The Conditional Volatility Premium on Currency Portfolios*

Joseph P. Byrne† and Ryuta Sakemoto‡

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Abstract

Our paper examines conditional risk-return relations in a number of currency investment strategies, while modeling economic states using a large number of underlying risk factors. We identify a time-varying relationship between currency returns and volatility risk for most currency portfolios. In particular, value and momentum portfolios present risk-return relationships which switch sign, depending upon economic states. The positive relationship for the value portfolio is associated with "flight to quality" periods and the mean reversion for nominal exchange rates during financial crises. The positive relationship for the momentum portfolio is linked to the US and global business cycles and investors require positive compensation for risk in recessions.

Keywords: Systematic Risk; Currency Carry Trade; Momentum; Value; Conditional Factor Model; Currency Variability

JEL codes: C12, C58, F3, G11, G15

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†Address: Edinburgh Business School (Economics), School of Social Sciences, Heriot-Watt University, Edinburgh, Scotland, UK. Email: <j.p.byrne@hw.ac.uk>

‡Address: Graduate School of Humanities and Social Sciences, Okayama University, Okayama-shi, Okayama-ken, Japan. Keio Economic Observatory, Keio University, Minato-ku, Tokyo, Japan. Email: <ryuta.sakemoto@gmail.com>

1. Introduction

Central to asset pricing research is testing the empirical relationship between systematic risk and return, given that investors require compensation if risk is priced. When risk is modeled by volatility and assumed to have a time invariant relationship to excess return, Sharpe ratios are state independent. This state independence assumption is open to question. In addition and despite its centrality to asset pricing, the literature has not converged on a consensus on the nature of the link between returns and risk factors, such as volatility. For stock market returns, French et al. (1987), Merton (1987), Scruggs (1998), Ghysels et al. (2005), and Guo and Whitelaw (2006) present positive risk-return relations for example, while Campbell (1987), Glosten et al. (1993) and Ang et al. (2006) report a negative empirical relationship between returns and risk, in the form of return volatility. The former studies indicate investors require a risk premium for additional volatility, while the latter indicates that agents are not averse to additional asset price variability.[1]

Our work extends the risk-return trade-off test to the under explored area of currency portfolios. Early asset pricing studies focused upon U.S. stock market returns (e.g. Ang et al., 2006; Guo and Whitelaw, 2006). Testing the risk and return nexus using alternative asset classes provides illuminating results, especially since a burgeoning literature has recently implemented portfolio approaches for the currency market. The influential work of Asness et al. (2013) moreover reveals that value and momentum effects are observed in many asset classes. A value strategy in the stock market exploits information on book-to-market ratios and buys higher book-to-market stocks (e.g. Fama and French, 1992;1993). A currency value strategy can exploit mean reversion to purchasing power parity, therefore using variation in real exchange rates (e.g. Taylor, 2002; Imbs et al., 2005; Boudoukh et al., 2016; Menkhoff et al., 2017). A cross-sectional momentum strategy goes long in high past

[1]Bansal and Yaron (2004) is a prominent early model motivating long run risks or uncertainty shocks as having risk premiums. See also the expanding literature on volatility risk premiums, e.g. Bali and Engle (2010), Bansal et al. (2014), and Della Corte et al., (2016a, 2020). These studies often differentiate between realized and option implied volatility, while our work focuses upon modeling the underlying factors driving currency volatility.

return assets and goes short in low past return assets, which can be employed in both stock and currency markets. Likewise for currencies, Koijen et al. (2018) highlight that carry strategies are applicable across assets. A currency carry trade focuses upon differentials between spot and forward rates, buying high and selling low forward premium currencies. See for example Lustig and Verdelhan (2007), Lustig et al. (2011) and Menkhoff et al. (2012a). In the stock market, Koijen et al. (2018) show that the carry is determined by the expected dividend yield minus the risk-free rate and a scaling factor.[2]

The currency portfolio literature has mainly focused upon currency carry trades and investigated systematic risk exposure to market and macroeconomic uncertainty in the cross-sectional context.[3] One prominent exception is Bakshi and Panayotov (2013) who use time series to investigate the relationship between FX market risk and currency carry portfolios. The exact ways in which FX market risk is associated with currency momentum and value portfolios using time series methods remains an open question.[4] Our study's first contribution is that we conduct a comprehensive intertemporal analysis of the link between risk and currency portfolio returns. We generalize and therefore extend the study of Bakshi and Panayotov (2013) to a wider array of currency portfolios, considering not only the currency carry but also value and momentum portfolios. In addition we investigate four new currency portfolios: dollar carry trade (Lustig et al., 2014), global imbalances (Della Corte et al., 2016b), "good" carry trade (Bekaert and Panayotov, 2020), and correlation risk in the FX market (Mueller et al., 2017). Each strategy is based upon a different mechanism and the previous literature focuses upon a risk premium in the cross-sectional context. Hence, there is an open question as to whether FX market risk influences these new currency portfolios in the time-series context. A comprehensive investigation is required,

[2]When covered interest rate parity is satisfied, the forward premium is equal to the interest rate differential.

[3]Christiansen et al. (2011), Menkhoff et al. (2012a), Atanasov and Nitschka (2014), Dobrynskaya (2014), Lettau et al. (2014), Berg and Mark (2018), Byrne et al. (2018) and Orlov (2019)

[4]Menkhoff et al. (2012b) and Eriksen (2019) report that high average returns of currency momentum portfolios cannot be explained by traditional risk factors, although they do not specifically investigate the risk-return relationship in a time-series context.

because the mechanisms that create positive payoffs are heterogeneous and combining different currency strategies leads to diversification of portfolio risk (Kroencke et al., 2014; Barroso and Santa-Clara, 2015). Our study is different from Bali and Yilmaz (2009), who focus upon the time series relationship between risk and a single currency return, since currency specific risk components are averaged out in the currency portfolios (Lustig et al., 2011).

The standard approach in asset pricing studies is to examine risk and return in portfolios using unconditional methods. The second contribution we make therefore, is to take into account a time-varying relation between conditional volatility and expected returns. A theoretical asset pricing model conditional upon economic states, was proposed by Backus and Gregory (1993). In contrast to unconditional models, conditional models employ information up to the current time and reflect changes in economic states (Jagannathan and Wang ,1996; Cochrane, 1996; Lettau and Ludvigson, 2001). The advantage of the conditional models is that it allows a time-varying relationship between asset returns and risk. Risk-return trade-offs have been widely investigated using the conditional models in the stock market literature (e.g. Whitelaw, 2000; Rossi and Timmermann, 2010; Ghysels et al., 2014; Adrian et al., 2019).[5] Whitelaw (2000) builds a general equilibrium model with a regime-switching consumption process and generates a time-varying and non-linear relation between volatility and expected returns in the stock market. Rossi and Timmermann (2010) find a non-monotonic relation between conditional volatility and expected returns in the stock market, and Ghysels et al. (2014) present work indicating that the positive risk-return relation is not observed in a “flight-to-quality” regime. In recent work, Adrian et al. (2019) find that expected returns on stock and bond markets depend upon the level of VIX and the relationships are nonlinear. To investigate the time-varying relationship between returns and risk, our study adopts a time-varying conditional factor model proposed by Ang and Kristensen (2012), which allows for smooth changes in coefficients. In the FX market,

[5] For research conditional asset pricing models more generally see *inter alia* Ferson and Schadt (1996), Lewellen and Nagel (2006) and Gagliardini et al. (2016).

Baillie and Kim (2015) and Sakemoto (2019) observe that utilising macro indicators results in smooth changes in risk.

The third contribution of our work on the volatility risk premium is to employ an empirical factor model to summarise more broadly macroeconomic and financial market information. This is important since economic states affect the relationship between conditional volatility and expected returns, see Backus and Gregory (1993), and Backus et al. (2001). Such a model is set out in the appendix to this paper. To capture economic states, we focus upon the common component of macro and financial information since it is non-diversifiable and linked to the business cycle (Jurado et al., 2015), while idiosyncratic information can be diversified. Furthermore, narrow macro indicators like consumption may suffer from measurement errors, with an unknown relationship between macro indicators and asset returns. Investors also extract macro-finance information broadly when implementing their investment strategies. Ludvigson and Ng (2007) construct several empirical factors that summarise macro indicators and uncover a positive risk-return relation for U.S. stocks. This factor model is also useful in predicting currency carry returns (Filippou and Taylor, 2017). In contrast to the previous literature, our study predicts conditional FX market volatility by a factor model, not currency portfolio returns. Moreover, our aim is to examine the risk-return relationship with currency portfolios, rather than predict FX volatility.

To preview our results, we find that the relationship between conditional volatility and expected returns is time-varying for most currency portfolios. This time variation is particularly strong for currency momentum and value portfolios. Importantly, we do not find formal statistical evidence of a link between returns and risk on the currency momentum and value portfolios with constant parameter models. When we reflect changes in economic states and adopt the time-varying model, we observe that the risk-return parameters occasionally change signs. This positive and negative risk-return relationship for the value portfolio is associated with flight to quality periods and we observe the positive risk-return relationship during financial crisis periods. This is related to the mean reversion for nominal exchange rates. This result is consistent with evidence from the Treasury market (Adrian et al., 2019) but less consistent with evidence from the stock market (Ghyselset al., 2014). Time variation in the risk-return nexus for the momentum portfolio is linked to business cycles: agents require positive compensation for risk in recessions.

The paper is organized as follows: Section 2 describes the currency volatility and currency portfolios. Section 3 then lays out the econometric methods implemented in our paper, and Section 4 describes the data. Section 5 presents empirical results, Section 6 conducts further analysis and Section 7 concludes.

2. Currency portfolios and volatility

This section describes the currency volatility data and portfolios used in our study. To examine risk-return trade-offs for a wide range of currency investment strategies, we construct several currency portfolios. These currency portfolios include, carry, momentum, value, "good" carry, dollar carry trade, global imbalances, and global correlation risk.

2.1. *Currency excess return and volatility*

This study computes a currency excess return using spot and forward rates and assuming a U.S. investor. Following Lustig et al. (2011) and Bakshi and Panayotov (2013), we take into account transaction costs using bid-ask prices. When the investor buys (sells) the foreign currency, she sells (buys) the one-month dollar forward at the bid (ask) price $F^{bid}_{i,t-1}$ ($F^{ask}_{i,t-1}$) at time $t-1$ and buys (sell) the dollar at $S^{bid}_{i,t}$ ($S^{ask}_{i,t}$) at time t. The excess return of going long $r^{long}_{i,t}$ and that of going short $r^{short}_{i,t}$ in the foreign currency are:

$$r^{long}_{i,t} = \frac{F^{bid}_{i,t-1} - S^{aks}_{i,t}}{S^{ask}_{i,t}}, \quad r^{short}_{i,t} = \frac{-F^{ask}_{i,t-1} + S^{bid}_{i,t}}{S^{bid}_{i,t}}. \tag{1}$$

Using the long and short returns, we calculate the total payoff $TR_t = \frac{r_{i,t}^{long} + r_{j,t}^{short}}{2}$. We consider K currency pairs in long (short) positions and the average of total payoffs $\overline{TR}_t^{(K)}$ is calculated as:

$$\overline{TR}_t^{(K)} = \sum_{k=1}^{K} \frac{TR_t^{(k)}}{K}. \tag{2}$$

The long and short positions are determined by a signal that will be explained in the next subsections. We consider $K = 2$ currency pairs in long (short) positions in the main analysis. An online Appendix provides results when $K = 3$ currency pairs in long (short) positions.

We adopt global FX volatility as our measure of volatility within intertemporal risk-return trade-off tests. We closely follow Menkhoff et al. (2012a), such that volatility in day d:

$$\sigma_{FX,d} = \sum_{i=1}^{K_d} \left(\frac{|rs_{i,d}|}{K_d} \right) \tag{3}$$

where $|rs_{i,d}|$ is the absolute value of daily spot rate return $rs_{i,d}$, and K_d is the number of currencies on day d. We employ the absolute returns, not squared returns and this allows us to mitigate effects of outliers, following for example Menkhoff et al. (2012) and Ghysels et al. (2014). Next, monthly global FX volatility in month t, $\sigma_{FX,t}$, is calculated as:

$$\sigma_{FX,t} = \frac{1}{T_t} \sum_{d=1}^{T_t} \sigma_{FX,d} \tag{4}$$

where T_t is the total number of trading days in month t. The monthly global FX volatility $\sigma_{FX,t}$ is employed in the later analysis.

2.2. *Carry strategy*

Our first currency portfolio is the most widely studied and it is constructed using forward discounts. This strategy exploits deviations from uncovered interest rate parity, and has been explored in the literature by Lustig et al. (2011), Menkhoff et al. (2012a) and Bakshi and Panayotov (2013). Intuitively, a high interest rate currency generates a higher return than a low interest rate currency because the interest rate difference is not offset by the change in the spot exchange rate. Following Lustig et al. (2011), a forward discount $FD_{i,t}$ is computed as the difference between forward and spot rates at time t:

$$FD_{i,t} = \frac{F_{i,t} - S_{i,t}}{S_{i,t}}. \tag{5}$$

When $FD_{i,t}$ is positive, this means that the interest rate in the foreign country i is higher than that in U.S., since we assume that the covered interest rate parity condition is satisfied.[6] In carry portfolios, investors go long in currencies in which there are high forward discounts. And investors short low forward discount currencies. This study considers strategies at a monthly frequency. We sort currencies using $FD_{i,t}$ and the two highest $FD_{i,t}$ currencies are in the long position and two lowest $FD_{i,t}$ currencies are in the short position in Equations (1) and (2) at the end of each month.

In addition to the standard carry portfolio, we adopt the "good" carry trade strategy proposed by Bekaert and Panayatov (2020). They find that only a limited number of "good" currencies avoid negative skewness and exhibit higher Sharpe ratios. Following Bekaert and Panayatov (2020), we employ the British pound, Canadian dollar, New Zealand dollar and Swedish krona and construct the carry portfolio based upon forward discounts.[7]

2.3. *Momentum strategy*

A momentum currency strategy uses past return as a characteristic, instead of a forward discount. Currency markets are liquid and there are no short-selling constraints. These market characteristics allow investors to implement momentum strategies (Menkhoff et al., 2012b). Menkhoff and Taylor (2007) survey many time series momentum strategies

[6]See for example Akram et al. (2008). After the global financial crisis, covered interest rate parity is not satisfied (Du et al., 2018; Chatziantoniou et al., 2020). This fact, however, does not impact our main conclusion. We employ a rolling regression approach, and hence can exclude the results derived from the recent data.

[7]We also construct the currency portfolio using six currency pairs. In addition to the four currency pairs introduced in this section, we employ the Danish krone and Swiss franc and euro in an online Appendix.

using technical trading rules and conclude that the profitability of technical trading rules depends upon market states. Menkhoff et al. (2012b) propose a cross-sectional momentum strategy that buy (sell) winner (loser) currencies, which generates a higher Sharpe ratio. Following Kroencke et al. (2014) and Barroso and Santa-Clara (2015), we employ the past three months cumulative currency excess return, $PCUM_{i,t}$, as a signal that is described as:

$$PCUM_{i,t} = \prod_{j=0}^{2}(1 + r_{i,t-j}^{long}) - 1 \tag{6}$$

Menkhoff et al. (2012b) report that momentum has persistence, but that including more than the past three months do not provide a higher return. We sort currencies based upon $PCUM_{i,t}$ and construct the momentum portfolio using Equations (1) and (2)

2.4. *Value strategy*

A value strategy exploits information of a fundamental value: if the price of currency i is undervalued compared to its perceived fundamental value, then investors invest in the currency i. For our purposes, perceived fundamental value is represented by purchasing power parity (PPP), and the exchange rate mean reverts to fundamentals in the long-run (e.g. Taylor, 2002; Boudoukh et al., 2016).

The fundamental value is computed as the cumulative five year change of the real exchange rate, as in Kroencke et al. (2014) and Barroso and Santa-Clara (2015). The fundamental value $VA_{i,t}$ is computed as:

$$VA_{i,t} = \frac{S_{i,t-3}CPI_{i,t-60}CPI_{US,t-3}}{S_{i,t-60}CPI_{i,t-3}CPI_{US,t-60}} \tag{7}$$

where $CPI_{i,t-3}$ is the price level of consumer goods in country i at $t-3$, and $CPI_{US,t-3}$ is the U.S. price level. We follow Kroencke et al. (2014) and employ a three month lag to avoid overlaps between momentum and value strategies. Further, Barroso and Santa-Clara (2015) document that a lag value is appropriate, since there is a time shift involved in the observation of price levels. If the fundamental value $VA_{i,t}$ is higher (lower) than one, then it indicates that the currency is overvalued (undervalued). We sort currencies based upon $VA_{i,t}$ and the lowest (highest) k currencies in the long (short) positions in Equations (1) and (2).

2.5. *Dollar carry trade*

The dollar carry trade is based upon the Average Forward Discount (AFD) that is calculated as the average forward discount on foreign currencies against the U.S. dollar (Lustig et al., 2014). AFD_t is calculated as:

$$AFD_t = \sum_{i=1}^{N} \frac{FD_{i,t}}{N}. \tag{8}$$

where N is the number of all currency pairs and $N = 10$ in this study. AFD is associated with the U.S. business cycles and AFD tends to be relatively high during the U.S. economic recessions because the U.S. short-term rate tends to be lower than foreign countries' interest rates.

