in Panel B is significant when evaluating for sub-sample ending in December 2014 ahead of the spike in CHF volatility driven by unexpected lift of CHF/EUR peg. Similarly, results for CAD/CAN are impacted by the low median FXIV used to set the high FXIV volatility indicator FX_hi_t. See text for further details.

using the VIX is that it accounts for and captures shorter-term variations. Additionally, although a three-month VIX volatility measure is available, it is not nearly as widely followed, and its underlying options are significantly less liquid. Since the focus of our analysis is on the relation between equity correlations and foreign exchange implied volatility (not the VIX), we do not believe that this choice impacts the interpretation of our results in any significant manner.

Individually, the coefficients for $FXIV_t \times FX\_hi_t$ and $Vix_t \times FX\_hi_t$ are statistically significant for about half of the evaluations, but more importantly, *jointly*, they are statistically significant in all estimations. These results are consistent with our theoretical premise of a link between foreign exchange volatility and global equity correlation, and that foreign exchange option-implied volatility does indeed predict future realized foreign exchange volatility. Since all the independent variables in equations (11) and (12) are known ex-ante at time t and the dependent variable is the equity correlation over time t to $t+3$, our findings suggest that foreign exchange option-implied volatility is useful in forecasting subsequent equity correlations between pertinent respective global equity markets.

Evaluating the estimated values of the coefficients in Panel A of Table 7, it appears at first that, due to its larger coefficient, the independent variable $Corr\ XY_{t-3,t}$ might have a larger economic significance on the estimated equity correlation than the joint variables related to FX implied volatility and the VIX. However, the difference in the size of the coefficients is simply due to the difference in scale or magnitude of the respective variables. Let us consider for example the case of Germany, the first country evaluated in Table 7 from left to right. In this evaluation, the estimate for the $Corr\ XY_{t-3,t}$ coefficient is 0.4305. Assuming an observation with a correlation of 0.62 (the average for the US/GER equity correlation during the economic crisis as reported in Panel B of Table 5) would yield an incremental 0.2669 to the correlation estimated by the model. Although the coefficients for $FXIV_t \times FX\_hi_t$ and $Vix_t \times FX\_hi_t$ are just −0.0037 and 0.0040, respectively, their combined impact onto the correlation estimated for the model is also material. Assuming an FX implied volatility for the EUR/USD pair of around 14 during an equivalent time of high volatility and a value of 45 for the VIX over the same period, would yield a combined 0.1282 ($-0.0037 \times 14 + 0.004 \times 45$) increase to the correlation estimated by the model. What matters is the joint significance of the two volatility-related independent variables. We test for the presence of multicollinearity by computing Value Inflation Factors (VIF) for the regressors in the evaluation of the estimates of relation (7). The results are reported in Panel A of the Appendix Table C2. A VIF above 4 suggests the potential presence of multicollinearity and a VIF above 10 indicates the presence of strong multicollinearity. The VIF values for $FXIV_t \times FX\_hi_t$ and $Vix_t \times FX_hi_t$in Table C2 are all above 8 and only two of them are below 10. Further confirmation of the presence of multicollinearity is included in Panel B of Table C2 where correlations between these two variables are shown to be above 0.93 for all country pairs. The correlations between the continuous values of FXIV and the VIX are also relatively high, as reported in Panel B of Table C2.

The bottom of Panel A in Table 7 shows the joint statistical significance of $FXIV_t \times FX\_hi_t$ and $Vix_t \times FX_hi_t$for all country pairs. These results are supportive of our hypothesis. In Panel B, the '*transformed*' independent variable $FXIV_t \times Vix_t \times FX\_hi_t$ which is now free from multicollinearity, is consistently positive for all country pairs. More importantly, the model evaluations reported in Panels A and B yield consistently more accurate forecasts of future equity correlations than the naïve model based solely on the most recently observed correlation. Panel C contains the difference in basis points between the average absolute value of residuals when comparing the naïve model to the two separate models of Panels A and B. In every country pair this difference is positive, indicating that, consistent with our main hypotheses, the proposed model is a better fit with smaller residuals on average. Untabulated results comparing the residuals of the estimated models reported in Panels A and B with a simplified model using just the most recently observed correlation $Corr\ XY_{t-3,t}$ as the independent variable also show that our proposed model is more accurate. Sub-section 4.6 discusses other model variations examined. When using these estimated correlations for portfolio optimization purposes, these marginal improvements can result in economically material enhancements in performance.

