Yield Curve Predictors of Foreign Exchange Returns*

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Abstract

In a no-arbitrage framework, any variable that affects the pricing of the domestic yield curve has the potential to predict foreign exchange risk premiums. The most widely used interest rate predictor is the difference in short rates across countries, known as carry, but the short rate is only one of many factors affecting domestic yield curves. We find that other yield curve predictors like changes of interest rates and term spreads significantly predict excess foreign exchange returns. Currency portfolio returns based on changes in interest rates and term spreads exhibit low skewness risk and have low correlation with carry returns. Predictability from these yield curve variables persists up to 12 months and is robust to controlling for other predictors of currency returns.

1 Introduction

In no-arbitrage models, a pricing kernel succinctly captures the effect of systematic factors which determine the prices of all securities in the economy. These factors drive the term structure of bond prices and the conditional dynamics of yield curves over time. In addition, the foreign exchange risk premium is determined by the differences in conditional volatilities of risk factors affecting the pricing kernels in each country. Thus, any factor potentially affecting domestic bond prices has the potential to predict foreign exchange risk premiums. The vast majority of studies examining the predictability of foreign exchange returns use only the very shortest maturities of bond yields, such as the differences between the one-month interest rates of two countries. This is commonly referred to as "carry" and the ability of carry to forecast currency returns is the subject of a voluminous literature.[1]

The literature's extensive focus on just short rate levels is surprising because it is well known that there is more than one risk factor affecting interest rates. Almost all modern term structure models, like Dai and Singleton (2000) among many others, specify the pricing kernel to contain at least three or more factors. These factors are reflected in the entire term structure of interest rates and its dynamic behavior over time. Thus, there should exist additional yield curve predictors other than just short-term interest rate differentials that predict foreign exchange returns. The focus of our paper is to examine the predictive ability over future foreign exchange returns by various yield curve variables in addition to the standard carry variable.

We start by specifying a motivating framework based on no-arbitrage models. In this setting, foreign exchange risk premiums are potentially determined by factors which drive risk premiums in each country. We focus on factors derived from domestic yield curves. Only in the special case where the effect of the factors driving bond risk premiums perfectly cancels across countries, is there no predictability from yield curve variables on foreign exchange excess returns. Predictability based on carry arises if risk premiums in individual countries are related to interest rate levels. We show that in multifactor term structure models, the effect of time-varying long-run means, which could arise through changing long-term inflation targets or shifts in monetary policy, can be captured by interest rate changes. The effect of factors driving time-varying risk premiums can be proxied by examining term spreads and changes in

[1] This literature includes studies documenting deviations from the Unbiasedness Hypothesis where differences in short rates, or equivalently forward rates, predict future exchange rates. Hodrick (1987), Lewis (1995) and Engel (1996) are survey articles of the early literature. Sarno (2005) provides a more recent update. This literature generally focuses on time-series relations, whereas we investigate cross-sectional relations.

long-term bond yields. Interest rate volatility is another potential risk factor which could predict foreign exchange returns.

We empirically examine the ability of levels and changes in interest rates, term spreads, and other term structure variables, to predict foreign exchange returns. We follow Burnside et al. (2006), Lustig and Verdelhan (2007), Lustig, Roussanov and Verdelhan (2009), Farhi et al. (2009) and other recent authors in examining cross-sectional predictability in a panel of currencies rather than focusing on bivariate currency pairs which is more commonly examined in the literature. The cross-sectional approach allows us to diversify country-specific idiosyncratic shocks and captures the systematic effects of risk factors. This results in greater power than pure time-series analysis on pairs of currencies. We examine cross-sectional predictability by forming portfolios of currency returns and by estimating cross-sectional regressions which control for the predictive power of other instruments known to forecast currency returns. A feature of our empirical work is that we consider predictability across horizons of up to one year. Long horizon currency predictability has typically been examined only in time-series contexts, such as Chinn (2006) and Bekaert, Wei and Xing (2007).

We find a striking economically strong and highly statistically significant ability of changes in interest rates and slopes of the yield curve to predict foreign exchange returns, above the predictability of carry.[2] A simple currency portfolio constructed based on changes of interest rate levels produces an annualized Sharpe ratio of 0.470 and exhibits slightly negative skewness. In comparison, a simple currency portfolio based on levels of the yield curve (similar to the carry trade portfolio) produces an annualized Sharpe ratio of 0.642, but exhibits significantly negative skewness, consistent with Jurek (2008) and other authors. A currency portfolio based on slopes of the yield curve exhibits an even larger Sharpe ratio of 0.809 and is less negatively skewed than carry returns.