The dollar carry trade is implemented by going long in all foreign currencies and going short in the U.S. dollar, when AFD is above the U.S. short-term interest rate. This trade is risky for a U.S. investor, since she shorts U.S. dollars during U.S. economic downturns when the demand of the U.S. dollar is high. When AFD is below the U.S. short-term interest rate, the dollar carry trade goes long (short) in the U.S. dollar (all foreign currencies). The payoff of the dollar carry trade is calculated as:

$$\overline{TR}_t^{(AFD)} = \sum_{n=1}^{N} \frac{r_{i,t}^{long}}{N} \quad if \quad AFD_t \geq \ 0$$
$$\overline{TR}_t^{(AFD)} = \sum_{n=1}^{N} \frac{r_{i,t}^{short}}{N} \quad if \quad AFD_t < 0. \tag{9}$$

2.6. *Global imbalances*

Global imbalance (IMB) portfolios are proposed by Della Corte et al. (2016b). This factor is based upon the theory that net debtor countries are riskier than net creditor countries, and hence these countries' currencies provide risk premia. In particular, the net debt countries which are funded by foreign currencies are riskier than those are funded by their own currencies.

The global imbalance factor is constructed in two steps (Della Corte et al. 2016b). Firstly, currencies are separated into two baskets based upon the net foreign asset to gross domestic product ratio (nfa).[8] Secondly, currencies are sorted within each nfa basket, based upon the share of foreign liabilities in domestic currency (ldc).[9] The short positions include two highest ldc currencies within the high nfa basket, which are robust against negative financial shocks. The long positions include two lowest ldc currencies within the low nfa basket, which are risky and provide risk premia. Then, we calculate the total payoff for the global imbalance strategy using Equation (2).

2.7. *Global correlation risk*

This paper also considers a FX correlation risk (ΔFXC) strategy that focuses upon counter-cyclical FX correlations. A portfolio that has low exposure to the correlation risk provides a higher return, since the portfolio does not work as a hedge during recessions.

Following Mueller et al. (2017), we construct a global FX correlation risk portfolio as follows. First, a time-varying correlation between FX spot rate returns is obtained and the rolling window size is three months (66 days). Second, we sort all 36 FX correlations into deciles and take the difference between the average correlation in the top decile and that in the bottom decile.[10] This is called the cross-sectional dispersion in time-varying FX correlation (FXC). Third, we pick up FXC at each end of month and take the innovation part of FXC (ΔFXC). Fourth, we obtain factor betas on ΔFXC using the following 36

[8]The data of foreign assets and liabilities, and gross domestic product are shared by Lane and Milesi-Feretti (2004, 2007).

[9]Data of the proportion of external liabilities denominated in foreign currency are constructed by Lane and Shambaugh (2010) and Benetrix et al. (2015).

[10]When we calculate FX spot rate returns, the base currency is the U.S. dollar.

month rolling regressions:

$$r_{i,t}^{long} = \alpha_i + \beta_{i,FXC}\Delta FXC + \epsilon_i. \tag{10}$$

Fifth, we sort the most traded currencies based upon $\beta_{i,FXC}$ and construct three currency portfolios. Portfolio 1 has low exposure to FX correlation risk and it does not work as a hedge during economic recessions, which leads to a higher return due to the compensation of the risk. The low (high) exposure portfolio is in the long (short) position and the total payoff is calculated by Equation (2).

2.8. *Expected sign of risk-return link for each portfolio*

A simple and standard model in financial economics would expect risk and return to be positively related, irrespective of economic states, in a static unconditional model. But this may not be the case for each portfolio strategy nor for a conditional model. In this subsection we explain the nature of the expected risk-return relationship for each currency strategy.

Expected signs obtained by the unconditional model are classified as the following three groups: positive (value), negative (carry, AFD, IMB, ΔFXC) and indeterminate (mom, good). The value strategy is expected to have a positive intertemporal risk-return relationship. This strategy focuses upon mean-reversion of real exchange rates, which reflects macroeconomic fundamentals. This mean reversion tends to happen during a market crash. Jorda and Taylor (2012) exploit this information to avoid crash risk, which supports our view that there is a positive intertemporal risk-return relationship for the value strategy.

The carry strategy is expected to have a negative risk-return relationship (Bhansali, 2007). Brunnermeier et al. (2009) show that carry trades have unwinding risk and Bakshi and Panayotov (2013) provide empirical evidence that carry trade returns are negatively associated with lagged FX market volatility. The dollar carry trade strategy (AFD) sells foreign currencies during the U.S. recession periods. Economic contractions in the U.S. cause high market uncertainty and an increase in the U.S. dollar demand (e.g. Lilley et al., 2019), which triggers unwind investment positions. Hence, the intertemporal relation may be negative. The global imbalance strategy (IMB) is expected to have a negative risk-return relationship since this strategy tends to sell safe haven currencies (Della Corte et al., 2016b). Low (high) interest rate currencies have positive (negative) exposure to correlation risk, as reported by Mueller et al. (2017). The intertemporal relationship for the global correlation risk strategy (ΔFXC) is expected to have a similar characteristic to the carry strategy.

The good carry strategy is constructed to mitigate the crash risk, and hence the intertemporal relationship may not be strong. There is no clear intertemporal risk-return pattern for the momentum strategy, as shown by Menkhoff et al (2012b) and this is partially explained due to the fact that many FX traders employ technical trades, which are not based upon economic fundamentals (Menkhoff and Taylor, 2007).

Table 1 summarises the expected intertemporal relationships between risk and returns for currency investing strategies.[11] However, these relationships may depend upon market states. Ghysels et al., (2014) focus upon the stock market and uncover that there is a negative intertemporal risk-return relationship during flight-to-quality periods, while they see a positive relationship during normal periods. Adrian et al. (2019) reveal that an increase in the stock market return and a decline in the Treasury return during moderate stock market volatility periods. These relationships reverse during extremely high volatility periods, including the global financial crisis in 2008.

The FX carry trade strategy is expected to have a similar pattern to the stock market, because it has exposure to downside stock market risk (Lettau et al., 2014). We expect strategies including the dollar carry, global imbalances and global correlation risk have

[11] The online Appendix provides the theoretical model to motivate the risk-return relationship. This follows Backus et al. (2001) and Lustig et al. (2011, 2014), setting up exchange rate returns as related to differences in stochastic discount factors, which are empirically proxied by currency volatility.

similar risk exposure to the carry, and hence they are expected to have positive (negative) risk-return relationships during normal (flight-to-quality) periods. In contrast, the value strategy is expected to have the opposite relationship since typical investing currencies are sold and the prices revert to the fundamental values during flight-to-quality periods (Ranaldo and Söderlind, 2010; Jorda and Taylor, 2012; Ready et al., 2017a). Therefore, the value strategy elicits a positive (negative) risk-return relationship during flight-to-quality (normal) periods.

3. Empirical methodology

This section describes the econometrics methods used to test risk-return trade-offs in FX markets, and to identify the time varying parameter for variance risk. We employ a factor model to summarise a large information set based upon many macroeconomic indicators. Regressing FX volatility onto common factors, we obtain predicted FX volatility. Furthermore, we use a conditional factor model that allows for a change in risk-return relationship.

3.1. *Factor model*

We begin by explaining the way in which we obtain common information, which underpins our volatility measure. The common information across macroeconomic data sets is extracted by principal components. Define $\mathbf{X}$ to be the $T \times N$ standardised macroeconomic time series matrix with elements, $x_{j,t}$, $j = 1, \ldots, N$, $t = 1, \ldots, T$, and N indicates the number of macroeconomic time series and T does that of time series observations. Each macroeconomic time series, $x_{j,t}$, is decomposed into a common factor, f_t, and an idiosyncratic component, $\epsilon_{j,t}$, as:

$$x_{j,t} = \Lambda_j f_t + \epsilon_{j,t} \tag{11}$$

where Λ_j is the loading on the common factor. To obtain the common factors and factor loadings, all data series should be stationary. Moreover, each macroeconomic indicator has different volatility and hence we transform the data series stationary series and implement standardisation.

Given the estimated common factors in Equation (11), we employ a factor model to obtain conditional volatility, since adopting many conditional variables may result in a dimensionality problem. Following Ludvigson and Ng (2007), FX volatility, $\sigma_{FX,t+1}$, is regressed onto a common factor f_t and an error term e_{t+1}:

$$\sigma_{FX,t+1} = \phi f_t + e_{t+1}. \tag{12}$$

Once we estimate the parameter ϕ, we obtain predicted FX volatility $\hat{\sigma}_{FX,t+1}$. We employ two types of global FX volatility for later analysis. The first one ($\sigma_{FX,t+1}$) is based upon the actual value as described in Section 2.1. The second one ($\hat{\sigma}_{FX,t+1}$.) is estimated by the factor model in Equation (12).

3.2. *Time-varying conditional factor model*

Next, we describe a nonparametric approach to estimate a time-varying conditional factor model. Let $ret_{i,t+1}$ be the excess return (average payoff) of currency portfolio i at time $t+1$, and $\sigma_{FX,t}$ is FX volatility. The excess return is represented by the following conditional factor model:

$$ret_{i,t+1} = \alpha_{i,t+1} + \beta_{i,t+1}\sigma_{FX,t} + \epsilon_{i,t+1} \tag{13}$$

where $\alpha_{i,t+1}$ is the time-varying conditional alpha and $\beta_{i,t+1}$ is the time-varying factor loading (or beta) for portfolio i. The error term $\epsilon_{i,t+1}$ has conditional expectation $E[\epsilon_t \mid \sigma_{FX,t}, \beta_{i,t+1}] = 0$ and conditional variance $E[\epsilon^2_{i,t+1} \mid \sigma_{FX,t}, \beta_{i,t+1}] = \Omega_{t+1}$. Following Ang and Kristensen (2012), we obtain $\alpha_{i,\tau}$ and $\beta_{i,\tau}$ at any point τ in the interval $0 \leq \tau \leq T$ to minimize the following local kernel-weighted least-squared residuals:

$$[\hat{\alpha}_{i,\tau}, \hat{\beta}_{i,\tau}] = \arg\min_{(\alpha,\beta)} \sum_{t=1}^{T} K_{h_i T}(t-\tau)(ret_{i,t+1} - \alpha_i - \beta_i \sigma_{FX,t})^2 \tag{14}$$

where $K_{h_iT} = K(z/(h_iT))/(h_iT)$ with $K(\cdot)$ being a kernel with bandwidth $h_i > 0$. We choose the Gaussian kernel, which is widely used in the finance literature. See for example Ang and Kristensen (2012) and Adrian et al. (2015). Estimated parameters $\hat{\alpha}_{i,\tau}$ and $\hat{\beta}_{i,\tau}$ are obtained by solving Equation (14). We need to choose bandwidths to solve Equation (14). Kristensen (2012), and Ang and Kristensen (2012) employ a "plug-in" method to select the bandwidths, since cross-validation procedures may provide extremely small bandwidths.[12]

4. Data

4.1. *Currency data*

This study uses daily spot and one-month forward rates against the U.S. dollar, obtained from Datastream. Following Kroencke et al. (2014) and Bakshi and Panayotov (2013), we employ the most liquid 10 currencies which are widely used in currency investment strategies.[13] Currency portfolios are rebalanced at the end of every month. The full time series span is from December 1983 to April 2017.[14]

4.2. *U.S. and global macroeconomic data*

U.S. and global macroeconomic data are central to our analysis as these are used to construct our empirical factor model. We employ 88 U.S. macroeconomic indicators, as in Ludvigson and Ng (2007). The groups of series included are: income, consumption,

[12]See Kristensen (2012), and Ang and Kristensen (2012).

[13]The most liquid 10 currencies are constructed by the Australian dollar (AUD), Canadian dollar (CAD), Danish krone (DKK), Swiss franc (CHF), British pound (GBP), Japanese yen (JPY), Norwegian krone (NOK), New Zealand dollar (NZD), Swedish krona (SEK), and euro (EUR). We replace the Deutsche mark with the euro prior to 1999.

[14]To compute real exchange rates, the Consumer Price Index is obtained from OECD/Main Economic Indicators.

employment, production, housing starts, producer and consumer prices, interest rates, money supply, and stock markets.

In addition to the U.S. data set, this study employs global macroeconomic data series and Filippou and Taylor (2017) address the idea that the global data are important for exchange rate markets. The global data series are obtained from the countries which have the most liquid 10 currencies and we employ 57 macroeconomic indicators: employment, production, producer and consumer prices, interest rates, foreign reserves, and stock markets.[15] The U.S. and the global data series are mainly downloaded from the Federal Reserve Bank of St. Louis, and extend from January 1984 to September 2016.[16] We linearly interpolate some quarterly values to obtain data at the monthly frequency, as in Vissing-Jørgensen and Attanasio (2003). U.S. factors are denoted by F_j and global factors are denoted by G_j. All data series are transformed based upon unit root tests and standardised to estimate factor models.

5. Empirical results

To assess relationships between risk and return, we present empirical evidence in this section. First, we report the summary statistics of the currency portfolios in Section 5.1. and the result of the unconditional model that employs actual FX volatility as risk in Section 5.2. Second, we estimate FX volatility using a large number of macroeconomic indicators in Section 5.3. Third, we investigate the risk-return relationship using the estimated FX volatility in Section 5.4. Finally, we present our main results that adopt the time-varying conditional model and how the risk-return relationship varies over time for each currency portfolio in Section 5.5.

[15] We do not include trade balance data since they cover a relatively shorter period compared with other global data. However, we include the trade balance data, it did not impact our results. We follow Filippou and Taylor (2017) and do not not prepare for the same data sets for all countries due to data availability

[16] As Equation (12) uses predicted FX volatility, currency portfolio returns extend by September 2016.

5.1. *Descriptive statistics*

We begin our empirical results section with summary statistics for each currency portfolio. Panel A of Table 2 shows that average annualised excess return, annualised standard deviation, return skewness, return kurtosis, monthly maximum values, monthly minimum values and Sharpe ratios. An average annual excess return of the carry portfolio which goes long in two currencies and goes short in two currencies is 3.03%. The carry portfolio shows negative skewness, which is a typical characteristic of carry portfolios (e.g. Brunnermeier et al., 2009; Bakshi and Panayotov, 2013). In contrast, the "good" carry trade portfolio does not have negative skewness and the Sharpe ratio is higher than that of the carry portfolio (Bekaert and Panayotov, 2020). Panel B of Table 2 reports the summary statistics for individual currency pairs. We note that the currency portfolios generate higher Sharpe ratios than the individual currency pairs, since the portfolios diversify risk.

5.2. *The risk-return relation estimated unconditionally*

Before estimating conditional models, we present unconditional results as a benchmark and motivation for our main approach. Actual volatility at time t ($\sigma_{FX,t}$) is regressed onto the expected return for each currency strategy i, at time $t{+}1$ ($ret_{i,t+1}$) and an unconditional model is written as:

$$ret_{i,t+1} = \alpha_i + \beta_i \sigma_{FX,t} + \epsilon_{i,t+1} \tag{15}$$

where α_i is the unconditional alpha and β_i is the unconditional beta.

Table 3 displays the parameter estimates for the unconditional model, and column (1) indicates that the estimated parameter for carry is negative and marginally statistically significant at the 10% level. This negative value of β implies that additional risk is associated with lower return, which is consistent with Bhansali (2007) and Bakshi and Panayotov (2013), although the unconditional beta is not strongly statistically significant. In contrast, the estimated carry α is statistically significant at the 5% level. The carry return is associated with a global business cycle, which means that past FX volatility is not sufficient to explain the expected return (Bakshi and Panayotov, 2013; Ready et al., 2017a; Byrne et al., 2019). Economic states which are captured as volatility in our study, are linked to changes in the investment opportunity set (Meron, 1973). When volatility bears a negative risk price in the cross-sectional context, the relationship between volatility and asset returns should be negative (Maio and Santa-Clara, 2012). The risk price on FX volatility is negative in the carry portfolio, as report by Menkhoff et al. (2012a), and hence β in the carry portfolio is negative.[17] Given that β is not important for any other portfolios and R^2s are consistently low, which contrasts with the result for the carry portfolio. Potentially the volatility beta β is washed out using an unconditional approach and a time varying approach would result in a better empirical model for currency risk and return.

5.3. *Volatility estimation results*

In the previous section we identified a weak unconditional relationship between expected return and volatility. Now, we investigate this relationship using a conditional approach. First, we examine estimated volatility using the factor model in Equation (12). Table 4 presents parameter estimates for the factor model and column (1) uses only U.S. common factors (F_j). We adopt a general-to-specific approach and only retain statistically significant parameters. The common factors F_1 and F_5 are the main drivers explaining future FX volatility. Following Ludvigson and Ng (2007), we obtain marginal-R^2 to interpret these factors, and F_1 is strongly linked to output variables such as industrial production growth.[18] This is associated with the idea that industrial production captures business cycles (e.g. Lustig et al. 2014). Furthermore, F_5 is associated with money supply and commercial banks' assets. Both level and squared terms of F_1 and F_5 are statistically

[17]Moreira and Muir (2017) and Suh (2019) report low volatility leads to a higher Sharpe ratio and a higher profit of the carry trade strategy.