4.6. Robustness checks

At the empirical level, relation (11) prompts consideration of a few additional varied specifications. This arises partially because of collinearity between two of the variables ($FXhigh_t$ and $Vixhigh_t$) and the fact that some of the estimated coefficients for these two variables are not statistically significant, though they are consistently jointly statistically significant. The estimated results of two specifications based on relation (11) are already reported in Table 7. To probe further into these points, we examine the following additional alternatives.

a. We consider a simple standard AR(1) form of relation (11), i.e.

$$CorrXY_{t,t+3} = \beta_0 + \beta_1 CorrXY_{t-3,t} + \varepsilon_t \tag{13}$$

The above specification provides a scenario which is slightly more advanced than simply considering ex-post correlations among the equity markets as a substitute for their ex-ante correlations.

b. We augment relation (13) with the VIX value for all observations, not only when either the VIX or the FX option implied volatility is high, that is, above a certain threshold.

$$CorrXY_{t,t+3} = \beta_0 + \beta_1 CorrXY_{t-3,t} + \beta_2 Vix_t + \varepsilon_t \tag{14}$$

The above specification considers the accuracy of predicting ex-ante equity correlations by using only the most recently observed correlation and the current value of the VIX as predictors, while ignoring FX option implied volatility.

c. We augment relation (13) with the variables $FXIV_t \times FX\_hi_t$ and Vix_t. This specification is similar to relation (11), except that in this variation the value of the VIX is not set to zero when the FX option implied volatility is not high, that is, not above its historical median.

$$CorrXY_{t,t+3} = \beta_0 + \beta_1 CorrXY_{t-3,t} + \beta_2 FXIV_t \times FX\_hi_t + \beta_3 Vix_t + \varepsilon_t \tag{15}$$

The above specification is consistent with our theoretical premise that the FX option implied volatility, when elevated, is predictive of subsequent equity correlations. Unlike relation (11), it utilizes the value of the VIX as a predictor across all levels of FX option implied volatility, that is, regardless of whether it is high or not.

d. Finally, we re-estimate relation (11) after standardizing the measurement of all the variables. Under this design, the magnitudes of the estimated coefficients indicate the relative economic significance or contribution of each of the variables. We note that the estimated standard errors stay the same as when the original measurement of the variables is used.

We estimate the above alternatives for pairwise correlations between the S&P 500 and each of the nine country equity indices and the STOXX. The estimated results yield marginal differences in predictive accuracy, with the best average accuracy still yielded by our main model, i.e. the specification in relation (11), followed by alternatives 'a', 'b', and 'c', above in increasing order of average accuracy. While alternative 'c' yields more accurate results for some of the pairwise correlations, the average residual across all pairs is still higher than for our main model. More importantly, alternative 'b' which omits the FX option implied volatility as a predictor variable, yields even less accurate correlation predictions. The predictions in alternative 'd' stay the same as in our main model since the purpose of this alternative is to provide an easier process to identify the relative economic significance of the variables.

For brevity, the tabulated results of the above alternative estimates are not reported.[11] Overall, as is also partially indicated in Table 7, the average predictive superiority of the main model (relation (11)) over the naïve model is 23.07 basis points, with a range of 9.74–46.51. Similarly, the average predictive improvements yielded by alternatives 'a' 'b', and 'c', again against the naïve model, are, respectively 19.30 (with a range of 6.26–41.13), 22.03 (with a range of 7.97–44.93), and 22.72 (with a range of 10.98–46.69). These improvements in our derived forecast measures attest to the superiority of our model driven by option-implied currency volatilities.