Portfolios based on interest rate changes and slopes contain information independent of carry returns and are not highly correlated with each other. In particular, the returns of the portfolio ranked on interest rate changes has a correlation of only 0.061 with carry returns. In cross-sectional currency regressions we find that interest rate levels (carry), changes in interest rates, and term spreads, all have significant coefficients and the predictability is economically

[2] While new compared to almost all academic work, some of these variables have been examined by industry practitioners, like Ilmanen and Sayood (1998, 2002) and related variables appear in industry models. These industry studies typically do not formally motivate the variables in a pricing kernel framework, rigorously measure their predictive power using the long samples we employ, nor control for the effect of many risk factors using robust econometric tests.

large and highly statistically significant. Remarkably, the predictability for these three variables persists up to 12 months.

While the literature on the predictability of foreign currencies is vast, our paper is most comparable to studies which use no-arbitrage term structure models to price foreign exchange rates.[3] All of these studies discuss two-country models whereas our focus is on the cross-section of G10 currencies or across 23 developed countries. We employ the no-arbitrage pricing framework to motivate how simple statistics constructed from the yield curve can potentially affect future foreign exchange returns and deliberately refrain from estimating a complicated term structure model, which cannot be tractably estimated on panels of countries with more countries than currency pairs.

Our paper is most related to Boudoukh, Richardson and Whitelaw (2006) who also use term structure variables to forecast exchange rates. In particular, they use long-maturity forward rates which are equivalent to the information in long yields or term spreads. Chen and Tsang (2009) also consider predicting exchange rates using level, slope, and curvature factors constructed from splines. These studies focus only on time-series, not cross-sectional, predictability, and do not use both portfolio formation and cross-sectional regressions in their analysis. Importantly, they do not interpret their term structure variables in a no-arbitrage setting.

Our paper is structured as follows. We begin by providing a motivating theoretical framework for our empirical investigation in Section 2. Section 3 describes our data and provides summary statistics. Section 4 considers currency returns from a portfolio framework. We present our empirical cross-sectional regression results in Section 5. Section 6 concludes.

2 Motivating Framework

Under no-arbitrage conditions there exists a stochastic discount factor or pricing kernel, M_{t+1}, which prices any payoff, P_{t+1}, at time $t+1$ so that the price, P_t, at time t satisfies

$$P_t = \mathrm{E}_t[M_{t+1} P_{t+1}], \tag{1}$$

or equivalently

$$\mathrm{E}_t[M_{t+1} R_{t+1}] = 1,$$

[3] This literature includes Hansen and Hodrick (1983), Fama (1984), Backus, Foresi and Telmer (2001), Brandt and Santa-Clara (2002), Hodrick and Vassalou (2002), Bansal (1997), Ahn (2004), Dong (2006), and Graveline (2006), among many others.

for any return R_{t+1} with a time $t+1$ payoff. In particular, the price of a n-period zero coupon bond, $P_t^{(n)}$, is given by

$$P_t^{(n)} = \mathrm{E}_t[M_{t+1}P_{t+1}^{(n-1)}] \tag{2}$$

and the price of a one-period bond simply discounts the one-period risk-free rate, r_t:

$$P_t^{(1)} = \exp(-r_t) = \mathrm{E}_t[M_{t+1}]. \tag{3}$$

The pricing kernel embodies risk premiums, which potentially vary over time. In structural approaches the pricing kernel is determined by preferences of a representative agent and production technologies to explain exchange rate risk premiums, like the habit consumption approach of Verdelhan (2010) and the long-run risk model used by Croce and Colacito (2006). We follow a reduced-form approach to tractably incorporate multiple factors. Suppose the domestic pricing kernel takes the form

$$M_{t+1} = \exp\left(-r_t - \tfrac{1}{2}\lambda_t^2 - \lambda_t \varepsilon_{t+1}\right), \tag{4}$$

where λ_t is a time-varying price of risk which prices the shock to the short rate, ε_{t+1}. In our analysis we specify all our shocks to be $N(0,1)$ and uncorrelated with each other. For simplicity we specify ϵ_{t+1} to be a scalar.

The price of risk, λ_t, is potentially driven by multiple factors. Time-varying prices of risk give rise to time-varying risk premiums on long-term bonds. An enormous body of previous research has found that priced risk factors include interest rate factors like the level and the slope of the yield curve and other yield curve variables in addition to macro variables like inflation and output (see, for example, the summary of affine term structure models by Piazzesi, 2003). In our exposition we concentrate on yield curve factors.