[18]See an online Appendix Figure A4.

significant at least at the 5% level in Table 4.

We add lagged FX volatility in column (2) of Table 4, since Guo and Whitelaw (2006), and Moreira and Muir (2017) report that lagged volatility is important to predict stock market volatility. We confirm the same result for FX volatility: including lagged FX volatility increases R^2 to 0.53. The empirical result also suggests that the lagged FX volatility drives out F_5, F_4^2, and F_5^2, while the real output factor F_1 remains statistically significant, which suggests that U.S. real output is strongly linked to future FX volatility.

Next, global common factors (G_j) are considered in the empirical model. Column (3) in Table 4 implies that the level and squared global factors G_5, G_1^2, and G_5^2 are statistically significant at least at the 5% level. G_1 is strongly correlated with producer price indices and G_5 is the short-term interest rate factor. There is marginal incremental information however by including the global factor, since a R^2 in column (3) is 0.40, which is almost similar to that of column (1).

Finally, we consider whether both global factors and lagged FX volatility explain volatility in column (4) of Table 4. We observe that the US real output factor and the lagged FX volatility are the main drivers of FX volatility. Global factors, in levels and squared, G_5, G_4^2, and G_5^2 have incremental information for the model: as mentioned, G_5 is the interest rate factor and G_4 is related to central banks' reserves. It is reasonable that global reserves and interest rate factors have different information from the U.S. real output factor. In summary, the U.S. factors, the global factors, and the past FX volatility predict future FX volatility.

FX volatility estimated by the factor model tracks actual FX volatility but with some advantages. Figure 1 compares the estimated and the actual FX volatilities. Interestingly, the actual volatility has more frequent spikes than the estimated volatility, which is consistent with the notion that actual volatility contains relatively more noise than signal. The converse is the case with model estimated volatility since it summarises a large amount of information. We will use the fitted value of the final model in Table 4 column (4) for the next risk-return trade-off analysis. Although the R^2 of column (2) is slightly higher than that of column (4), while employing the latter model is more reasonable since it includes both U.S. and global information.

5.4. *The risk-return relation estimated by factor model*

Given we have estimated future FX volatility, we now investigate risk-return relations using a factor model. Utilising the estimated volatility allows us to take investors' expectations into account. Furthermore, if risk-return trade-offs in foreign exchange rate markets are associated with business cycles, it is reasonable to employ global macroeconomic information. To extract information from a large number of macroeconomic indicators, we adopt an empirical factor model (e.g. Ludvigson and Ng, 2007). We repeat the same estimation reported in Table 3, while we replace actual FX volatility with estimated FX volatility based upon the discussion in the previous section.

Table 5 presents the risk-return relation between estimated FX volatility and expected currency portfolio returns. We find the risk-return parameters for the carry and IMB portfolios are negative and statistically significant and R^2s are also improved compared with those of Table 3. These results highlight the importance of the common component across macroeconomic measures as in Ludvigson and Ng (2007) and Jurado et al. (2015). However, the risk-return relationships for the other portfolios are insignificant using the factor model, which is not revealed by the previous literature.

In summary, we observe that the factor model enhances the negative risk-return relationships for some currency portfolio results including carry and IMB but not others.

5.5. *Time-varying risk-return relation*

The negative relation between conditional volatility and the expected return on carry and global imbalance portfolios may be due to a lack of time variation of the parameters. Although we extract investors' information by adopting the empirical factor model, it may not be sufficient to fully reflect changes in economic states. Indeed, the relationship between conditional volatility and expected returns varies over time in the U.S. and European stock markets (e.g. Rossi and Timmermann, 2010; Ghysels et al., 2014; Aslanidis et al., 2016). This study employs the time-varying conditional factor model proposed by Ang and Kristensen (2012), which does not impose any specifications on conditioning variables and parameters, and allows continuous changes in model parameters.

Now, we move on to our main empirical findings and Figure 2 presents time-varying risk-return parameters with 90% confidence intervals. We adopt the same model in Table 5 and the risk-return parameter of the carry portfolio is negative whereas the magnitude varies over time. It is close to zero around the years 2000 and 2012, while there are troughs around 1997 and 2006.[19] We expect that the carry portfolio has both positive and negative risk-return relationships, which is similar to the stock market results uncovered by Ghysels et al. (2014) and Adrian et al. (2019). In particular, the carry trade strategy shares the common characteristic with the stock market, and both carry and stock portfolios are vulnerable during flight-to-quality periods.[20] However, the empirical result provides that the negative relationship is observed in most periods. This is different from the results in the stock market, which shows the negative intertemporal relationship during only flight-to-quality periods. This discussion is also applicable to the IMB, and ΔFXC portfolios, which provides the negative risk-return relationships in most periods.

Interestingly, for both value and momentum portfolios the risk-return parameters exhibit wider fluctuations and indeed flip signs, as demonstrated by Figure 2. This could help understand why we do not observe significant relations between conditional volatility and expected returns in Table 5. The momentum portfolio parameter reaches 0.2 and that of the value portfolio attains 0.4. Ghysels et al. (2014) and Adrian et al. (2019) posit that the negative intertemporal risk-return relationships are associated with flight-

[19] We also estimate the time-varying relations with actual FX volatility in an online Appendix. The impact becomes weaker than that of the estimated FX volatility model.

[20] Recent studies about relationships between the global financial crisis and the carry trade are provided by Ready et al. (2017b), Bussiere et al. (2019) and Lilley et al. (2019).

to-quality episodes. Jorda and Taylor (2012) suggest that the value strategy creates a better performance during market turmoil, since nominal exchange rates mean revert to the fundamental values.

To investigate how flight-to-quality episodes affect the intertemporal relationships, we focus upon three crisis periods: the Long Term Capital Management (LTCM) crisis, the global financial crisis and the euro debt crisis. The LTCM crisis is defined from January 1998 to April 1999 (Kho et al., 2000), the global financial crisis is defined from August 2007 to March 2009 (Bekaert et al., 2014) and the euro debt crisis is defined from January 2010 to December 2012 (Stracca, 2015). Table 6 demonstrates the average return and the Sharpe ratio for each currency strategy during the crisis periods. We note that the value strategy generates the highest returns and the Sharpe ratio during the LTCM and global financial crises. This confirms our result that the flight-to-quality episodes are positively associated with the risk-return relationship for the value strategy due to the mean reversion, which is different from the stock market evidence (Ghysels et al., 2014) but similar to the Treasury market (Adrian et al., 2019). The financial crises cause strong demand for safe haven currencies, which tend to be undervalued during normal periods and result in the strong performance of the value strategy (Ranaldo and Söderlind, 2010; Jorda and Taylor, 2012; Ready et al., 2017a).

In contrast, Table 6 illustrates that flight-to-quality episodes have less of an impact upon the momentum portfolio. This is because the momentum trade does not focus upon specific economic fundamentals for each country, see Menkhoff and Taylor (2007) and Menkhoff et al. (2012b). Figure 2 provides empirical evidence that there exist the positive risk-return relationships for the momentum and value portfolios during the global financial crisis, while the results suggest that different mechanisms work in these two strategies. Another observation worth mentioning is that the carry and the global imbalance strategies suffer large losses during the global financial crisis, consistent with other work (Brunnermeier et al., 2009). Finally, from Table 6 we can see that for each investment strategy the Sharpe ratio can vary across different crises. Given that Sharpe ratios are not state independent, this also reinforces the point that the relationship between returns and volatility is not constant.

6. Further analysis and discussion

The results obtained in the previous section demonstrate the importance of introducing time variation when examining a variety of currency investment strategies. In this section we provide further analysis. First, we use a rolling regression approach that is widely employed to obtain time-varying coefficients. Second, we formally test whether time-varying risk-return relations are associated with business cycles. Third, we discuss the relationship between our results and related studies. Finally, we use different specifications for FX volatility estimation.

6.1. *Rolling regression approach*

Section 6 presented formal statistical evidence of time-varying relations between conditional volatility and returns. Given we use a data intensive non-parametric approach, we may, however, have insufficient data to successfully draw confidence intervals. We also employ therefore a more conservative rolling regression approach to examine time variations (e.g. Lustig et al., 2011). We choose a rolling window size as an optimal bandwidth employed in the previous section.

Figure 3 demonstrates the time-varying relations obtained by the rolling regressions. Our main findings remain the same and the risk–return parameters on the momentum and the value portfolios flip signs. More importantly, both parameters increase in the financial crisis and these confidence intervals are above zero. Derived optimal bandwidths of good carry, AFD, and ΔFXC portfolios are large, and the estimation periods are short. In addition, we find that the zero axis is within error bands more frequently for the rolling regression, since the nonparametric regression fits local data and has a more flexible functional form.[21]

6.2. *Characterizing changes in risk-return trade-offs*

Having found that the risk-return trade-off varies over time, we explore whether these changes are driven by business cycles. We observed that the value, carry and global imbalance strategies were associated with the flight to quality episodes (Ghysels et al., 2014; Adrian et al., 2019). However, the time-varying risk-return relationship for the momentum strategy may be driven by other mechanisms in the previous section. We consider that one possible driving force is changes in the macroeconomic environment. To investigate whether macroeconomic states impact the relationship, we regress a change in the risk-return parameter $\beta_{i,t}$ in Equation (13) for each result onto changes in U.S. and global industrial production growths and those in changes in U.S. and global short-term rate. We employ global industrial production growth and global short-term rate as first principal components of G10 countries excluding U.S. data. Then, following Lustig et al. (2014) and Bekaert and Panayotov (2020), we extract a residual by regressing the U.S. variable onto the global variable.

The change in $\beta_{i,t}$ of the momentum portfolio is driven by U.S. industrial production growth and the global short-term rate. Weak business conditions are proxied by low industrial production growth and a high interest rate (Ang and Kristensen, 2012; Lustig et al., 2014). Results in Table 7 indicate that the momentum portfolio is consistent with the risk story. U.S. industrial production growth, ΔIP_{us}, and the global short-term rate, Δi_{world}, are statistically significant at the 1% level. Also the estimated coefficient in Table 7 on ΔIP_{us} has a negative sign and Δi_{world} has a positive sign. This is consistent with the momentum risk-return relationship being counter-cyclical: risk requires greater compensation in a downturn, than would otherwise be the case. Finally, the result of the ΔFXC

[21] For an econometric critique of rolling windows in conditional asset pricing models see Gagliardini et al. (2016).

portfolio is similar to that of the momentum portfolio, while the change in $\beta_{i,t}$ for the ΔFXC portfolio is slow, we should be cautious to conclude that the risk-return trade-off hold for the ΔFXC portfolio.

6.3. *Discussion of counter-cyclicality*

Having uncovered a countercyclical-risk-return relationship in the momentum portfolio, we consider why this portfolio displays this clear pattern. This contrasts with investment strategies focused upon single currency pairs, because Menkhoff and Taylor (2007) report that FX traders frequently employ technical trades which are not based upon macroeconomic fundamentals.

We focus upon cross-sectional currency portfolios which are rebalanced at a monthly frequency. This monthly rebalancing operation is associated with institutional and/or individual investors who have substantial financial knowledge. For instance, Calvet et al. (2009) find that Swedish households with greater knowledge tend to rebalance their financial portfolios more actively. Cohn et al. (2015) conduct an experiment with financial professionals and observe that they become more risk-averse in financial downturns. In theory, Chien et al. (2012) consider why most investors do not rebalance their portfolios frequently, and therefore a small number of the professional investors account for aggregate risk shocks. This mechanism causes a counter-cyclical risk price which is consistent with our momentum results. The momentum strategy is widely employed in currency markets by professional investors, as reported by Pojarliev and Levich (2010).

6.4. *Other factors of FX volatility*

We consider other factors that may be associated with global FX volatility. Market liquidity is important for the FX markets and may impact FX volatility. Credit and liquidity risks are important for the FX markets and may impact FX volatility. Following Brunnermeier et al. (2009) and Menkhoff et al. (2012a), we employ the TED spread as a credit factor and the global bid-ask spread (BAS) as a FX market liquidity factor. The TED spread is calculated as the spread between three-month Treasury Bill and three-month LIBOR.[22] The details about the global BAS are provided by an online Appendix. Both variables have autocorrelation and we use innovation components by taking a first difference or residuals for the AR(1) model (Menkhoff et al., 2012a). Table A3 presents that including ΔTED causes a marginal increase in the R^2. Table A4 confirms that employing FX volatility estimated by the factor model with ΔTED does not change our conclusion.

Investors' expectation for macroeconomic indicators may be important for FX volatility.[23] We employ a change in expected inflation for the United States and for other countries (respectively $\Delta DEI - US$ and $\Delta DEI - G$) from Chen et al. (1986) and Cooper et al., (2020). We also use newspaper based equity market volatility (EMV) proposed by Baker et al. (2019). EMV is constructed by texts related to macroeconomic news. Table A3 presents empirical evidence that our estimation results are robust after controlling for different measures of expectations.

7. Conclusion

We explore intertemporal risk-return relationships for currency investment strategies. It is well known that the carry strategy has negative risk-return relationship because it takes exposure to FX volatility and downside stock market risk (Menkhoff et al., 2012a; Bakshi and Panayotov, 2013; Dobrynskaya, 2014; Lettau et al., 2014). Recently, many new currency investment strategies are proposed in the literature and the risk exposure is actively explored in the cross-sectional context. However, intertemporal risk-return relationships are still open, except for the carry strategy. We do not assume that the discussion of the carry strategy is applicable to the other strategies because their portfolio construction motivation is based upon different theories. Therefore, we investigate intertemporal

[22]To calculate the TED spread, we cannot cover the entire sample period by LIBOR. We employ the three-month interbank rate in the U.S. to cover a longer period.

[23]Balduzzi et al. (2001) investigate the effectiveness for the term structure.

risk-return relationships for momentum (Menkhoff et al, 2012a), value (Asness et al, 2013), dollar carry trade (Lustig et al. 2014), global imbalances (Della Corte et al. 2016b), good carry trade (Bekaert and Panayotov, 2020), and foreign exchange rate correlations (Mueller et al. 2017).

We introduce a time-varying relation in our analysis of the FX market, since a conditional relationship between excess return and systematic risk is frequently considered to be a key characteristic in the stock market (Whitelaw, 2000). We find that the intertemporal risk-return relationships for the momentum and value portfolios vary over time. There is a positive risk-return relationship for the value portfolio during flight to quality periods, while the relationship becomes negative during more normal periods. This result is consistent with the Treasury market (Adrian et al., 2019) and is the opposite result to the stock market (Ghysels et al., 2014). The value strategy focuses upon mean reversion to the fundamental values for exchange rates. Investors demand safe haven currencies which are categorized as the low interest rate currencies during the flight to quality periods, which leads to mean reversion to the fundamental values (Jorda and Taylor, 2012).

In contrast, the momentum strategy is less affected by the flight to quality periods. The time-varying intertemporal risk-return relationship is counter-cyclical for the momentum portfolio. Investors require positive compensation for risk in recessions. We also uncover that the intertemporal risk-return relationships for the carry and the global imbalance portfolios vary over time while the signs are negative for most periods, which suggests that the time variation does not play an important role for these strategies.

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Table 1. Expected signs for currency portfolios

Strategy	*carry* (i)	*mom* (ii)	*value* (iii)	*good* (iv)	AFD (v)	IMB (vi)	ΔFXC (vii)
Signs	Negative	$\times$	Positive	$\times$	Negative	Negative	Negative

Notes: This table summarises expected signs for currency portfolios including seven strategies: (i) carry, (ii) momentum, (iii) value, (iv) "good" carry (good, Bekaert and Panayotov, 2020), (v) Average Forward Discount (AFD, Lustig et al., 2014), (vi) global imbalances (IMB, Della Corte et al., 2016b), and (vii) global correlation risk (ΔFXC, Mueller et al., 2017). Carry, momentum, value, global imbalance and "good" carry portfolios include four currency pairs. $\times$ indicates indeterminate.