We consider a variant of relation (11) and test a straightforward relation between equity market correlations and FXIV.[12] The results are reported in the Appendix Table C1. All country pairs show a strong and statistically significant positive relation between FXIV and equity correlations. The high values of R^2, irrespective of any econometric shortcomings, reflect the high predictability potential of the estimated relations. In addition, the positive relation between FXIV and equity correlations is unequivocal.

We then examine more closely the results in Table 7 for some country pairs. We investigate our empirics for Switzerland further since the estimated results in Table 7 indicate low (10%, Panel A) or no (Panel B) statistical significance. We note that the Swiss Central Bank shocked the market in January 2015 when it terminated pegging the Swiss Franc to the Euro. This action caused a huge unexpected spike in the Swiss Franc volatility in January 2015. (See Figure 4 and Section 4.4). To account for this exogenous event, we re-estimated the model using a sub-sample of the data ending in December 2014. The results improve substantially, yielding estimated coefficients that are statistically significant at the 5% level or below. An explanatory note on this robustness check is added to the footnote of Table 7.

A central tenet of our theoretically supported hypothesis is that FXIV is positively associated with increases in equity correlation for the pertinent country pair when values for FXIV are elevated. In the evaluation of relation (7) for Canada, this is captured by setting FX_hi_t to 1 when the corresponding FXIV is above its historical median. The bottom of Panel A in Table 7 reports the median value for FXIV for each country pair. The threshold for CAD/CAN is by far the lowest in our sample at an annualized 7.5%. The strong and symbiotic trading relationship between the U.S. and Canada leads to a stable USDCAD foreign exchange rate with low volatility. Unlike the other country pairs in our sample, the FXIV and equity correlation relation predicted by our models is only more evident at somewhat higher levels of FXIV than its historical median. An explanatory note on this robustness check is added to the footnote of Table 7.

4.6.1. Pooled (Panel) estimation

We report the results of our analysis using pooled (panel) data estimation in Table 8. These results convey a more generalized set of outcomes since all the pairwise country data are now jointly considered in the estimation process.

To stay thorough, we consider three alternatives of the pooling (panel) estimation methodology, i.e. two-way random effects, two-way fixed effects, and pooling with clustered errors. Under the two-way random or two-way fixed effects, the cross-sectional and time-series variations are simultaneously accounted for. We also experiment with one-way random effects and one-way fixed effects. The results stay robust, though marginally different from the two-way effect alternatives. The 'pooled clustered errors' alternative that we also employ for consistency with our prior Autoreg estimation results, includes double clustered standard errors to account for the fact that the observations are naturally clustered around country pairs and possibly across time as well.

To stay consistent with our prior models and results, we evaluate three different models labeled Models 1 through 3. The specifications in these three models replicate those in the relations that we already estimated.

Model 1 shows the relation between subsequent equity correlations and FXIV when FXIV values are high, i.e. above their historical median. This is the same specification that is estimated and reported in Panel B of Table 7. All the estimated coefficients in Model 1 under each of the three alternatives that are reported in Table 8 are highly statistically significant; and have the expected *a priori* correct signs. In particular, the statistically significant and positive coefficients for $FXIV_t \times Vix_t \times FX\_hi_t$ in this model under the three alternatives confirm our prior results that increases in FXIV and/or the VIX are associated with increases in equity correlations. We now further confirm this conclusion under a more generalized framework that considers all pairwise countries together.

Model 2 shows that recently observed equity correlations and the continuous value of FXIV are positively associated with increases in subsequent equity correlations. The specification in this model, which sets future correlations directly against FXIV, is the same as the one already considered and reported in the Appendix Tables C1 and C2. The estimated results of Model 2 in Table 7 further confirm the pairwise country results in Tables

Table 8. Panel data estimates of the relation between future equity correlations and foreign exchange option-implied volatilities.