We assume a similar pricing kernel in foreign country i:

$$M_{t+1}^i = \exp\left(-r_t^i - \tfrac{1}{2}(\lambda_t^i)^2 - \lambda_t^i \varepsilon_{t+1}^i\right). \tag{5}$$

The foreign pricing kernel prices all bonds in the foreign country through a similar relation to equation (2),

$$P_t^{i,(n)} = \mathrm{E}_t[M_{t+1}^i P_{t+1}^{i,(n-1)}],$$

where $P_t^{i,(n)}$ is the time t price of the foreign n-period zero coupon bond denominated in foreign currency.

Let the spot exchange rate S_t^i at time t express the amount of U.S. dollars per unit of foreign currency i. Increases in S_t^i represent an appreciating foreign currency relative to a depreciating

U.S. dollar. Investing \$1 in any dollar return R_{t+1} for a U.S. investor satisfies $\mathrm{E}_t[M_{t+1}R_{t+1}] = 1$. Similarly, for an investor in country i starting with one unit of foreign currency, converting to U.S. dollars at rate S^i_t, receiving the dollar return R_{t+1}, and then converting back to foreign currency at the end of the period at $1/S^i_{t+1}$ satisfies $\mathrm{E}_t[M^i_{t+1}S^i_t/S^i_{t+1}R_{t+1}] = 1$. Thus, under complete markets we must have $M_{t+1} = M^i_{t+1}S^i_t/S^i_{t+1}$ and thus the exchange rate change is the ratio of the pricing kernels in the foreign and domestic country:

$$\frac{S^i_{t+1}}{S^i_t} = \frac{M^i_{t+1}}{M_{t+1}}. \tag{6}$$

This is derived by many authors including Bansal (1997) and Backus, Foresi and Telmer (2001). We denote natural logarithms of our variables as $s^i_{t+1} = \log S^i_{t+1}$, $m^i_{t+1} = \log M^i_{t+1}$ and $m_{t+1} = \log M_{t+1}$. The rate of foreign currency appreciation relative to the U.S. dollar, Δs^i_{t+1}, is given by:

$$\begin{aligned} \Delta s^i_{t+1} &= s^i_{t+1} - s^i_t = m^i_{t+1} - m_{t+1} \\ &= r_t - r^i_t + \tfrac{1}{2}(\lambda^2_t - (\lambda^i_t)^2) + \lambda_t \varepsilon_{t+1} - \lambda^i_t \varepsilon^i_{t+1}. \end{aligned} \tag{7}$$

Under this setting, the foreign exchange risk premium of the ith currency, rp^i_t, is half the difference in the spread of the conditional variances of the domestic and foreign pricing kernels:

$$rp^i_t \equiv \mathrm{E}_t[\Delta s^i_{t+1} + r^i_t - r_t] = \tfrac{1}{2}(\lambda^2_t - (\lambda^i_t)^2). \tag{8}$$

We follow the literature and define the risk premium, rp^i_t, to be the expected excess continuously compounded rate of return to purchasing foreign currency i, investing the proceeds in a foreign money market for one period to earn the foreign interest rate, r^i_t, and then converting the funds back into domestic currency. Note that uncovered interest rate parity (UIP) assumes that the right-hand side of equation (8) is zero. Under UIP, if the foreign interest rate is greater than the U.S. interest rate, $r^i_t > r_t$, then the foreign currency is expected to depreciate, $\mathrm{E}_t[\Delta s^i_{t+1}] < 0$. However, equation (8) shows that any factor affecting the prices of domestic or foreign prices of risks potentially has the ability to predict foreign exchange excess returns.[4]

In equation (8) investing in foreign currency has a high expected excess return when the difference between the variance of the domestic pricing kernel, λ^2_t, and the variance of the foreign pricing kernel, $(\lambda^i_t)^2$, is large. When the domestic pricing kernel is more volatile than its

[4] In incomplete markets, it is possible that certain factors affect only exchange rate returns and not domestic or foreign bond prices. For example, Brandt and Santa-Clara (2002) incorporate an additional risk factor to match exchange rate volatility, but this factor is not priced and does not affect foreign exchange risk premiums.

foreign counterpart, domestic risk premiums are high while foreign risk premiums are relatively low. Therefore, a U.S. investor putting money outside the country has to be compensated at a relatively high level given the already high domestic risk premiums. This causes the foreign exchange risk premium to be high. The important intuition conveyed by the exchange rate risk premium in equation (8) is that unless the variance terms exactly cancel, then any factor potentially affecting the domestic country, or the foreign country, or both countries, may affect expected foreign currency returns.