Table 2. Descriptive Statistics

Panel A: Currency portfolios							
	Mean	Std.dev	Skew	Kurt	Max	Min	SR
carry	3.03	8.91	-0.40	4.82	10.84	-10.57	0.34
mom	1.63	9.44	0.44	4.96	12.52	-6.90	0.17
value	3.46	9.09	0.07	4.75	11.19	-10.34	0.38
good	4.04	8.07	0.56	5.58	12.77	-7.33	0.50
AFD	4.50	8.27	0.03	3.80	10.32	-7.29	0.54
IMB	1.45	9.46	-0.93	9.93	10.49	-18.26	0.15
ΔFXC	2.53	8.32	-0.25	4.56	7.09	-10.65	0.30

Panel B: Individual currency pairs							
	Mean	Std.dev	Skew	Kurt	Max	Min	SR
AUD	1.65	11.34	-0.34	4.76	9.59	-15.87	0.15
CAD	0.26	7.33	-0.46	7.28	8.35	-12.77	0.04
DKK	1.72	10.77	-0.02	3.49	9.77	-10.33	0.16
EUR	0.29	10.90	-0.07	3.42	9.54	-10.38	0.03
JPY	-1.42	11.29	0.47	4.72	16.26	-10.58	-0.13
NZD	2.63	11.80	-0.19	5.01	13.58	-13.01	0.22
NOK	1.39	11.09	-0.26	3.69	7.89	-12.12	0.13
SEK	0.82	11.05	-0.21	3.97	9.49	-14.36	0.07
CHF	-0.57	11.68	0.17	3.78	13.78	-11.36	-0.05
GBP	1.27	10.25	-0.01	5.32	14.92	-11.90	0.12

Notes: This table reports annualised mean, annualised standard deviations, skewness, kurtosis, maximum, minimum, and the Sharpe ratio (SR) of excess returns of currency portfolios and individual currency pairs. Panel A employs seven currency portfolios: carry, momentum, value, "good" carry (good, Bekaert and Panayotov, 2020), Average Forward Discount (AFD, Lustig et al., 2014), global imbalances (IMB, Della Corte et al., 2016b), and global correlation risk (ΔFXC, Mueller et al., 2017). Carry, momentum, value, global imbalance and "good" carry portfolios include four currency pairs. Panel B presents summary statistics of currency pairs' excess returns and they are calculated against the U.S. dollar. These results include transaction costs. The main data sample period extends from January 1984 to April 2017, while AUD starts from November 1989 and NZD does from June 1990. We replaced the Deutsche mark with the euro prior to 1999.

Table 3. Expected Return and Volatility Risk

	(1) carry	(2) mom	(3) value	(4) good
α	1.00**	0.42	0.19	0.83
	(0.43)	(0.55)	(0.48)	(0.38)
β	-0.07*	-0.03	0.01	-0.05
	(0.05)	(0.05)	(0.04)	(0.04)
adj-R^2(%)	0.6	-0.1	-0.2	-0.2
	(5) AFD	(6) IMB	(7) ΔFXC	
α	0.79	0.62	0.40	
	(0.48)	(0.94)	(0.51)	
β	-0.04	-0.05	-0.02	
	(0.05)	(0.10)	(0.05)	
adj-R^2(%)	0.1	0.1	-0.2	

Notes: This table presents time series regressions of excess returns of the currency portfolio on a constant and lagged global FX volatility. We run the following time-invariant regression model: $ret_{i,t+1} = \alpha_i, + \beta_i \sigma_{FX,t} + \epsilon_{i,t+1}$, where i indicates the i's currency portfolio. We employ seven currency portfolios: carry, momentum, value, "good" carry (good, Bekaert and Panayotov, 2020), Average Forward Discount (AFD, Lustig et al., 2014), global imbalances (IMB, Della Corte et al., 2016b), and global correlation risk (ΔFXC, Mueller et al., 2017). The standard errors are reported in parentheses and obtained by the Newey and West (1987) procedure with optimal lag selection according to Andrews (1991). The adjusted R^2 is also reported. *,**, and *** indicate significance at the 10%, 5% and 1% levels, respectively. The sample period is between January 1984 and September 2016.

Table 4. Results of Volatility Estimation Using the Factor Model

	(1)	(2)	(3)	(4)
constant	9.48***	4.72***	9.61***	4.41***
	(0.22)	(0.44)	(0.25)	(0.43)
F_1	1.00***	0.71***	1.11***	0.96***
	(0.21)	(0.20)	(0.26)	(0.26)
F_2			0.35**	
			(0.16)	
F_5	0.31**			
	(0.15)			
F_1^2	0.40***	0.21**		
	(0.06)	(0.09)		
F_2^2			-0.25*	
			(0.14)	
F_3^2			-0.19* *	
			(0.09)	
F_4^2	0.51***		0.53***	
	(0.15)		(0.13)	
F_5^2	0.18***			
	(0.06)			
G_5			0.28**	0.37**
			(0.14)	(0.18)
G_1^2			0.43***	
			(0.07)	
G_4^2				-0.09**
				(0.05)
G_5^2			0.08***	0.09**
			(0.02)	(0.04)
σ_{t-1}^2		0.52***		0.57***
		(0.04)		(0.04)
adj-R^2	0.39	0.53	0.40	0.51

Notes: This table presents time series regressions of future global FX volatility on common factors. The common factors are obtained as in Ludvigson and Ng (2007), and F_j indicates U.S. and G_j indicates global factors. We also include square terms of the U.S. and the global factors. The standard errors are reported in parentheses and obtained by the Newey and West (1987) procedure with optimal lag selection according to Andrews (1991). The adjusted R^2 is also reported. *,**, and *** indicate significance at the 10%, 5% and 1% levels, respectively. The sample period is between January 1984 and September 2016.

Table 5. Expected Return and Volatility Risk: Factor Model

	(1) carry	(2) mom	(3) value	(4) good
α	3.48***	-0.17	-0.20	0.89
	(0.70)	(1.11)	(0.98)	(0.39)
β	-0.31***	0.03	0.05	-0.05
	(0.07)	(0.11)	(0.10)	(0.06)
adj-R^2(%)	7.6	-0.2	-0.1	-0.0
	(5) AFD	(6) IMB	(7) ΔFXC	
α	0.56	3.38**	1.28	
	(0.79)	(1.66)	(0.95)	
β	-0.02	-0.31*	-0.10	
	(0.08)	(0.17)	(0.09)	
adj-R^2(%)	-0.2	6.9	0.7	

Notes: This table presents time series regressions of excess returns of the currency portfolio on a constant and predicted global FX volatility, $\hat{\sigma}_{FX,t}$, which is obtained by the factor model. We run the following time-invariant regression model: $ret_{i,t+1} = \alpha_{i,} + \beta_i \hat{\sigma}_{FX,t} + \epsilon_{i,t+1}$, where i indicates the i's currency portfolio. We employ seven currency portfolios: carry, momentum, value, "good" carry (good, Bekaert and Panayotov, 2020), Average Forward Discount (AFD, Lustig et al., 2014), global imbalances (IMB, Della Corte et al., 2016b), and global correlation risk (ΔFXC, Mueller et al., 2017). Carry, momentum, value, global imbalance and "good" carry portfolios include four currency pairs. The standard errors are reported in parentheses and obtained by the Newey and West (1987) procedure with optimal lag selection according to Andrews (1991). The adjusted R^2 is also reported. *,**, and *** indicate significance at the 10%, 5% and 1% levels, respectively. The sample period is between January 1984 and September 2016.

Table 6. Excess returns and the Sharpe ratio during financial crises

	carry	mom	value	good	AFD	IMB	ΔFXC
Panel A: Excess returns							
LTCM	-0.38	0.02	1.24	-0.13	0.40	0.08	0.31
GFC	-1.06	0.08	1.34	-0.23	0.08	-1.93	-0.48
EURO	0.10	-0.14	-0.19	-0.07	-0.39	-0.07	0.34
Average	-0.45	-0.02	0.80	-0.14	0.03	-0.64	0.06
Panel B: Sharpe ratio							
LTCM	-0.11	0.01	0.36	-0.07	0.24	0.05	0.10
GFC	-0.24	0.02	0.29	-0.09	0.02	-0.32	-0.13
EURO	0.04	-0.05	-0.08	-0.04	-0.14	-0.02	0.15
Average	-0.10	-0.01	0.19	-0.07	0.04	-0.10	0.04

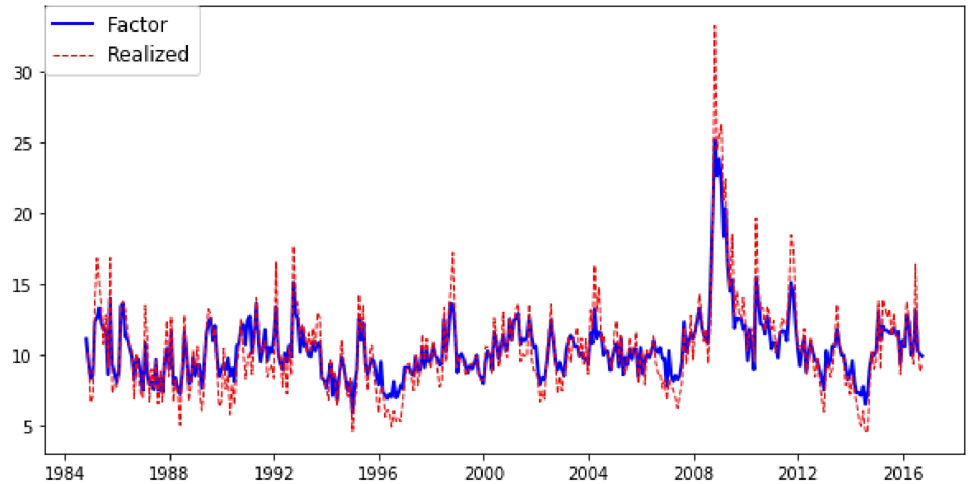
Notes: This table presents excess returns and the Sharpe ratio for currency portfolios during the financial crises. The currency portfolios include carry, momentum, value, "good" carry (good, Bekaert and Panayotov, 2020), Average Forward Discount (AFD, Lustig et al., 2014), global imbalances (IMB, Della Corte et al., 2016b), and global correlation risk (ΔFXC, Mueller et al., 2017). Carry, momentum, value, global imbalance and "good" carry portfolios include four currency pairs. The LTCM crisis is defined from January 1998 to April 1999 (Kho et al., 2000), the global financial crisis (GFC) is defined from August 2007 to March 2009 (Bekaert et al., 2014) and the euro debt crisis (EURO) is defined from January 2010 to December 2012 (Stracca, 2015). In addition, we provide average values across three crises. The Sharpe ratio is calculated at a monthly frequency.

Table 7. Explaining Changes in Risk-return Trade-offs

	(1) carry	(2) mom	(3) value	(4) good
constant	-0.14	-0.02	-0.02	0.00
	(0.21)	(0.22)	(0.21)	(0.02)
Δi_{us}	0.02	0.59	1.31*	-0.05
	(0.61)	(0.64)	(0.68)	(0.05)
Δi_{world}	0.12	0.31***	-0.27**	0.01
	(0.13)	(0.12)	(0.11)	(0.01)
ΔIP_{us}	0.37*	-0.41***	0.47**	0.01
	(0.19)	(0.14)	(0.19)	(0.02)
ΔIP_{world}	0.04	-0.05	-0.02	-0.01
	(0.08)	(0.05)	(0.06)	(0.01)
adj-R^2(%)	1.2	2.7	6.5	0.2
	(5) AFD	(6) IMB	(7) ΔFXC	
constant	0.00	-0.18	-0.08**	
	(0.02)	(0.34)	(0.04)	
Δi_{us}	-0.05	0.89	0.11	
	(0.04)	(1.07)	(0.10)	
Δi_{world}	0.01	0.25	0.08**	
	(0.01)	(0.16)	(0.03)	
ΔIP_{us}	0.01	0.50	-0.07**	
	(0.01)	(0.30)	(0.03)	
ΔIP_{world}	-0.01	-0.01	-0.01	
	(0.01)	(0.12)	(0.02)	
adj-R^2(%)	1.8	1.9	7.5	

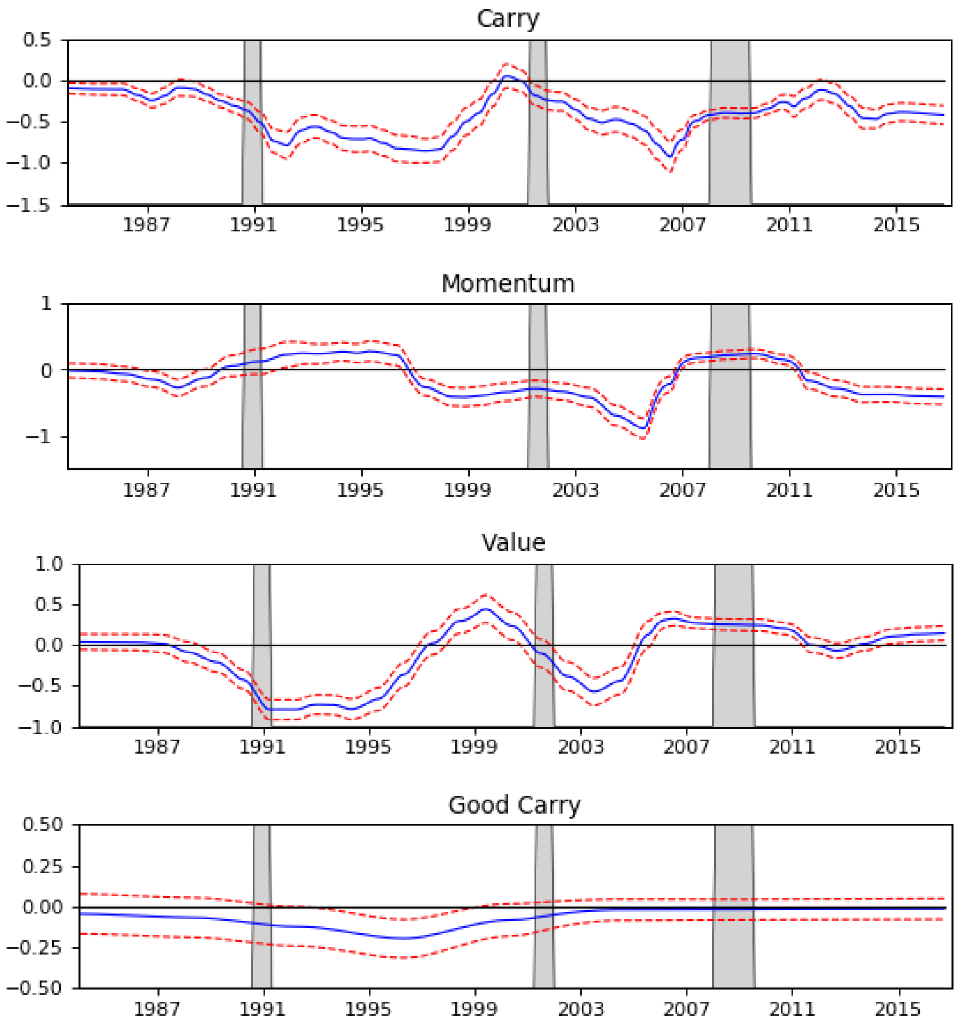
Notes: This table presents the results of the time-varying $\beta_{i,t}$ on U.S. and global short rates, and U.S. and global industrial production as: $\beta_{i,t} = a_i + b_1\Delta i_{us,t} + b_2\Delta i_{world,t} + b_3\Delta IP_{us,t} + b_4\Delta IP_{world,t} + e_{i,t}$. i_{world} and IP_{world} are residuals by regressing the U.S. variables onto the global variables which are obtained by first principal components. We employ seven currency portfolios: carry, momentum, value, "good" carry (good, Bekaert and Panayotov, 2020), Average Forward Discount (AFD, Lustig et al., 2014), global imbalances (IMB, Della Corte et al., 2016b), and global correlation risk (ΔFXC, Mueller et al., 2017). Carry, momentum, value, global imbalance and "good" carry portfolios include four currency pairs. The standard errors are reported in parentheses and obtained by the Newey and West (1987) procedure with optimal lag selection according to Andrews (1991). The adjusted R^2 is also reported. *,**, and *** indicate significance at the 10%, 5% and 1% levels, respectively. The sample period is between January 1984 and September 2016.

Figure 1. Actual and factor volatility



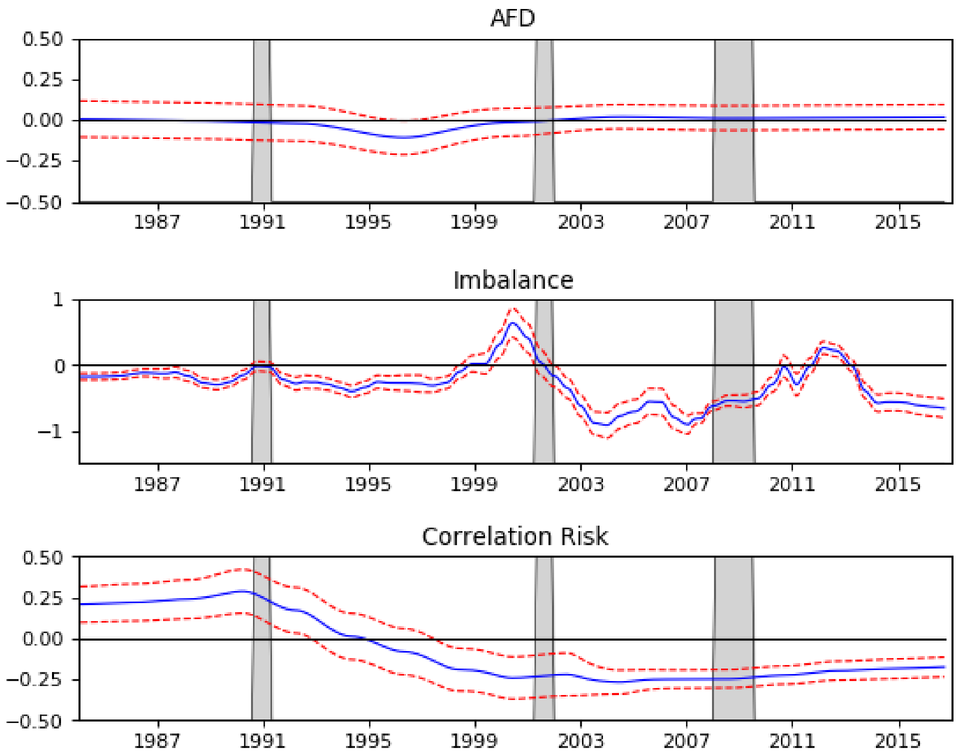
Notes: This figure presents actual and factor model volatility. The actual global FX volatility is calculted as: $\sigma_{FX,t} = \frac{1}{T_t}\sum_{d=1}^{T_t}\sigma_{FX,d}$ where $\sigma_{FX,d}$ is the daily global FX volatility and T_t is the total number of trading days in month t. The factor model volatility is estimated as: $\sigma_{FX,t+1} = \phi f_t + e_{t+1}$ where f_t is the common factors extracted from U.S. and global macroeconomic indicators. The sample period is between January 1984 and September 2016.