	Model 1			Model 2	Model 3
	Pooled Clustered Errors	Two-way Random Effects	Two-way Fixed Effects	Pooled Clustered Errors	Pooled Clustered Errors
Intercept	0.1146*** (16.22)	0.2674*** (7.18)	0.5136*** (14.05)		0.1182*** (16.51)
Corr $XY_{t-3,t}$	0.7127*** (50.48)	0.3209*** (16.87)	0.2719*** (13.28)	0.7903*** (65.77)	0.7054*** (49.43)
$FXIV_t$				0.0081*** (14.56)	
$FXIV_t \times FX\_hi_t$					−0.0054*** (−3.77)
$Vix_t \times FX\_hi_t$					0.03721*** (5.28)
$FXIV_t \times Vix_t \times FX\_hi_t$	0.6069*** (5.03)	0.8945*** (4.20)	0.5391** (2.05)		
R-square	0.5242	0.1139	0.8108	0.8862	0.5274
Obs./DFE	2484	2481	2222	2484	2484
Multicollinearity?	No	No	No	No	Yes

This Table reports panel (pooled) data estimated results of three-month ahead correlations against FX implied volatility (FXIV) and other variables. Nine pairwise country equity correlations plus the STOXX index are pooled together. Three different model variations are reported. Three alternative pooling (panel) estimation methodologies are considered, i.e. two-way random effects, two-way fixed effects, and pooling with clustered errors. The last row discloses the detection of multicollinearity between independent variables. Correlations are measured between daily S&P 500 returns and U.S. dollar returns for other indices. The variable *Corr* $XY_{t-3,t}$ is the most recent three-month correlation up until observation day. $FXIV_t \times FX\_hi_t$ is the interaction of the value of the 3-month option-implied foreign exchange volatility ($FXIV_t$) with a dummy variable set to 1 when foreign exchange volatility is above its historical median and set to 0 otherwise. $Vix_t \times FX\_hi_t$ is the interaction of the VIX on observation day with the same dummy variable. The numbers below the coefficient estimates are t-statistics. The asterisks *, **, and *** indicate statistical significance at the 10%, 5%, and 1% level, respectively. The full sample period includes monthly observations from Jan 1, 1999 to May 31, 2020.

C1 and C2, but now under a more generalized panel data analysis. The presence of positive and statistically significant coefficients for *Corr* $XY_{t-3,t}$and $FXIV_t$ are thus further verified.[13]

Finally, again for consistency with our pairwise estimation, Model 3 considers a specification that includes the two volatility variables separately, knowing that they are correlated. The specification in this model replicates the same relation that is already estimated and reported for each of the pairwise countries in Panel A, Table 7. Under panel estimation, the results of Model 3 lead to the same conclusions as those drawn by the results for Model 1. But, separating the interaction term in Model 1 into two separate terms in Model 3 leads to multicollinearity and a change in the sign of the coefficient for $FXIV_t \times FX\_hi_t$. The same detailed discussions that we offered earlier (see Section 4.5) for interpretation and evaluation of the estimated results of this specification apply here.

5. Economic significance of model application in portfolio management

Using Markowitz optimization, we form and compare the performance of two rolling-forward portfolios, one based on historical correlations and the other on the correlation forecasts of our model. To ensure an apples-to-apples comparison, both portfolios estimate expected monthly returns as the three-year historical average. For constructing the covariance matrix in the Markowitz optimization, once again both portfolios use the three-year historical averages for standard deviation of returns. The sole difference in the construction of the two portfolios lies in the estimate of equity correlations. For the control or comparison portfolio, or the naïve portfolio in our study, we employ the historical equity correlations observed over the most recent three-month period. This is a common assumption among practitioners as equity correlations tend to be somewhat stable. In contrast, the model-driven portfolio employs equity correlation forecasts generated by our proposed model. Therefore, the difference in performance for these two evaluated portfolios can be attributed entirely to the correlation forecasts employed.

Table 9. Evaluation of portfolio optimization improvement yielded by the information content of FXIV.