Equation (8) is the motivating framework for examining the predictability of various factors which drive risk premiums in domestic or foreign bond markets, which may also predict foreign exchange risk premiums. Our goal is not to estimate a complicated term structure model that jointly prices domestic and foreign term structures and exchange rates, but rather we seek to provide motivation for how various transformations of the yield curve may serve as approximations of factors driving risk premiums. We begin in Section 2.1 by showing how a one-factor model for the price of risk, where the price of risk is a function of the short rate, produces the standard carry trade. Then, in Sections 2.2-2.4, we extend the framework to allow for multiple factors to affect the prices of risk. In this richer environment, long-term bond yields and other statistics capturing the dynamics of the yield curve may be simple instruments to capture the effect of these additional risk factors. We summarize in Section 2.5.

2.1 Differentials in Short Rates (Carry)

We start with a simple one-factor model of the yield curve, which dates back to at least Vasicek (1977). We parameterize the short rate in the U.S., r_t, and the short rate in foreign country i, r_t^i, as

$$\begin{aligned} r_{t+1} &= \theta + \rho r_t + \sigma_r \varepsilon_{r,t+1} \\ r_{t+1}^i &= \theta + \rho r_t^i + \sigma_r \varepsilon_{t+1}^i, \end{aligned} \tag{9}$$

where for simplicity we assume the same parameters in the U.S. and the foreign country.

Risk premiums enter long-term bond prices. The price of a two-period bond is given by

$$\begin{aligned} P_t^{(2)} &= \mathrm{E}_t[M_{t+1}\mathrm{E}_{t+1}[M_{t+2}]] \\ &= \mathrm{E}_t\left[\exp\left(-r_t - \tfrac{1}{2}\lambda_t^2 - \lambda_t \varepsilon_{r,t+1} - r_{t+1}\right)\right] \end{aligned} \tag{10}$$

which simplifies to

$$P_t^{(2)} = \exp(\tfrac{1}{2}\sigma_r^2 - r_t - \theta - \rho r_t - \sigma_r \lambda_t).$$

The yield on the two-period bond is

$$y_t^{(2)} = -\tfrac{1}{2}\log P_t^{(2)} = -\tfrac{1}{4}\sigma_r^2 + \tfrac{1}{2}(r_t + \theta + \rho r_t) + \tfrac{1}{2}\sigma_r \lambda_t, \tag{11}$$

which can also be written as

$$y_t^{(2)} = \text{Jensen's term} + EH_t + \tfrac{1}{2}\sigma_r \lambda_t, \tag{12}$$

where the Jensen's term is given by $-\frac{1}{4}\sigma_r^2$ and the Expectations Hypothesis (EH) term, EH_t, is the average expected short rate over the maturity of the long bond,

$$EH_t = \tfrac{1}{2}(r_t + \mathrm{E}_t[r_{t+1}]) = \tfrac{1}{2}(r_t + \theta + \rho r_t).$$

Ignoring the Jensen's term, the long-term yield comprises an EH term plus a risk premium term, $\frac{1}{2}\sigma_r\lambda_t$. Positive risk premiums with $\lambda_t > 0$ give rise to an upward-sloping yield curve. Note that the form of a long-bond yield in equation (12) holds under very general parameterizations of a short-rate and risk premium processes.

We assume that the price of risk in each country is driven by a global factor, z_t, and the local short rates. Specifically, we specify the conditional variances of the pricing kernel take the form:[5]

$$\begin{aligned} \lambda_t^2 &= z_t - \lambda r_t \\ (\lambda_t^i)^2 &= z_t - \lambda r_t^i. \end{aligned} \tag{13}$$

This is similar to the multi-factor setup of Backus, Foresi and Telmer (2001), Ahn (2004), and Brandt and Santa-Clara (2002). Domestic long-maturity yields reflect both the global and local price of risk components.

The foreign exchange risk premium is given by a linear difference in short rates:

$$rp_t^i = \tfrac{1}{2}\lambda(r_t^i - r_t), \tag{14}$$

which is the standard carry trade predictor of foreign exchange returns.[6] The common global risk factor is not present in the exchange rate risk premium because it affects both the domestic

[5] Strictly speaking these prices of risk may be negative and the square root is not defined. This can be avoided by changing equation (9) to a Cox, Ingersoll and Ross (1985) model. The small possibility of non-positivity does not detract from our main goal to motivate different yield curve variables as predictors for foreign exchange risk premiums.

[6] The linear form is purely for simplicity and we below discuss first-order approximations to the quadratic form in equation (8).

and foreign pricing kernels symmetrically. Under the condition $\lambda > 0$, low interest rates in the U.S. coincide with high foreign exchange excess returns on average, giving a version of the carry trade. An equally weighted portfolio of $i = 1 \ldots N$ currencies all with the same parameters would have a risk premium of

$$rp_t^p = \tfrac{1}{2}\lambda(\overline{r_t^i} - r_t),$$

where $\overline{r_t^i} = \frac{1}{N}\sum r_t^i$ is the average short rate across the N foreign countries.