Figure 2. Time-varying trade-off between volatility and expected return: Kernel estimation



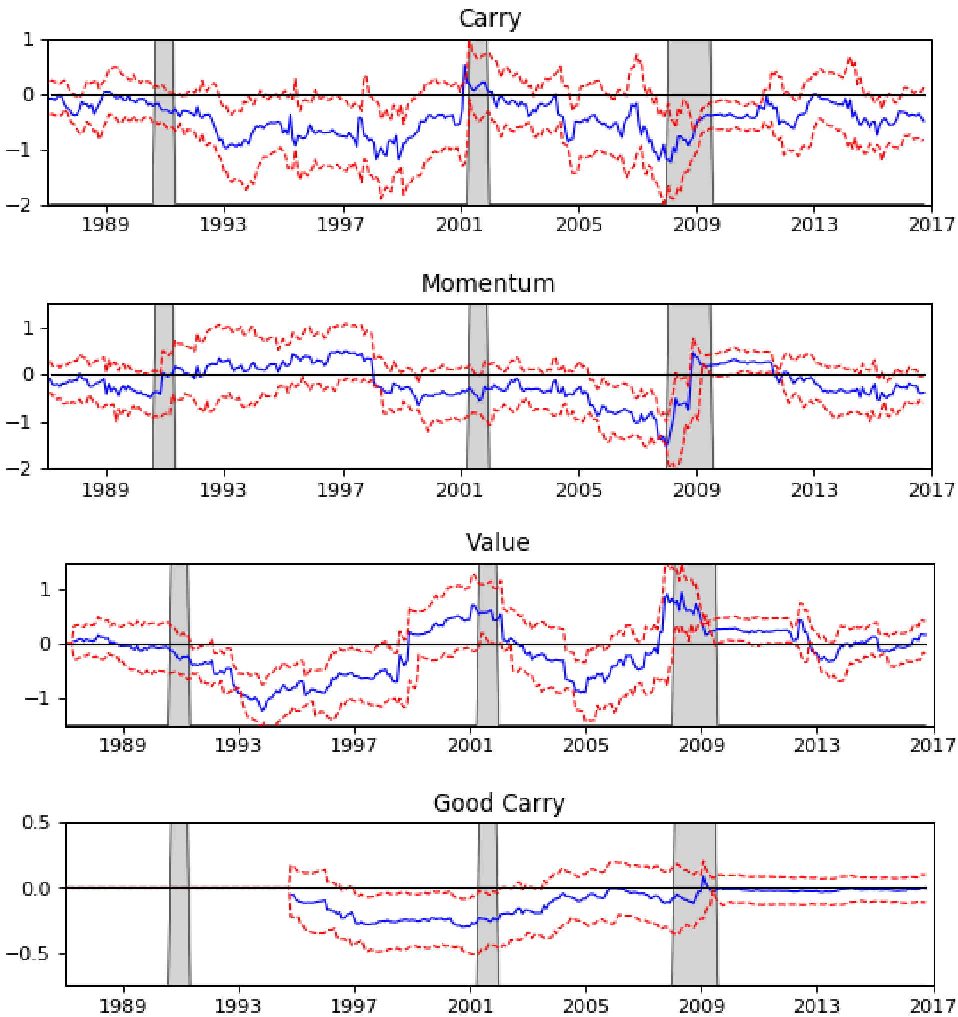
Notes: See the next page

Figure 2. continued



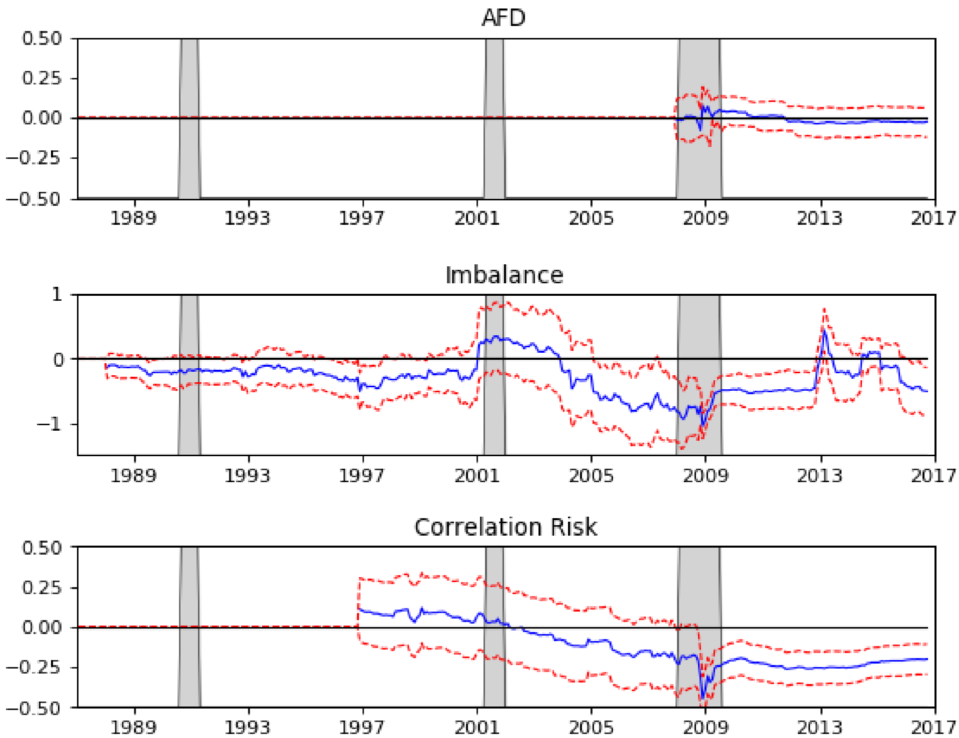
Notes: This figure provides plots of the estimated parameters with 90% confidence intervals. Ang and Kristensen (2012) estimation method is employed and predicted global FX volatility is obtained by the factor model. The confidence intervals are estimated based upon the standard errors derived by Ang and Kristensen (2012). We employ seven currency portfolios: carry, momentum, value, good carry (Bekaert and Panayotov, 2020), Average Forward Discount (AFD, Lustig et al., 2014), global imbalances (IMB, Della Corte et al., 2016b), and global correlation risk (ΔFXC, Mueller et al., 2017). The shaded regions are NBER recessions.

Figure 3. Time-varying trade-off between volatility and expected return: Rolling regression



Notes: See the next page.

Figure 3. continued



Notes:This figure provides plots of the estimated parameters with 90% confidence intervals. A rolling regression approach is employed and predicted global FX volatility is obtained by the factor model. The rolling window size corresponds to the size of bandwidth used by the kernel estimation. We employ seven currency portfolios: carry, momentum, value, good carry (Bekaert and Panayotov, 2020), Average Forward Discount (AFD, Lustig et al., 2014), global imbalances (IMB, Della Corte et al., 2016b), and global correlation risk (ΔFXC, Mueller et al.,2017). The shaded regions are NBER recessions.

The Conditional Volatility Premium on Currency Portfolios

Joseph P. Byrne and Ryuta Sakemoto

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This material provides additional results which are not reported in the main text. These include A Theoretical framework, B Global financial crisis and carry trades, C Global bid-ask spread, Figure A1 Conditional trade-off between actual volatility and return, Figure A2 Rolling regression trade-off between actual volatility and return, Figure A3 Conditional trade-off between volatility and larger number of currencies and Figure A4-A9 marginal R^2 from empirical factor model. Table A1 is bandwidth estimation, Table A2 presents excess returns for six currency pair portfolios during financial crises, Table A3 presents results of volatility estimation using other factor models, Table A4 shows that expected return and volatility risk using the extended factor model, and Table A5-A6 provides data definition.

A. A theoretical framework

While making essentially an empirical contribution, this paper adopts a no-arbitrage asset pricing model to investigate the relationship between FX volatility and expected returns on currency portfolios. According to the asset market view, exchange rates are related to country pricing kernels.[1] Following Backus et al. (2001) and Lustig et al. (2011, 2014), the logarithm of the stochastic discount factor in currency i at $t+1$, m^i_{t+1}, is determined by a global state variable, z_{t+1}:

$$m^i_{t+1} = a^i + b^i z_{t+1} + u^i_{t+1} \tag{A-1}$$

where a^i is a parameter, b^i is the factor loading, and u^i_{t+1} is the idiosyncratic iid gaussian shock.[2] Backus et al. (2001) proposition 1 states that if there are no arbitrage opportunities, the change in the exchange rate (Δs^i_{t+1}) between two currencies, say United States dollar (USD) and British pound (GBP), is equal to the difference between their stochastic discount factors, respectively m_{t+1} and m^i_{t+1}. Therefore exchange rates are a function of the global state variable z_{t+1}, based upon Equation (1):

$$\Delta s^i_{t+1} = m_{t+1} - m^i_{t+1} = a - a^i + (b - b^i)z_{t+1} + u_{t+1} - u^i_{t+1} \tag{A-2}$$

where the two idiosyncratic shocks u_{t+1} and u^i_{t+1} are iid with the variance σ^2_u.

Furthermore, the conditional variance of the change in the exchange rate is also the difference between the two stochastic discount factors, and written as:

$$var_t(\Delta s^i_{t+1}) = (b - b^i)^2 var_t(z_{t+1}) + 2\sigma^2_u. \tag{A-3}$$

Using Equation (3), we obtain the aggregate conditional variance of the change in the exchange rate:

$$\sigma_{FX,t} = \frac{1}{K}\sum_{i=1}^{K} var_t(\Delta s^i_{t+1}) = (\frac{1}{K}\sum_{i=1}^{K}(b - b^i)^2) var_t(z_{t+1}) + 2\sigma^2_u. \tag{A-4}$$

[1]For other applications and discussions of the asset market view of exchange rates, see also Brandt et al. (2006), Maurer et al. (2019), Lustig and Verdelhan (2019), and Burnside and Graveline (2020).

[2]For instance, we consider global industrial production or global inflation as examples of the global state variable which affects all stochastic discount factors. Backus et al. (2001) do not include the idiosyncratic shock, while this difference does not affect our conclusion.

This is an affine transformation of the state variable $var_t(z_{t+1})$ from Equation (3). Following Lustig and Verdelhan (2007), the risk premium of the currency portfolio is described as the covariance between the expected return of the currency portfolio and the logarithm of the stochastic discount factors:

$$E_t(r^i_{t+1}) = -cov_t(\Delta s^i_{t+1}, m_{t+1}) = \beta^i var_t(z_{t+1}) + \sigma^2_u \tag{A-5}$$

where $\beta^i = b(b - b^i)$ corresponds to the estimated coefficient of the regression between conditional variance and expected returns. The parameter β^i is positive or negative based upon the underlying link between the stochastic discount and state factors. Thus, to examine conditional risk-return trade-offs for currency portfolios, and whether the volatility risk premium is positive, we implement an empirical variant of Equation (5) in the following analysis.

B. Global financial crisis and carry trades

The carry portfolio is also widely used by professional investors, but does not display the same behaviour as the momentum and value portfolios. There are several studies which indicate that the global financial crisis impacted carry returns, and hence there are specific reasons why the carry portfolio does not display the time-varying pattern of momentum and value portfolios. Bussiere et al. (2019) investigate deviations from uncovered interest rate parity condition, which underpins carry returns. They find that investor's expectational errors are negatively correlated with interest rate differentials before the global financial crisis in 2008, while the correlation signs change after the crisis. They conclude that the systematic change in investor expectations is the main reason that carry dissipated after the crisis.[3] Ready et al. (2017b) propose a two-country general equilibrium model

[3]Lilley et al. (2019) observe that the change in capital flows after the global financial crisis and highlight the importance of the U.S. dollar as a safe haven currency.

with commodity exporting and importing countries. In their model, interest rates and real exchange rate are jointly determined. They illustrate a commodity exporting country demands less precautionary saving, leading to higher interest rates and the positive carry return. They regard the global financial crisis as a large productivity shock in the commodity importing countries, causing declines in the commodity price and the carry return.

C. Global bid-ask spread

We use a cross-sectional currency bid-ask spread measure as a proxy of liquidity. We follow Menkhoff et al. (2012a) and calculate the bid-ask spread (BAS) in day d as:

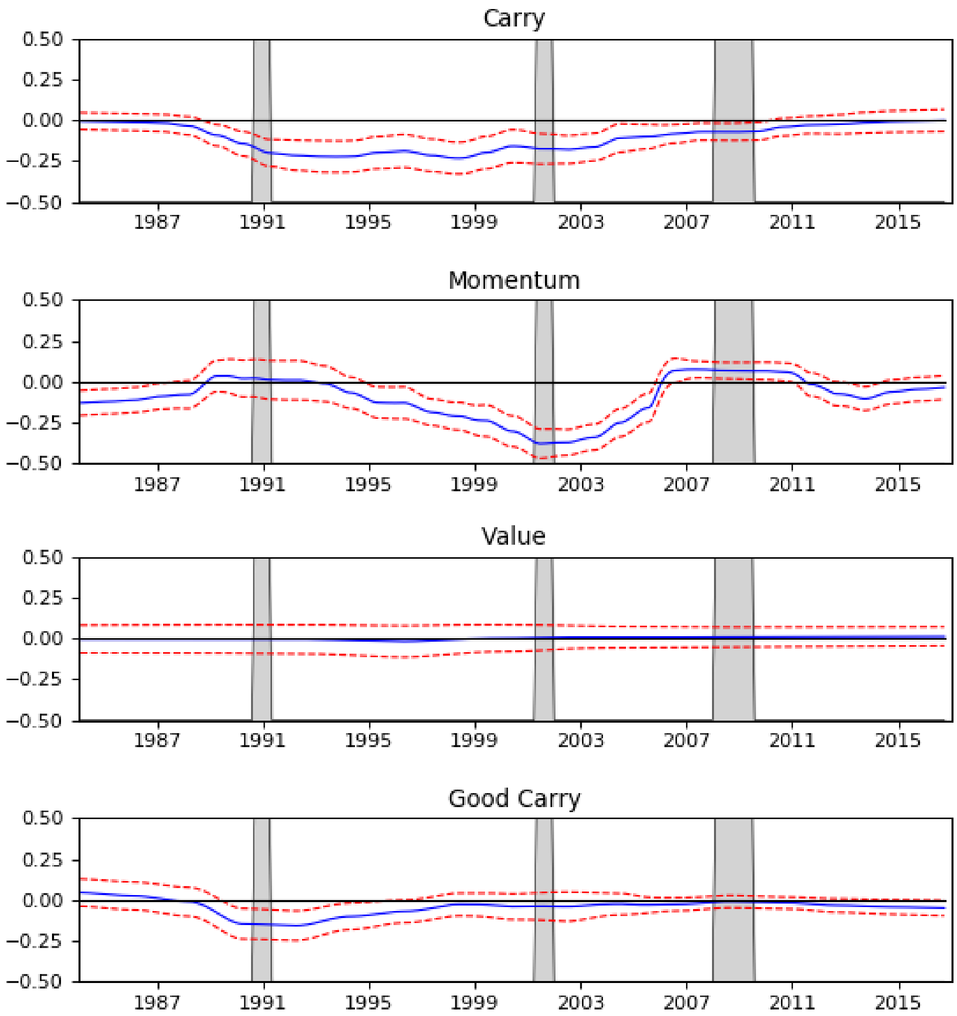
$$\psi_{FX,d} = \sum_{i=1}^{K_d} \left(\frac{BAS_{i,d}}{K_d} \right) \tag{A-6}$$

where $BAS_{i,d}$ is the bid-ask spread of currency i and K_d is the number of currencies on day d. Monthly global BAS in month t, $\psi_{FX,t}$, is calculated as:

$$\psi_{FX,t} = \frac{1}{T_t} \sum_{d=1}^{T_t} \psi_{FX,d} \tag{A-7}$$

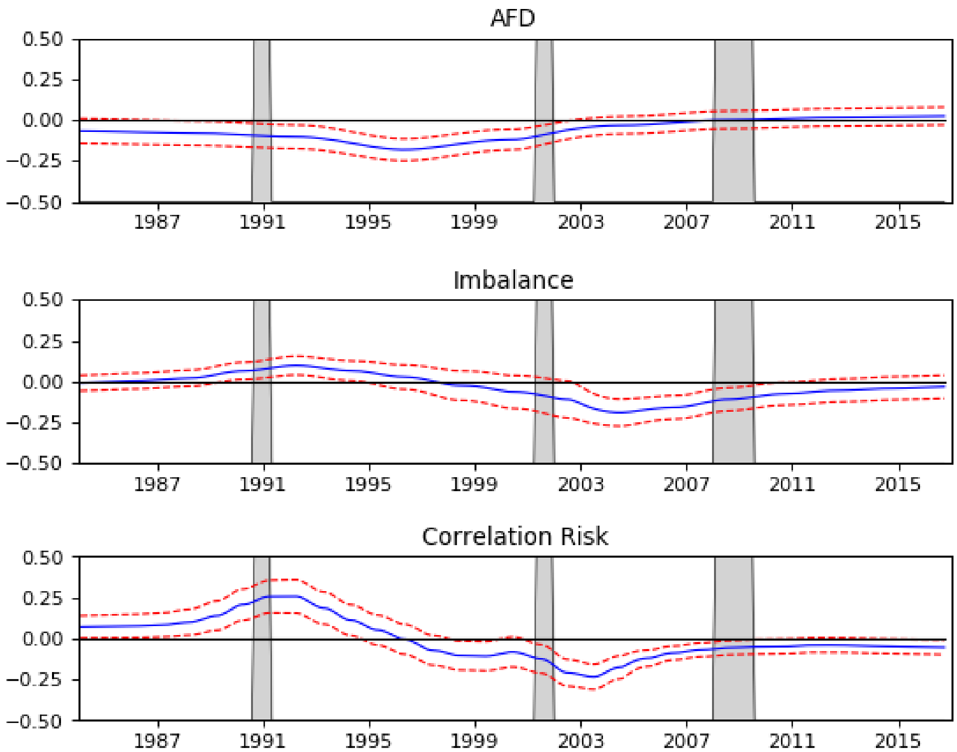
where T_t is the total number of trading days in month t. We adopt an innovation component, $\Delta\psi_{FX,t}$ in the factor model.