	Model-driven Portfolio	Optimized Naïve Portfolio
Panel A: Cumulative returns		
Returns	170.13%	149.19%
Panel B: Average monthly performance		
Returns	0.657%	0.593%
Standard deviation	5.494%	5.416%
Panel C: Sharpe Ratios		
Avg. Annual Sharpe Ratios	0.623	0.565
Cumulative Sharpe Ratios	10.585	9.603

This Table compares the returns, standard deviation of returns, and Sharpe Ratios of a portfolio mean-variance optimized according to Markowitz (1952) with naïve correlation estimates based on recently observed three-month correlations versus a similarly optimized portfolio but whose correlations estimates are based on our proposed model driven by foreign exchange implied volatility. Correlations between the U.S. equity market and foreign equity markets are obtained directly from our model estimates. Correlation among foreign equity markets are estimated based on the simplification that CORR(*fgn_a, fgn_b*) = CORR(*mkt, fgn_a*) × CORR(*mkt, fgn_b*) where the U.S. equity market represents the market portfolio. For both portfolios, estimated monthly returns and standard deviations are based on three-year historical averages. Performance results based on monthly returns from December 31, 2003 to May 31, 2020. December 2003 is the earliest date for which three years of historical data is available for calculating historical returns and standard deviations for all equity markets in our sample.

The first optimized portfolios are formed with data for the three-year period ending on December 31, 2003. Thus, the performances of the initial two portfolios are measured over the first three months of 2004, and then the portfolios are rebalanced. Both portfolios are constructed using ex-ante forecasts within each rolling round, while performance is measured over time t to time $t + 3$. After the first rebalancing, performances are once again measured over the subsequent three-month period and the process is repeated over the entire sample period by rolling forward three months at a time for portfolio rebalancing while measuring performance monthly.

Our proposed model only directly computes correlation forecasts for country pairs including the U.S. For our model-driven portfolio we estimate correlations for country pairs excluding the U.S. as $\mathrm{CORR}(fgn\_a, fgn\_b) = \mathrm{CORR}(mkt, fgn\_a) \times \mathrm{CORR}(mkt, fgn\_b)$ where *fgn_a* and *fgn_b* represent two separate foreign equity markets and *mkt* represents the U.S. equity market. This simplified assumption is consistent with the premise that total variance of returns for a given security is a combination of the variance attributable to the uncertainty of a market benchmark plus the variance attributable to the security-specific risks. This concept was pioneered by Sharpe (1963). By employing this approximation we are able to produce estimates for the entire correlation matrix of the model-driven portfolio and not just the correlations with the U.S. market.

We report the performances of the two aforementioned portfolios side by side in Table 9. This Table is added here for your convenience. The cumulative return of the model-driven portfolio is more than 20% higher than that for the naïve portfolio (see Panel A). This consequential difference represents a large tangible potential economic gain for employing our proposed model, calculated with easy-to-reproduce ex-ante estimates. We also compute monthly averages for returns and standard deviation of returns for both portfolios (see Panel B). While standard deviation of returns for the model-driven portfolio is modestly higher than that for the naïve portfolio, the small difference is more than compensated by the increase in returns. This is clearly demonstrated by the superior Sharpe Ratio, a risk-adjusted performance measurement, for the model-driven portfolio reported in Panel C.

Other approaches to portfolio optimization that rely on correlation forecasts are likely to similarly benefit from the forecasts produced by our proposed model.

6. Summary and conclusions

The areas of portfolio optimization and risk management require accurate equity correlations forecasts. Among practitioners and academics alike, it is commonplace to use the most recent period of equity correlations as the best subsequent period forecast. We posit and test a new theoretically supported empirical model involving taking advantage of the information contained in currency option-implied volatility to improve upon global equity correlations predictions. We test our model by using extensive currency and equity data across ten global markets over 250 months and show that correlation predictions can be greatly enhanced indeed.

The measurement and forecasting of global equity market correlations have so far been mostly confined within the boundaries of equity markets. Resorting to external variables is a rare practice since such variables are often considered to be unrelated to equities. We depart from this position and hypothesize that variables such as option-implied foreign exchange volatilities may indeed possess valuable information even though they may at first appear 'seemingly unrelated'.

We first establish a theoretical framework linking foreign exchange rates volatility to global equity correlations. See Figure 1. The key components include a stochastic model of exchange rates, Taylor-rule-based market expectations of interest rates, assumptions related to parity conditions including an international Fisher effect, and the assumption that broad equity market values should reflect the discounted present value of future aggregate cash payouts, and that these payouts are linearly related to each country's output.[14] We build and test an empirical model based on this framework and evaluate its relative forecast accuracy extensively. We show that when exchange rate volatility is high, the correlation between pertinent broad equity markets is also high.