In this model, although long-term yields reflect the risk premium in equation (11), long-term bonds have no extra predictive power for exchange rate returns above short rate differentials in equation (14). In fact, using long-term bonds would be less efficient for estimating predictive relations for exchange rate returns because long-term bonds embed both the common risk factor z_t and the local short-rate factor whereas only local risk factors matter for expected exchange rate determination. In this simple setting only differences in short rates are useful for predicting foreign exchange returns. We now turn to a richer specification for risk premiums where there is a role for long-term bonds and other yield curve transformations in predicting exchange rates.

2.2 Yield Curve Changes

We make one change to the setup that provides a role for past yield curve dynamics to influence exchange rate returns. We change the short rate to depend on both a time-varying long-run mean, θ_{t+1}, as well as past short rates:

$$\begin{aligned} r_{t+1} &= \theta_{t+1} + \rho r_t + \sigma_r \varepsilon_{t+1} \\ \theta_{t+1} &= \theta_0 + \phi\theta_t + \sigma_\theta v_{t+1}, \end{aligned} \tag{15}$$

with corresponding equations with the same parameter values for the foreign short rate. This is a two-factor short rate model formulated by Balduzzi, Das and Foresi (1998). Time-varying conditional mean factors are also used by Balduzzi et al. (1996) and Dai and Singleton (2000). An economic motivation for a stochastic mean is given by Kozicki and Tinsley (2001) who argue that the long-run mean shifts due to agents' perceptions of long-term inflation or monetary policy targets. A setting where the Fed changes its reaction function to output and inflation shocks would also result in a reduced-form model of a changing conditional mean (see Ang et al., 2009).

The model of the short rate in equation (15) has shocks to both the short rate and the long-run mean. This model is empirically relevant if the long-run mean exhibits significant swings over time. Figure 1 shows that this is the case and plots the estimated long-run mean together with the short rate using one-month USD LIBOR as data in the period after January 1960. Appendix A contains details on the estimation of this model. The figure graphs the long-run mean component $\theta_t/(1-\rho)$ so it is directly interpretable on the same scale as the short rate. The conditional long-run mean ranges between 2.38% and 12.7%. As expected, this is a smaller range than the actual one-month LIBOR rate, which has minimum and maximum values of 0.41% and 20.3%. Clearly there is variation in the long-run mean consistent with previous estimates by Balduzzi, Das and Foresi (1998), Kozicki and Tinsley (2001), and many others.

We use Figure 1 only to motivate the use of long-term mean factors. The plot in Figure 1 is a time-series estimate based on a long sample of U.S. short rates and does not exploit any term structure information. Econometric models with highly persistent variables are not easily estimated on short samples, which is the case for most non-U.S. countries. The estimate of θ_t is also based over the full sample and is not a conditional estimator which can be used to predict cross-sectional exchange rate movements using information only observable at the beginning of each month.

However, Figure 1 shows that the long-run conditional mean is correlated with the short rate with a correlation of 0.43 and generally follows a similar path to the short rate. This is by construction because θ_t can be considered to be a filtered estimator of past short rate shocks.[7] We exploit this feature below in deriving a simple estimator for θ_t based on short rate changes which can be interpreted as an approximation of a long-run conditional mean factor. This is exactly the economic specification of Kozicki and Tinsley (2001) where changes in inflation targets determine long-term conditional means of interest rates. In summary, Figure 1 is suggestive that a predictor motivated from a time-varying long-term mean of the short rate does have significant variation. We now derive the implications for a time-varying long-term mean factor on foreign exchange risk premiums.

Suppose that prices of risk now depend on the time-varying conditional mean, θ_t, rather than the short rate, r_t:

$$\begin{aligned} \lambda_t^2 &= z_t - \lambda\theta_t \\ (\lambda_t^i)^2 &= z_t - \lambda\theta_t^i. \end{aligned} \tag{16}$$

An economic motivation for equation (16) would be that the end-point to which interest rates are mean reverting, which embeds implicit or explicit inflation targets, determines risk premiums

[7] In fact, the reduced-form model for the short rate is a restricted ARMA(2,1) model.

rather than the temporary fluctuations of r_t. Then, foreign exchange excess returns depend on differentials in conditional means:

$$rp_t^i = \tfrac{1}{2}\lambda(\theta_t^i - \theta_t). \tag{17}$$

The conditional mean θ_t is unobserved and there are several ways to estimate its value. First, θ_t is priced in long-term bonds with equation (12) now taking the form

$$y_t^{(2)} = \text{Jensen's term} + EH_t + \tfrac{1}{2}\sigma_r\sqrt{z_t - \lambda\theta_t},$$

where the Expectations Hypothesis term is

$$EH_t = \tfrac{1}{2}(r_t + \theta_0 + \phi\theta_t + \rho r_t).$$

But, long-term bond yields also reflect short-term rate movements, r_t, and global factors, z_t, in addition to providing information about θ_t. Thus, extracting information on θ_t requires a potentially complicated term structure model – we do not pursue this avenue because we seek to use simple statistics of the yield curve in cross-sectional tests and joint estimations of term structure models across multiple countries are computationally challenging.