Figure A1. Time-varying trade-off between volatility and expected return: Actual volatility



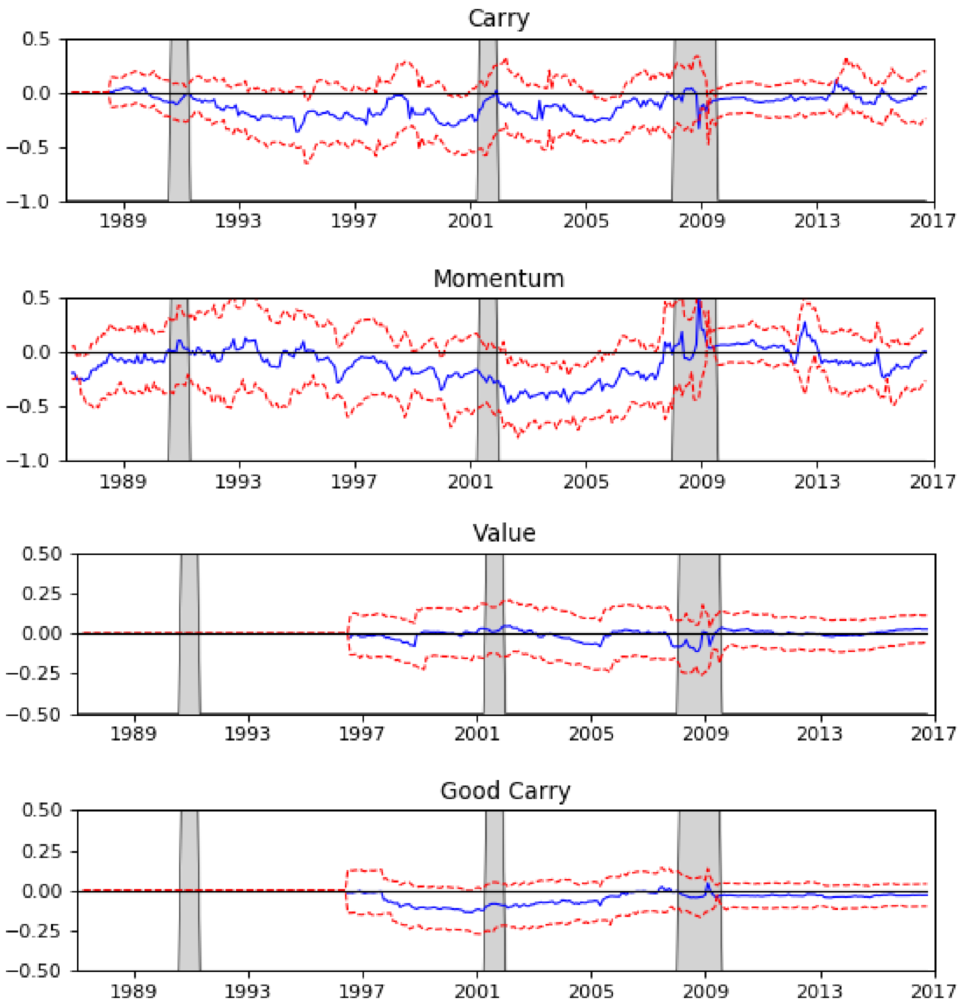
Notes: See the next page

Figure A1. continued



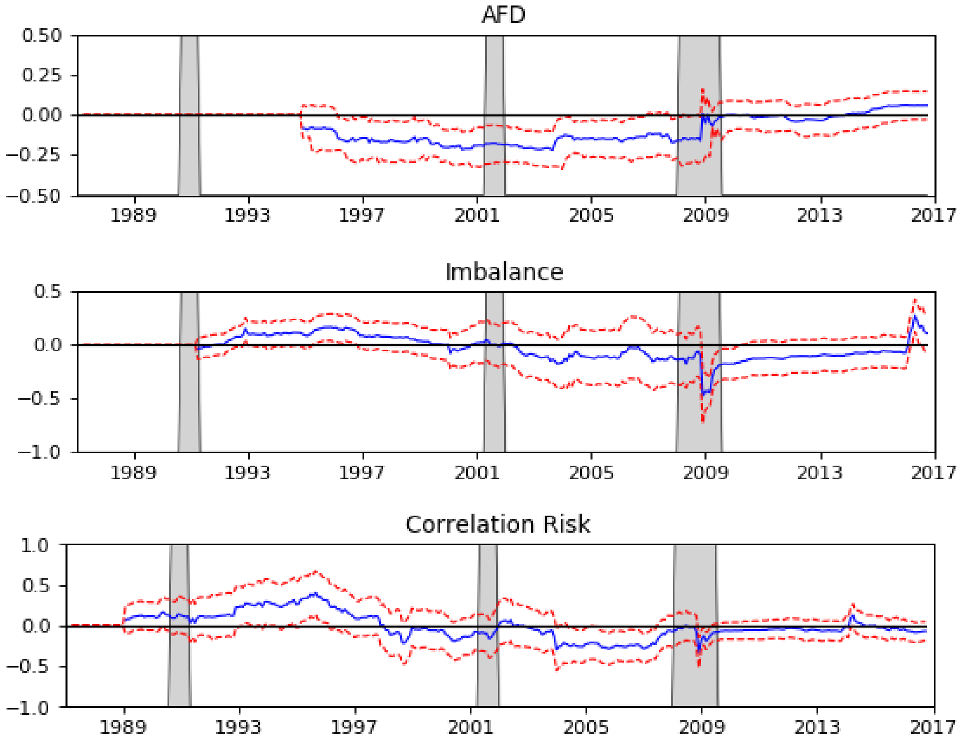
Notes: This figure provides plots of the estimated parameters with 90% confidence intervals. Ang and Kristensen (2012) estimation method is employed and predicted global FX volatility is actual volatility. The confidence intervals are estimated based upon the standard errors derived by Ang and Kristensen (2012). We employ seven currency portfolios: carry, momentum, value, good carry (Bekaert and Panayotov, 2020), Average Forward Discount (AFD, Lustig et al., 2014), global imbalances (IMB, Della Corte et al., 2016b), and global correlation risk (ΔFXC, Mueller et al., 2017). The shaded regions are NBER recessions.

Figure A2. Time-varying trade-off between volatility and expected return: Actual volatility



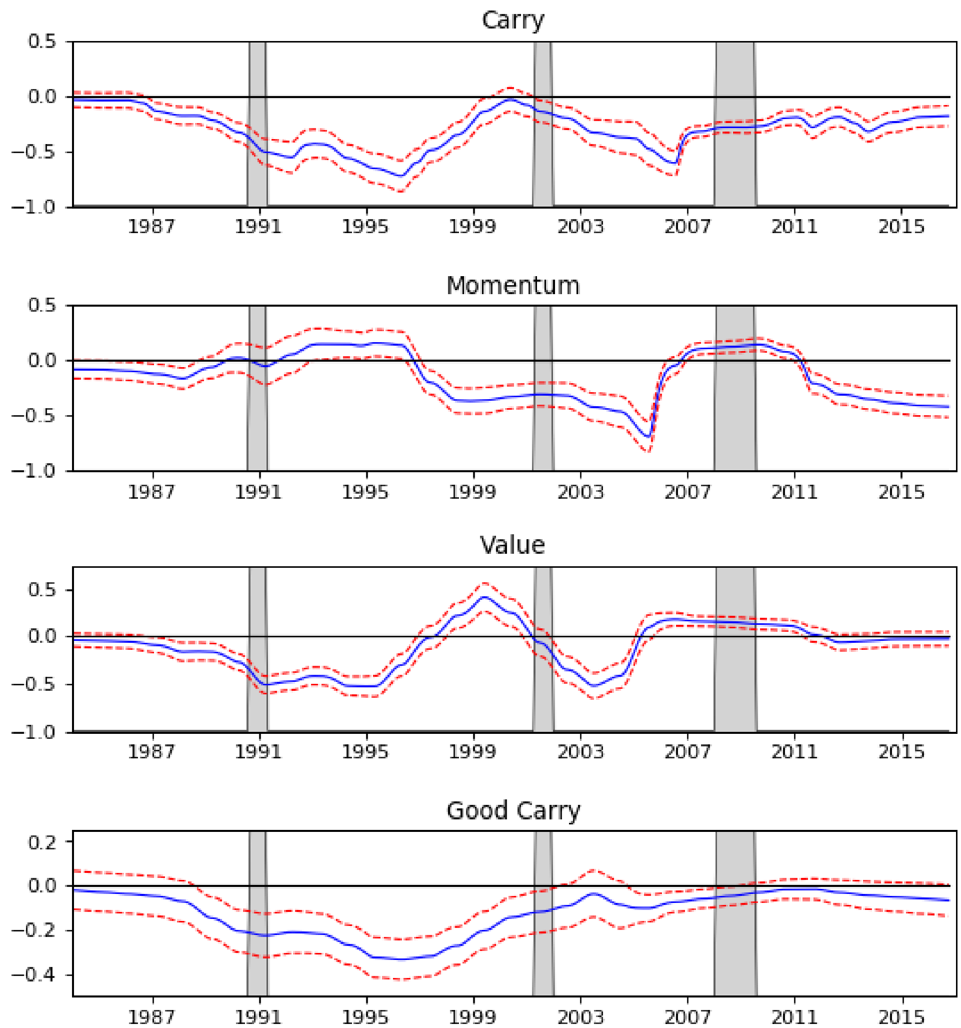
Notes: See the next page.

Figure A2. continued



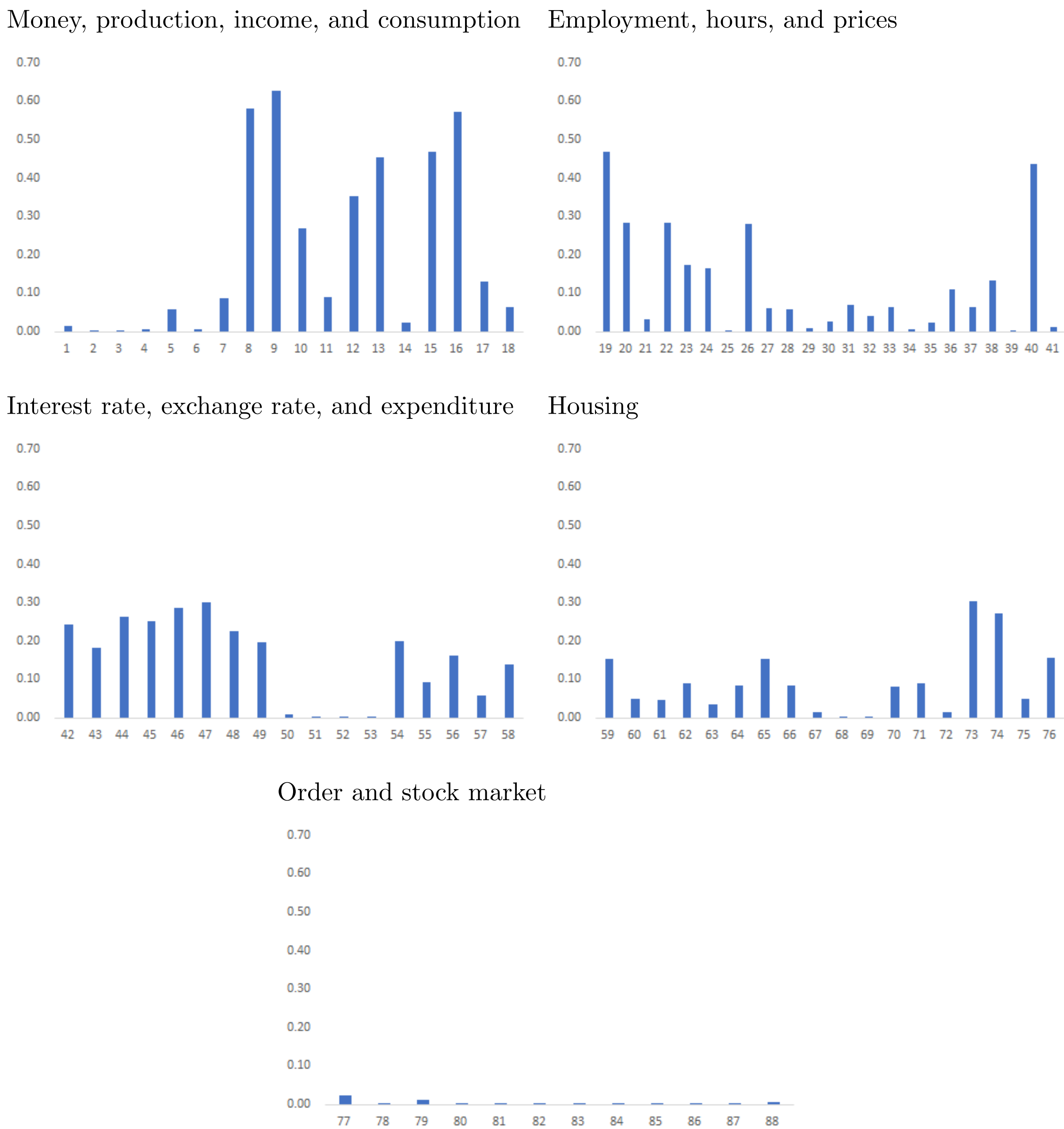
Notes: This figure provides plots of the estimated parameters with 90% confidence intervals. A rolling regression approach is employed and predicted global FX volatility is actual volatility. The rolling window size corresponds to the size of bandwidth used by the kernel estimation. We employ seven currency portfolios: carry, momentum, value, good carry (Bekaert and Panayotov, 2020), Average Forward Discount (AFD, Lustig et al., 2014), global imbalances (IMB, Della Corte et al., 2016b), and global correlation risk (ΔFXC, Mueller et al., 2017). The shaded regions are NBER recessions.