Our derived relations between international equity market correlations and exchange rate volatility levels are at first contemporaneous. Next, we posit that an effective predictor of exchange rate volatility should therefore be effective in predicting future global equity market correlations. We find that option-implied foreign exchange rate volatility is a good predictor of subsequently observed exchange rate volatility, especially for one-month and three-month horizons. We show empirically that this variable is related to subsequent world equity market correlations. In other words, the information contained in currency option-implied volatilities is an effective *ex-ante* predictor of future global equity market correlations.

Since the relation between equity correlations and the value of the VIX as a proxy for equity volatility is well established, our full model includes both option-implied foreign exchanged volatility and the VIX as predictor variables. We show that jointly, option-implied foreign exchange volatility and the VIX yield further insights into a relation that is often estimated by simply using the most currently observed equity correlation as a predictor variable. Our results are robust both on a country-pair by country-pair basis as well as under a panel (pooled) data analysis across all countries combined. Our panel analyses results are robust under varied pooled estimation methodologies including two-way random effects and two-way fixed effects.

A potential further improvement to the performance of our model could involve the investigation, evaluation, and ultimate use of an even more accurate forecast of future currency volatility, which would then in turn improve the accuracy of the pairwise global equity correlation forecasts. These potential new currency volatility forecasts could also then be used in our model to forecast global equity correlations for country pairs for which pertinent option-implied currency volatilities are not available. This is an interesting area of future research.

To exhibit the relevance of our proposed models and their empirics to real life, we apply the model's *ex-ante* correlation estimates to a real life portfolio formation. The results indicate superior performance over a portfolio that is formed on naïve historical data. The cumulative return of the model-driven portfolio is shown to be more than 20% higher than that for the naïve portfolio. This consequential difference represents a large tangible potential economic gain that is highly valuable to portfolio managers, brokerage firms, and investors. Our simulation employs *ex ante* data and is easily replicable by practitioners and researchers. Coupled with advanced portfolio optimization techniques, the benefits of *ex-ante* equity correlation estimates (forecasts), similar to the ones produced by our proposed model, could be even greater. This also represents another area for further research.

Notes

1. We are deeply indebted to one of the reviewers for succinctly summarizing the various theoretical components of the paper.

2. For comparison, see Zellner (1962).
3. We correct for autocorrelation in the error term by modeling the random error term with an autoregressive feature. It is not the same as the error correction model of Engle and Granger (1987).
4. See Garman and Klass (1980), p. 74.
5. These measures are readily available from Bloomberg. See Section 3 on data and sources.
6. Jorion (1995) finds that option-implied volatility forecasts outperform other time series models. He also suggests that a linear transformation of the series of interest further improves the forecasts.
7. Correlations are measured using daily returns of the U.S. dollar denominated value of the equity indices provided by Datastream. To address the time zone effect, we lag the Japanese but not the Australian and New Zealand markets by one day when calculating correlations.
8. The estimated specification is: $y_t = x_t'\beta + \upsilon_t$, where $\upsilon_t = \varphi_1\upsilon_{t-1} - \varphi_2\upsilon_{t-2} - \ldots - \varphi_m\upsilon_{t-m} + \epsilon_t$, and $\epsilon_t \sim IN(0, \sigma^2)$
9. In addition, it may account for omitted variables, if any.
10. For instance, December contains Boxing Day as an additional holiday for the U.K. stock market, reducing the number of overlapping open days with the U.S. market. The same is true in May with a Bank holiday in the U.K. in the beginning of the month and Memorial Day holiday in the U.S. the end of the month.
11. Robustness check detailed results are available from the first author.
12. In order to isolate the relation between the two regressors and equity correlations, the intercept is dropped.
13. For brevity, only pooling with clustered errors are reported in Table 8.
14. We thank an anonymous reviewer for succinctly and eloquently summarizing our theoretical framework.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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