A second way to estimate θ_t is to exploit the dynamics of the short rate. Note that

$$r_t - \rho r_{t-1} = \theta_t + \sigma_r \varepsilon_t$$

and since $\rho \approx 1$, we have

$$\theta_t \approx \Delta r_t - \sigma_r \varepsilon_t.$$

A similar expression will hold for country i. Now the foreign exchange risk premium in equation (17) can be approximated by

$$rp_t^i \approx \lambda(\Delta r_t^i - \Delta r_t) + \varepsilon_t^{rp,i}, \tag{18}$$

where $\varepsilon_t^{rp,i} = \sigma_r(\varepsilon_t - \varepsilon_t^i)$.

Suppose we hold a portfolio of $i = 1 \ldots N$ currencies each with identical parameters with equal weights in each currency. Suppose that the ith country risk premium error, $\varepsilon_t^{rp,i}$, is diversifiable across countries, so

$$\frac{1}{N}\sum_{i=1}^{N} \varepsilon_t^{rp,i} \to 0 \qquad \text{as} \qquad N \to \infty.$$

This is guaranteed by the assumption of independent idiosyncratic errors. Then, the currency portfolio would have an average expected excess rate of return of

$$rp_t^p \approx \lambda \left(\overline{\Delta r_t^i} - \Delta r_t\right), \tag{19}$$

where

$$\overline{\Delta r_t^i} = \frac{1}{N}\sum_{i=1}^{N} \Delta r_t^i$$

is the average change in short rates across countries. Intuitively, short rate changes provide information about persistent time-varying conditional means. If these factors are priced then ranking on changes in short rates across currencies may lead to differences in expected returns.

In our empirical work we also consider changes in long-term bond yields and term spreads, which we now motivate in terms of levels.

2.3 Long Yields and Term Spreads

Rather than the price of risk depending on short rate factors, several authors including Brennan, Wang and Xia (2004) and Lettau and Wachter (2009), among others, have parameterized the price of risk factor itself to be a time-varying latent process. Brandt and Kang (2004) provide an empirical estimation of such a specification. When the price of risk itself is latent, term spreads, changes in long yields, and changes in term spreads all potentially have forecasting power for exchange rates. To motivate this case, assume the pricing kernel is given by the same form as equation (4) and the short rate is given by the one-factor model in equation (9). We make one change and assume that the price of risk is itself a latent process and follows

$$\lambda_{t+1} = \lambda_0 + \delta\lambda_t + \sigma_\lambda u_{t+1}. \tag{20}$$

with identical parameters for country i.[8]

From equation (8) the exchange rate risk premium depends on the latent λ_t values, which is repeated here for convenience:

$$rp_t^i = \tfrac{1}{2}(\lambda_t^2 - (\lambda_t^i)^2).$$

[8] An alternative approach is to let r_t depend on the level and term spread directly, as in Brennan and Schwartz (1979) and Schaefer and Schwartz (1984). Our example is by design an extreme motivating case where exchange rates are only predicted by long-term bonds and not by interest rates. Of course, it is easy to incorporate both effects into a model where interest rate levels and term spreads are factors and both have independent predictive power for exchange rates.

This is a quadratic form and for pedagogical exposition we employ a linearization. We observe that

$$\begin{aligned}\lambda_t^2 &= (\lambda_t - \mathrm{E}[\lambda_t] + \mathrm{E}[\lambda_t])^2 \\ &= (\lambda_t - \mathrm{E}[\lambda_t])^2 + 2\mathrm{E}[\lambda_t](\lambda_t - \mathrm{E}[\lambda_t]) + \mathrm{E}[\lambda_t]^2.\end{aligned}$$