Figure A3. Time-varying trade-off between volatility and expected return: Six currencies



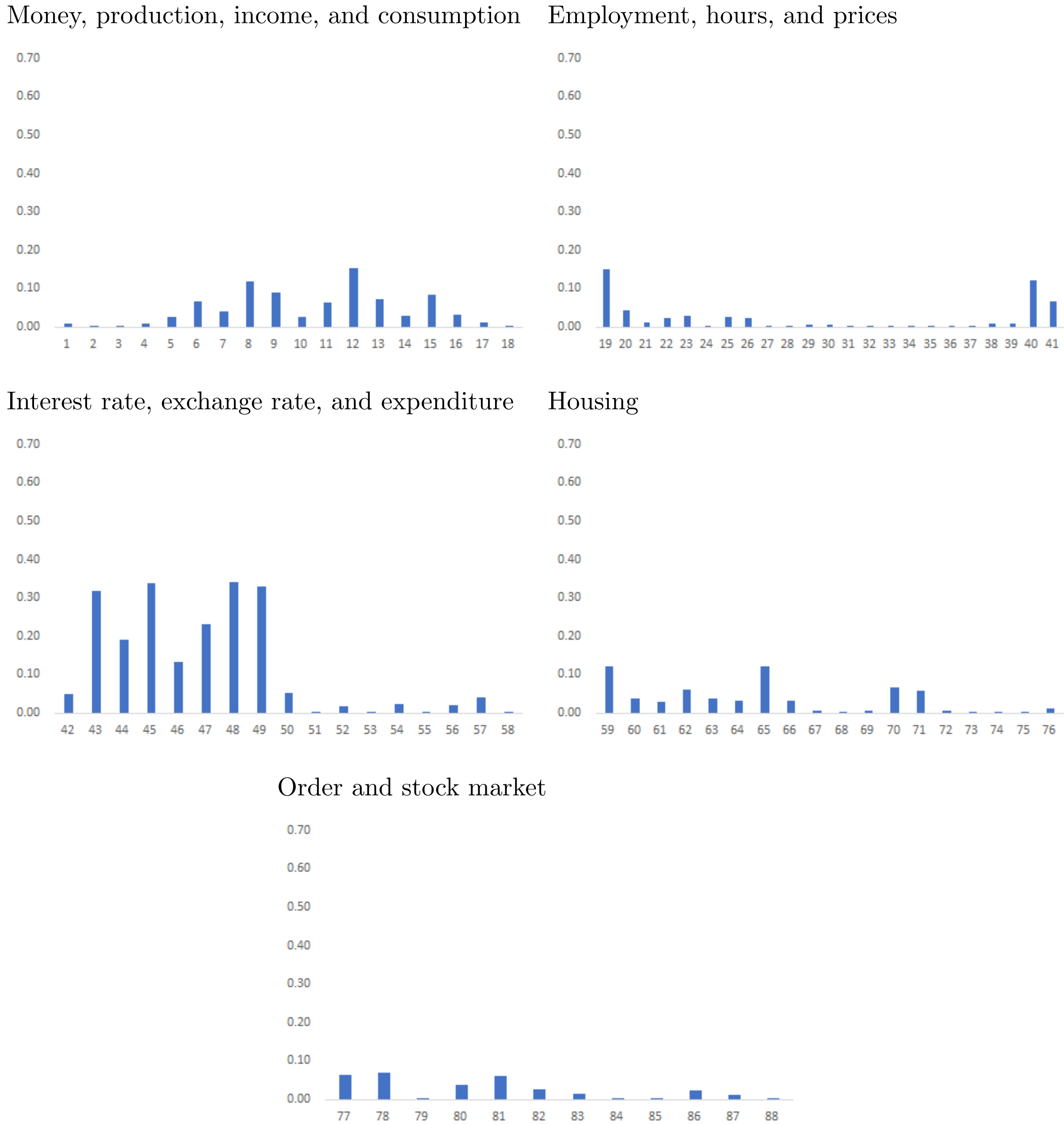
Notes: This figure provides plots of the estimated parameters with 90% confidence intervals. Three currencies go long and three currencies go short. Ang and Kristensen (2012) estimation method is employed and predicted global FX volatility is obtained by the factor model. The confidence intervals are estimated based upon the standard errors derived by Ang and Kristensen (2012). We employ seven currency portfolios: carry, momentum, value, good carry (Bekaert and Panayotov, 2020),

Figure A4. Marginal R^2 for F_1



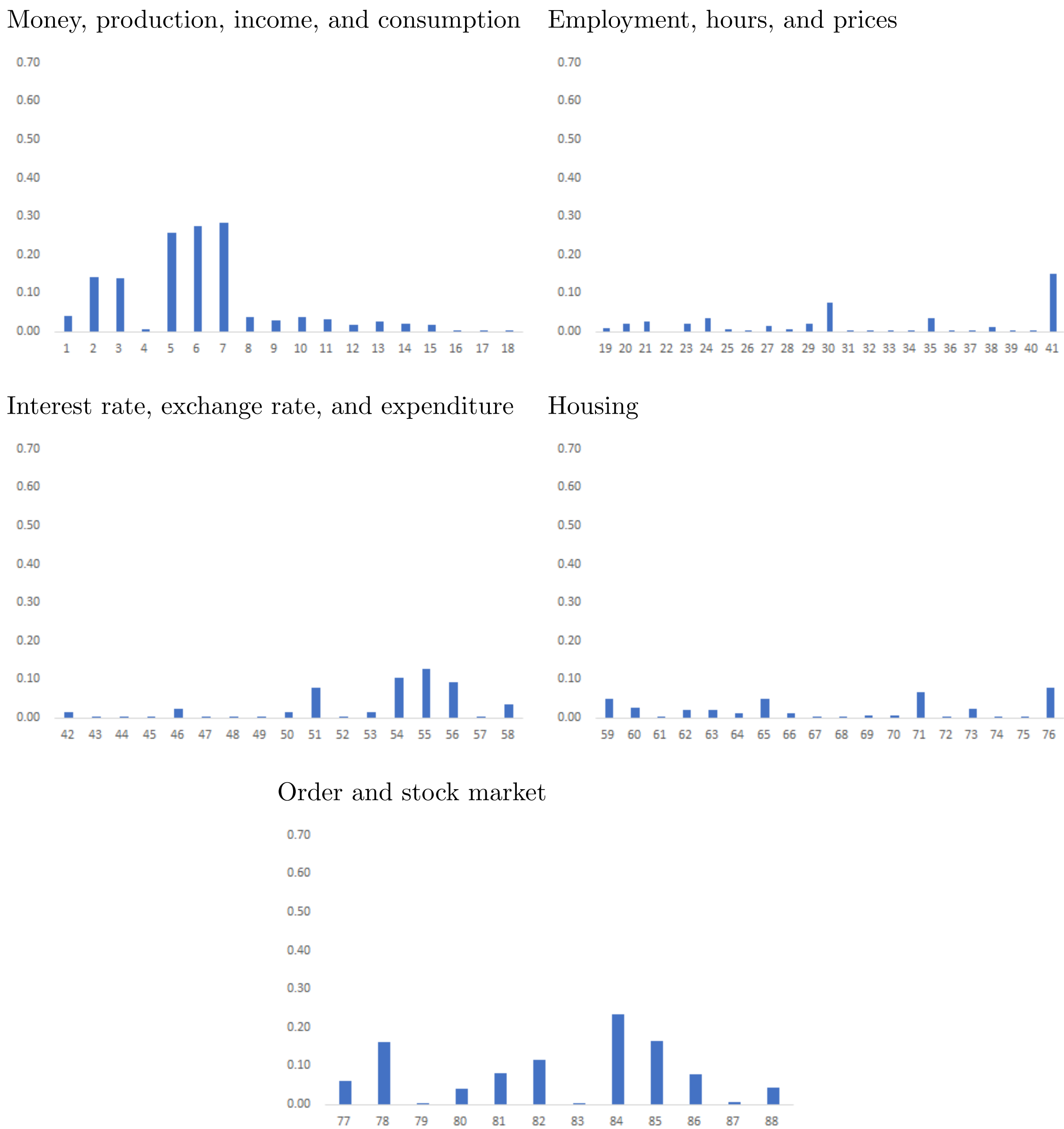
Notes: This figure present the R-square from regressing the U.S. macroeconomic series number given on the x-axis onto the estimated factor named in the heading. See the Table A5 for a description of the numbered series.

Figure A5. Marginal R^2 for F_4



Notes: This figure present the R-square from regressing the U.S. macroeconomic series number given on the x-axis onto the estimated factor named in the heading. See the Table A5 for a description of the numbered series.

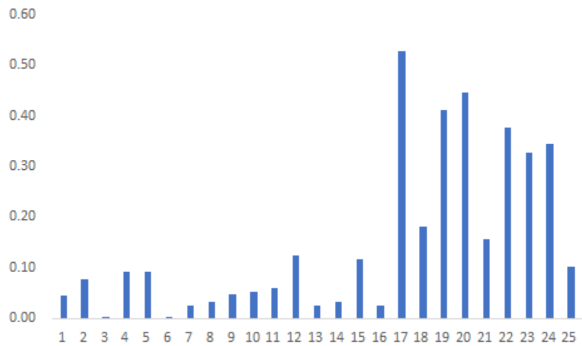
Figure A6. Marginal R^2 for F_5



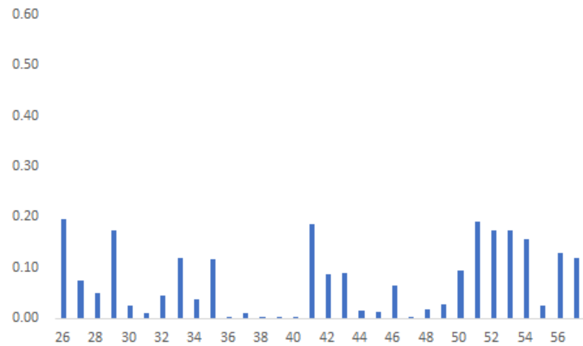
Notes: This figure present the R-square from regressing the U.S. macroeconomic series number given on the x-axis onto the estimated factor named in the heading. See the Table A5 for a description of the numbered series.

Figure A7. Marginal R^2 for G_1

Production, employment, and PPI



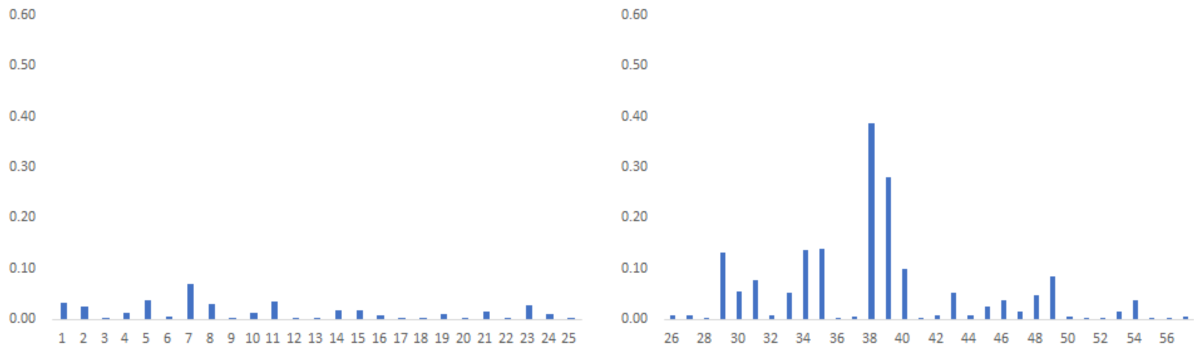
CPI, interest rate, reserves, and stock market



Notes: This figure present the R-square from regressing the global macroeconomic series number given on the x-axis onto the estimated factor named in the heading. See the Table A6 for a description of the numbered series.

Figure A7. Marginal R^2 for G_4

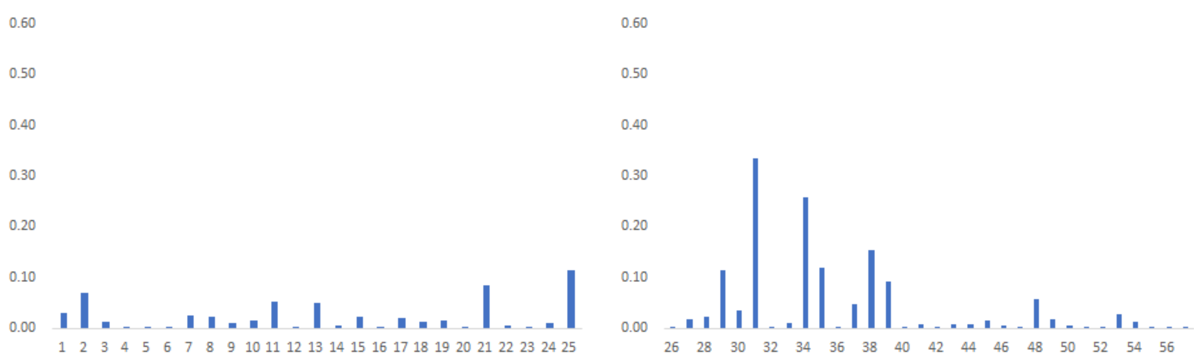
Production, employment, and PPI | CPI, interest rate, reserves, and stock market



Notes: This figure present the R-square from regressing the global macroeconomic series number given on the x-axis onto the estimated factor named in the heading. See the Table A6 for a description of the numbered series.

Figure A8. Marginal R^2 for G_5

Production, employment, and PPI | CPI, interest rate, reserves, and stock market



Notes: This figure present the R-square from regressing the global macroeconomic series number given on the x-axis onto the estimated factor named in the heading. See the Table A6 for a description of the numbered series.

Table A1 Estimates of Bandwidths

	carry	mom	value	good	AFD	IMB	ΔFXC
Actual Volatility	107.1	75.94	299.35	289.7	260.7	172.5	119.5
Factor Model	53.7	66.3	78.3	257.2	115.0	47.7	154.2

Notes: This table reports estimates of bandwidths and the values are reported as monthly equivalent units. We employ the method proposed by Ang and Kristensen (2012). We employ seven currency portfolios: carry, momentum, value, good carry (Bekaert and Panayotov, 2020), Average Forward Discount (AFD,Lustig et al., 2014), global imbalances (IMB, Della Corte et al., 2016b), and global correlation risk (ΔFXC, Mueller et al.,2017).

Table A2. Excess returns during financial crises: Six currency pairs

	carry	mom	value	good
LTCM	-0.01	0.28	0.85	-0.24
GFC	-1.02	-0.25	0.63	-0.44
EURO	-0.11	-0.28	-0.18	-0.07

Notes: This table present excess returns for currency portfolios during the financial crises. The currency portfolios include carry, momentum, value and "good" carry (good, Bekaert and Panayotov, 2020). Carry, momentum, value, and "good" carry portfolios include six currency pairs. The LTCM crisis is defined from January 1998 to April 1999 (Kho et al., 2000), the global financial crisis (GFC) is defined from August 2007 to March 2009 (Bekaert et al., 2014) and the euro debt crisis (EURO) is defined from January 2010 to December 2012 (Stracca, 2015)

Table A3. Results of Volatility Estimation Using Other Factor Models

	(1)	(2)	(3)	(4)
constant	4.41***	4.34***	4.41***	4.21***
	(0.22)	(0.43)	(0.43)	(0.47)
F_1	0.96***	0.98***	0.96***	0.91***
	(0.26)	(0.26)	(0.27)	(0.24)
G_5	0.37**	0.36**	0.37**	0.39**
	(0.18	(0.17)	(0.18)	(0.18)
G_4^2	-0.09**	-0.09**	-0.09**	-0.09**
	(0.04	(0.04)	(0.05)	(0.04)
G_5^2	0.09**	0.09**	0.09**	0.09**
	(0.04)	(0.04)	(0.04)	(0.04)
ΔTED		0.90**		
		(0.43)		
ΔBAS			-0.26	
			(12.12)	
$\Delta DEI-US$				-0.01
				(0.21)
$\Delta DEI-G$				-0.14
				(0.11)
EMV				0.04
				(0.03)
σ_{t-1}^2	0.57***	0.57***	0.57***	0.54***
	(0.04)	(0.04)	(0.04)	(0.04)
adj-R^2	0.51	0.52	0.51	0.52

Notes: This table presents time series regressions of future global FX volatility on common factors. The common factors are obtained as in Ludvigson and Ng (2007), and F_j indicates U.S. and G_j indicates global factors. We also include a change in TED spread (Brunnermeier et al., 2009), that in global BAS (Menkhoff et al., 2012a), that in expected inflation ($\Delta DEI-US$ and $\Delta DEI-G$, Chen et al., 1986) and newspaper based equity market volatility (EMV, Baker et al., 2019). The standard errors are reported in parentheses and obtained by the Newey and West (1987) procedure with optimal lag selection according to Andrews (1991). The adjusted R^2 is also reported. *,**, and *** indicate significance at the 10%, 5% and 1% levels, respectively. The sample period is between January 1984 and September 2016.

Table A4. Expected Return and Volatility Risk: Extended Factor Model

	(1) carry	(2) mom	(3) value	(4) good
α	3.47***	-0.11	-0.11	0.84
	(0.69)	(1.10)	(1.10)	(0.61)
β	-0.31***	0.03	0.03	-0.05
	(0.07)	(0.11)	(0.11)	(0.06)
adj-R^2(%)	7.6	-0.2	-0.1	-0.0
	(5) AFD	(6) IMB	(7) ΔFXC	
α	0.56	3.38**	1.32	
	(0.79)	(1.65)	(0.93)	
β	-0.02	-0.32*	-0.10	
	(0.08)	(0.17)	(0.09)	
adj-R^2(%)	-0.2	7.0	0.8	

Notes: This table presents time series regressions of excess returns of the currency portfolio on a constant and predicted global FX volatility, $\hat{\sigma}_{FX,t}$, which is obtained by the factor model including the TED spread. We run the following time-invariant regression model: $ret_{i,t+1} = \alpha_{i,} + \beta_i \hat{\sigma}_{FX,t} + \epsilon_{i,t+1}$, where i indicates the i's currency portfolio. We employ seven currency portfolios: carry, momentum, value, "good" carry (good, Bekaert and Panayotov, 2020), Average Forward Discount (AFD, Lustig et al., 2014), global imbalances (IMB, Della Corte et al., 2016b), and global correlation risk (ΔFXC, Mueller et al., 2017). Carry, momentum, value, global imbalance and "good" carry portfolios include four currency pairs. The standard errors are reported in parentheses and obtained by the Newey and West (1987) procedure with optimal lag selection according to Andrews (1991). The adjusted R^2 is also reported. *,**, and *** indicate significance at the 10%, 5% and 1% levels, respectively. The sample period is between January 1984 and September 2016.