From equation (20) we can write

$$\lambda_t^2 = \text{constant} + \text{quadratic} + \frac{2\lambda_0}{1-\delta}\lambda_t, \tag{21}$$

where the quadratic term is $(\lambda_t - \mathrm{E}[\lambda_t])^2$. Assuming the quadratic variation is small then

$$\lambda_t^2 \approx \text{constant} + \frac{2\lambda_0}{1-\delta}\lambda_t,$$

and we can approximate the risk premium as

$$rp_t^i \approx \frac{\lambda_0}{1-\delta}(\lambda_t - \lambda_t^i). \tag{22}$$

Exchange rate returns depend on prices of risk, but these prices of risk are not observed in short rate dynamics. In fact, in this stylized case foreign exchange excess returns are not predicted by short rates. Prices of risk show up in long-bond prices or term spreads, which take the form

$$y_t^{(2)} = -\tfrac{1}{4}\sigma_r^2 + \tfrac{1}{2}((1+\rho)r_t + \theta) + \tfrac{1}{2}\sigma_r\lambda_t$$

for the long yield and

$$y_t^{(2)} - r_t = -\tfrac{1}{4}\sigma_r^2 + \tfrac{1}{2}((1-\rho)r_t + \theta) + \tfrac{1}{2}\sigma_r\lambda_t$$

for the term spread. In this special case the change in the long-term yield captures both shocks in the short rate and innovations in the Sharpe ratio factor:

$$\Delta y_t^{(2)} = \frac{1}{2}(1+\rho)\Delta r_t + \frac{1}{2}\sigma_r\Delta\lambda_t.$$

Since $\rho \approx 1$, the term spread provides a direct estimate of λ_t:

$$y_t^{(2)} - r_t \approx \text{constant} + \tfrac{1}{2}\sigma_r\lambda_t.$$

Thus, we can obtain an estimate of the exchange rate risk premium using term spreads:

$$rp_t^i \approx \frac{2\lambda_0}{\sigma_r(1-\delta)}\left((y_t^{(2),i} - r_t^i) - (y_t^{(2)} - r_t)\right). \tag{23}$$

An equally weighted portfolio of N foreign currencies would have a risk premium that depends on the average term spread across countries, $\overline{(y_t^{(2),i} - r_t^i)}$:

$$rp_t^p \approx \frac{2\lambda_0}{\sigma_r(1-\delta)}\left(\overline{(y_t^{(2),i} - r_t^i)} - (y_t^{(2)} - r_t)\right).$$

2.4 Interest Rate Volatility

We finally consider a case where interest rate volatility predicts foreign exchange risk premiums. We take a two-factor model of the short rate where volatility is stochastic:

$$\begin{aligned} r_{t+1} &= \theta + \rho r_t + \sqrt{v_t}\varepsilon_{t+1} \\ v_{t+1} &= v_0 + \kappa v_t + \sigma_v \sqrt{v_t}\eta_{t+1}. \end{aligned} \tag{24}$$

This is the model of Longstaff and Schwartz (1992) where the second factor is identified with the conditional volatility of the short rate. A similar specification is used by Balduzzi et al. (1996). Empirically since $\rho \approx 1$, we compute sample estimates of v_t by using interest rate changes.

We let the pricing kernel now price fluctuations in the short rate volatility, η_{t+1}. Specifically, we assume

$$M_{t+1} = \exp\left(-r_t - \tfrac{1}{2}\lambda_v^2 v_t - \lambda_v \sqrt{v_t}\eta_{t+1}\right), \tag{25}$$

where we shut off any potential pricing of risk for regular short rate shocks, ε_{t+1}, to highlight the role of volatility. Assuming country i has the same parameters, the exchange rate risk premium is then given by

$$rp_t^i = \tfrac{1}{2}(\lambda_v^2(v_t - v_t^i)). \tag{26}$$

Thus, interest rate volatility potentially may affect foreign exchange returns.

2.5 Summary

In summary, the expected return for investing in foreign currencies depends on the spread in conditional volatilities of each country's stochastic discount factor. Conditional volatility of a country's stochastic discount factor affects the term structure of yields. Therefore, any factor that affects the domestic term structure of yields may potentially also forecast foreign exchange risk premiums. In addition to differential spreads in short rates, which is the traditional carry trade, foreign exchange returns may potentially be predicted by changes in interest rates, long-bond yields, and term spreads, and interest rate volatility. We now examine the predictive power in the cross section of foreign exchange returns of these various term structure factors.

3 Data and Summary Statistics

3.1 Data

The data used in our analysis consists of a panel of 23 currencies. The currencies are divided into a set of G10 currencies (Australia, Canada, Switzerland, Germany, United Kingdom, Japan, Norway, New Zealand, Sweden, and the United States) and a set of non-G10 developed countries (Austria, Belgium, Denmark, Spain, Finland, France, Greece, Hong Kong, Ireland, Italy, Netherlands, Portugal, and Singapore).[9] During the sample period we study, the euro was introduced and some European currencies became defunct. To account for the introduction of the euro, we eliminate a currency once it joins the European single currency, with one exception: we splice the data for Germany with the data for euro. Germany is the country with the largest GDP among the countries in the euro, hence we consider the German Deutsche Mark to be representative of the euro prior to December 1998. This assumption is used by many previous authors.