Table A5: Definition of Data:U.S.

Number	Transform	Description
Money		
1	lnDF	M1 Money Stock, Billions of Dollars, Monthly, SA
2	lnDF	M2 Money Stock, Billions of Dollars, Monthly, SA
3	lnDF	M3 Money Stock, Billions of Dollars, Monthly, SA
4	lnDF	Total Reserves excluding Gold for United States, Dollars, Monthly, Not SA
5	lnDF	Commercial and Industrial Loans, All Commercial Banks, Billions of U.S. Dollars, Monthly, SA
6	lnDF	Total Assets, All Commercial Banks, Billions of U.S. Dollars, Monthly, SA
7	lnDF	Loans and Leases in Bank Credit, All Commercial Banks, Billions of U.S. Dollars, Monthly, SA
Production		
8	lnDF	Industrial Production Index, Index 2012=100, Monthly, SA
9	lnDF	Industrial Production: Manufacturing (NAICS), Index 2012=100, Monthly, SA
10	lnDF	Industrial Production: Durable Consumer Goods, Index 2012=100, Monthly, SA
11	lnDF	Industrial Production: Nondurable Consumer Goods, Index 2012=100, Monthly, SA
12	lnDF	Industrial Production: Business Equipment, Index 2012=100, Monthly, SA
13	lnDF	Industrial Production: Materials, Index 2012=100, Monthly, SA
14	lnDF	Industrial Production: Energy Materials: Energy, total, Index 2012=100, Monthly, SA
15	lnDF	Industrial Production: Business supplies, Index 2012=100, Monthly, SA
16	lnDF	Industrial Production: Construction supplies, Index 2012=100, Monthly, SA
Income and Consumption		
17	lnDF	Personal Income, Billions of Dollars, Monthly, SA Annual Rate
18	lnDF	Disposable Personal Income, Billions of Dollars, Monthly, SA Annual Rate
Employment and Hours		
19	lnDF	All Employees: Total Nonfarm Payrolls, Thousands of Persons, Monthly, SA
20	lnDF	Civilian Employment Level, Thousands of Persons, Monthly, SA
21	lnDF	Civilian Labor Force, Thousands of Persons, Monthly, SA
22	DF	Civilian Unemployment Rate, Percent, Monthly, SA
23	DF	Average Weekly Hours of Production and Nonsupervisory Employees: Total private, Hours, Monthly, SA
24	DF	Average Weekly Overtime Hours of Production and Nonsupervisory Employees: Manufacturing, Hours, Monthly, SA
25	DF	Average (Mean) Duration of Unemployment, Weeks, Monthly, SA
26	DF	Unemployment Rate: 20 years and over, Percent, Monthly, SA
Prices		
27	lnDF	Consumer Price Index for All Urban Consumers: All Items, Index 1982-1984=100, Monthly, SA
28	lnDF	Consumer Price Index: Total All Items: Wage Earners for the United States, Index 2010=1, Monthly, Not SA
29	lnDF	Consumer Price Index for All Urban Consumers: All Items Less Food and Energy, Index 1982-1984=100, Monthly, SA
30	lnDF	Consumer Price Index for All Urban Consumers: Energy, Index 1982-1984=100, Monthly, SA
31	lnDF	Consumer Price Index for All Urban Consumers: All items in New York-Northern New Jersey-Long Island, Monthly, Not SA
32	lnDF	Producer Price Index by Commodity for Final Demand: Finished Goods, Index 1982=100, Monthly, SA
33	lnDF	Producer Price Index by Commodity for Final Demand: Finished Goods Less Foods and Energy, Index 1982=100, Monthly, SA
34	lnDF	Producer Price Index by Commodity for Final Demand: Finished Consumer Foods, Crude, Index 1982=100, Monthly, SA
35	lnDF	Producer Price Index by Commodity for Final Demand: Finished Consumer Foods, Processed, Index 1982=100, Monthly, SA
36	lnDF	Producer Price Index by Commodity for Intermediate Demand by Commodity Type: Processed Goods for Intermediate Demand, Index 1982=100, Monthly, SA
37	lnDF	Producer Price Index by Commodity for Intermediate Demand by Commodity Type: Unprocessed Goods for Intermediate Demand, Index 1982=100, Monthly, SA
38	lnDF	Producer Price Index by Commodity for Intermediate Demand by Commodity Type: Materials for Durable Manufacturing, Index 1982=100, Monthly, SA
39	DF	Average Hourly Earnings of Production and Nonsupervisory Employees: Total Private, Dollars per Hour, Monthly, SA

Continued: Definition of Data:U.S.

Number	Transform	Description
40	lnDF	Indexes of Aggregate Weekly Payrolls of Production and Nonsupervisory Employees: Total Private, Index 2002=100, Monthly, SA
41	DF	Consumer Opinion Surveys: Confidence Indicators: Composite Indicators: OECD Indicator for the United States, Normalised (Normal=100), Monthly, SA
Interest Rate		
42	DF	Effective Federal Funds Rate, Percent, Monthly, Not SA
43	DF	10-Year Treasury Constant Maturity Rate, Percent, Monthly, Not SA
44	DF	3-Month Treasury Bill: Secondary Market Rate, Percent, Monthly, Not SA
45	DF	3-Year Treasury Constant Maturity Rate, Percent, Monthly, Not SA
46	DF	3-Month or 90-day Rates and Yields: Certificates of Deposit for the United States, Percent, Monthly, Not SA
47	DF	6-Month Treasury Bill: Secondary Market Rate, Percent, Monthly, Not SA
48	DF	5-Year Treasury Constant Maturity Rate, Percent, Monthly, Not SA
49	DF	7-Year Treasury Constant Maturity Rate, Percent, Monthly, Not SA
Exchange Rate		
50	lnDF	Japan / U.S. Foreign Exchange Rate, Japanese Yen to One U.S. Dollar, Monthly, Not SA
51	lnDF	Canada / U.S. Foreign Exchange Rate, Canadian Dollars to One U.S. Dollar, Monthly, Not SA
52	lnDF	U.S. / U.K. Foreign Exchange Rate, U.S. Dollars to One British Pound, Monthly, Not SA
Expenditure		
53	DF	Prices for Personal Consumption Expenditures: Chained Price Index: PCE excluding food and energy, Percent Change from Preceding Period, Monthly, SA
54	lnDF	Personal Consumption Expenditures, Billions of Dollars, Monthly, SA Annual Rate
55	lnDF	Personal Consumption Expenditures: Durable Goods, Billions of Dollars, Monthly, SA Annual Rate
56	lnDF	Personal consumption expenditures excluding food and energy, Billions of Dollars, Monthly, SA Annual Rate
57	lnDF	Personal Consumption Expenditures: Services, Billions of Dollars, Monthly, SA Annual Rate
58	lnDF	Personal Consumption Expenditures: Nondurable Goods, Billions of Dollars, Monthly, Seasonally Adjusted Annual Rate
Housing		
59	lnDF	Housing Starts: Total: New Privately Owned Housing Units Started, Thousands of Units, Monthly, SA Annual Rate
60	lnDF	Housing Starts in Midwest Census Region, Thousands of Units, Monthly, SA Annual Rate
61	lnDF	Housing Starts in Northeast Census Region, Thousands of Units, Monthly, SA Annual Rate
62	lnDF	Housing Starts in South Census Region, Thousands of Units, Monthly, SA Annual Rate
63	lnDF	Housing Starts in West Census Region, Thousands of Units, Monthly, SA Annual Rate
64	lnDF	New Private Housing Units Authorized by Building Permits, Thousands of Units, Monthly, SA Annual Rate
65	lnDF	Housing Starts: Total: New Privately Owned Housing Units Started, Thousands of Units, Monthly, SA Annual Rate
66	lnDF	New Private Housing Units Authorized by Building Permits, Thousands of Units, Monthly, SA Annual Rate
67	lnDF	New Privately-Owned Housing Units Completed: 1-Unit Structures, Thousands of Units, Monthly, SA Annual Rate
68	lnDF	New Privately-Owned Housing Units Completed: 2-4 Unit Structures, Thousands of Units, Monthly, SA Annual Rate
69	lnDF	New Privately-Owned Housing Units Completed: 5-Unit Structures or More, Thousands of Units, Monthly, SA Annual Rate
70	lnDF	Privately Owned Housing Starts: 1-Unit Structures, Thousands of Units, Monthly, SA Annual Rate
71	lnDF	Privately Owned Housing Starts: 5-Unit Structures or More, Thousands of Units, Monthly, Seasonally Adjusted Annual Rate
72	lnDF	Housing Starts: 2-4 Units, Thousands of Units, Monthly, SA Annual Rate
73	lnDF	New Privately-Owned Housing Units Under Construction: Total, Thousands of Units, Monthly, SA
74	lnDF	New Privately-Owned Housing Units Under Construction: 1-Unit Structures, Thousands of Units, Monthly, SA
75	lnDF	New Privately-Owned Housing Units Under Construction: 2-4 Unit Structures, Thousands of Units, Monthly, SA

Continued: Definition of Data:U.S.

Number	Transform	Description
76	lnDF	New Privately-Owned Housing Units Under Construction: 5-Unit Structures or More, Thousands of Units, Monthly, SA
Order		
77	DF	Current New Orders; Diffusion Index for FRB - Philadelphia District, Index, Monthly, SA
78	DF	Future New Orders; Diffusion Index for FRB - Philadelphia District, Index, Monthly, SA
79	DF	Current New Orders; Percent Reporting No Change for FRB - Philadelphia District, Percent, Monthly, SA
80	DF	Current New Orders; Percent Reporting Increases for FRB - Philadelphia District, Percent, Monthly, SA
81	DF	Future New Orders; Percent Reporting Increases for FRB - Philadelphia District, Percent, Monthly, Not SA
82	DF	Future New Orders; Percent Reporting Decreases for FRB - Philadelphia District, Percent, Monthly, SA
83	DF	Future New Orders; Percent Reporting No Change for FRB - Philadelphia District, Percent, Monthly, SA
Stock Market		
84	lnDF	Total Share Prices for All Shares for the United States, Index 2010=1, Monthly, Not SA
85	level	Fama and French Market Factor
86	level	Size Factor
87	level	Value Factor
88	level	Momentum Factor

Notes: This Table shows each series, the transformation applied to the series, and a brief data description. In the transformation column, level denotes level of the series, ln denotes logarithm, and lnFD and lnFD2 denote the first and second difference of the logarithm. The data source is Federal Reserve Bank St.Louis. The data period is from December 1983 to September 2016.

Table A6: Definition of Data: Global

Number	Transform	Description
Production		
1	lnDF	Production of Total Industry in Australia, Index 2010=100, Quarterly, SA
2	lnDF	Production of Total Industry in Canada, Index 2010=100, Monthly, SA
3	lnDF	Production of Total Industry in Denmark, Index 2010=100, Monthly, SA
4	lnDF	Production of Total Industry in Germany, Index 2010=100, Monthly, SA
5	lnDF	Production of Total Industry in Japan, Index 2010=100, Monthly, SA
6	lnDF	Production of Total Industry in Norway, Index 2010=100, Monthly, SA
7	lnDF	Production of Total Industry in New Zealand, Index 2010=100, Quarterly, SA
8	lnDF	Industrial Production Index in the United Kingdom, Index 2012=100, Monthly, SA
9	lnDF	Production of Total Industry in Sweden, Index 2010=100, Monthly, SA
Employment		
10	lnDF	Harmonized Unemployment Rate: Total: All Persons for Australia, Percent, Monthly, SA
11	lnDF	Unemployment Rate: Aged 15 and Over: All Persons for Canada, Percent, Monthly, SA
12	lnDF	Harmonized Unemployment Rate: Total: All Persons for Sweden, Percent, Monthly, SA
13	lnDF	Harmonized Unemployment Rate: Total: All Persons for Sweden, Percent, Monthly, SA
14	lnDF	Unemployment Rate: Aged 15-64: All Persons for Japan, Percent, Monthly, SA
15	lnDF	Registered Unemployment Rate for the United Kingdom, Percent, Monthly, SA
16	DF	Harmonized Unemployment Rate: Total: All Persons for Sweden, Percent, Monthly, SA
Prices		
17	lnDF	Producer Prices Index: Economic Activities: Total Manufacturing for Australia, Index 2010=1, Quarterly, Not SA
18	lnDF	Producer Prices Index: Economic Activities: Total Manufacturing for Canada, Index 2010=1, Monthly, Not SA
19	lnDF	Domestic Producer Prices Index: Manufacturing for Denmark, Index 2010=100, Quarterly, Not SA
20	lnDF	Domestic Producer Prices Index: Manufacturing for Germany, Index 2010=100, Monthly, Not SA
21	lnDF	Producer Prices Index: Total Consumer Goods for Japan, Index 2010=1, Monthly, Not SA
22	lnDF	Domestic Producer Prices Index: Manufacturing for Norway, Index 2010=100, Quarterly, Not SA
23	lnDF	Domestic Producer Prices Index: Manufacturing for New Zealand, Index 2010=100,

Continued: Definition of Data: Global

Number	Transform	Description
		Quarterly, Not SA
24	lnDF	Wholesale (Producer) Price Index in the United Kingdom, Index 2010=100, Quarterly, Not SA
25	lnDF	Producer Prices Index: Economic Activities: Total Manufacturing for Sweden, Index 2010=1, Monthly, Not SA
26	DF	Consumer Price Index of All Items in Australia, Index 2010=100, Quarterly, Not SA
27	lnDF	Consumer Price Index: Total, All Items for Canada, Index 2010=1, Monthly, Not SA
28	lnDF	Consumer Price Index: All Items for Denmark, Index 2010=100, Monthly, Not SA
29	lnDF2	Consumer Price Index of All Items in Germany, Index 2010=100, Monthly, Not SA
30	lnDF2	Consumer Price Index of All Items in Japan, Index 2010=100, Monthly, Not SA
31	lnDF	Consumer Price Index: All Items for Norway, Index 2010=100, Monthly, Not SA
32	lnDF2	Consumer Price Index: All Items for New Zealand, Index 2010=100, Quarterly, Not SA
33	lnDF2	Consumer Price Index of All Items in the United Kingdom, Index 2010=100, Monthly, Not SA
34	lnDF2	Consumer Price Index: All Items for Sweden, Index 2010=100, Monthly, Not SA
Interest Rate		
35	lnDF	3-Month or 90-day Rates and Yields: Bank Bills for Australia, Percent, Monthly, Not SA
36	lnDF	3-Month or 90-day Rates and Yields: Interbank Rates for Canada, Percent, Monthly, Not SA
37	DF	3-Month or 90-day Rates and Yields: Interbank Rates for Sweden, Percent, Monthly, Not SA
38	DF	3-Month or 90-day Rates and Yields: Interbank Rates for Germany, Percent, Monthly, Not SA
39	DF	Immediate Rates: Less than 24 Hours: Central Bank Rates for Japan, Percent, Monthly, Not SA
40	DF	3-Month or 90-day Rates and Yields: Interbank Rates for Norway, Percent, Monthly, Not SA
41	DF	3-Month or 90-day Rates and Yields: Bank Bills for New Zealand, Percent, Monthly, Not SA
42	DF	3-Month or 90-day Rates and Yields: Treasury Securities for the United Kingdom, Percent, Monthly, Not SA
43	DF	3-Month or 90-day Rates and Yields: Interbank Rates for Sweden, Percent, Monthly, Not SA
44	DF	3-Month or 90-day Rates and Yields: Eurodollar Deposits for Switzerland, Percent, Monthly, Not SA
Reserves		
45	lnDF	Total Reserves excluding Gold for Australia, Dollars, Monthly, Not SA
46	lnDF	Total Reserves excluding Gold for Canada, Dollars, Monthly, Not SA
47	lnDF	Total Reserves excluding Gold for Germany, Dollars, Monthly, Not SA
48	lnDF	Total Reserves excluding Gold for Japan, Dollars, Monthly, Not SA
49	lnDF	Total Reserves excluding Gold for United Kingdom, Dollars, Monthly, Not SA
Stock Markets		
50	lnDF	Total Share Prices for All Shares for Australia, Index 2010=1, Monthly, Not SA
51	lnDF	Total Share Prices for All Shares for Canada, Index 2010=1, Monthly, Not SA
52	lnDF	Total Share Prices for All Shares for Denmark, Index 2010=1, Monthly, Not SA
53	lnDF	Total Share Prices for All Shares for Germany, Index 2010=1, Monthly, Not SA
54	lnDF	Total Share Prices for All Shares for Japan, Index 2010=1, Monthly, Not SA
55	lnDF	Total Share Prices for All Shares for New Zealand, Index 2010=1, Monthly, Not SA
56	lnDF	Total Share Prices for All Shares for the United Kingdom, Index 2010=1, Monthly, Not SA
57	lnDF	Total Share Prices for All Shares for Sweden, Index 2010=1, Monthly, Not SA

Notes: This Table shows each series, the transformation applied to the series, and a brief data description. In the transformation column, level denotes level of the series, ln denotes logarithm, and lnFD and lnFD2 denote the first and second difference of the logarithm. The data source is Federal Reserve Bank St.Louis. The data period is from December 1983 to September 2016.