We gather short-term and long-term interest rate variables from Global Financial Data at a monthly frequency. We also collect data at a daily frequency to compute volatility of short-term interest rates. Our short-term interest rates are rates at which currency traders at major financial institutions might realistically trade. Thus, we use one-month interbank deposit rates as our preferred measure of short rates. We also collect long-term interest rates using, where available, 10-year government bond yields. Since currency exchanges rates were fixed under the Bretton Woods system, we begin our sample in January 1975, which is well after the breakdown of Bretton Woods in the early 1970's, and end in August 2009. Our sample represents 415 months in total and includes the worst months of the global 2007-9 financial crisis. Appendix B contains further details on our data.

Table 1 defines the various interest rate predictors motivated from the theoretical setting of Section 2. We collect short rates, long rates, and construct changes in short rates and long rates. Since short rates and long rates are highly correlated – which is often referred to as the level factor (see, for example, Knez, Litterman and Scheinkman, 1994) – we construct a "Level" factor which is the average of short and long rates.[10] We refer to first differences in the Level

[9] "G10" refers to the ten most liquid currencies, rather than the Group of Ten. In our study, a country is developed if it was considered "developed" by Morgan Stanley Capital International (MSCI) as of June 2007. Much of our non-G10 countries are adopters of the euro.

[10] Unfortunately due to lack of data availability we are unable to obtain a yield curve convexity factor, which requires information on intermediate maturity bonds.

factor as "Change." The term spread, "Term," is the difference between the long and short rate. We also consider changes in term spreads. Finally, we construct interest rate volatility by taking the standard deviation of daily short rate changes over the past 12 months.

All our portfolio strategies involve ranking currencies based on these interest rate predictors. To help with interpretations, we consider interest rate variables relative to their U.S. equivalents. For example, our carry trade is based on ranking currencies on short rate differentials, $r_t^i - r_t$, where r_t^i is the short rate in country i and r_t is the U.S. short rate. The portfolio strategies we employ are long-short positions that take zero net positions and all of our regression specifications include time fixed effects. Thus, subtracting the U.S. equivalents at each month has no effect on our analysis.

For each currency we obtain the end-of-month exchange rate in terms of dollar price of one unit of foreign currency which we denote as S_t^i. We define the excess foreign exchange (FX) return on currency i over the next month, denoted Π_{t+1}^i, as

$$\Pi_{t+1}^i = S_{t+1}^i / S_t^i (1 + r_t^i) - (1 + r_t). \tag{27}$$

This is the profit from borrowing one USD at r_t to purchase $1/S_t^i$ units of foreign currency i and depositing the proceeds at r_t^i. This is the empirical counterpart, specified in arithmetic terms, of the foreign exchange risk premium in equation (8), which is specified in logarithmic terms.

We keep the U.S. dollar in our sample and take the perspective of an investor in the United States. All currency portfolio returns are expressed in U.S. dollars. In our data, the excess FX return on U.S. dollars is zero in each month, and all interest rate differentials for the U.S. are zeroes. Keeping the U.S. dollar in our sample maintains complete symmetry, which makes it easy to convert our results to the perspective of an investor located in a different country as only the foreign exchange rate would need to be applied.

3.2 Summary Statistics

We begin by presenting some basic features of data to help guide our empirical design. Table 2 reports means and sample ranges of our variables for the G10 currencies in Panel A and non-G10 currencies in Panel B. Our currency returns are expressed in percentage terms per month. The short rate, long rate, levels, and term spreads are all expressed in terms of differentials relative to the U.S. For example, investing in Australian dollars financed by U.S. dollars and rebalancing every month results, on average, in a net profit of 0.153% per month, or 1.84% per year. During the sample period the Australian dollar interest rate was on average higher than the U.S. dollar rate by 0.214% per month, or 2.57% per year. The Australian dollar depreciated against the U.S. dollar by approximately this difference over this period, but the trade was profitable because of the interest earned in Australian interbank rates (a positive carry). The Australian dollar excess return exhibited monthly volatility of 3.201% per month, or annualized volatility of 11.09% per year. Since all returns and interest rates are computed relative to the U.S., the row for the USD is all zeros.

Table 2 shows that among the G10 currencies, currencies with lower short rates than the U.S. dollar (CHF, DEM, and JPY) tend to produce low future excess currency returns. In particular, the correlation between the column labeled "Excess FX Return Mean", which is the excess next one-month holding period return on buying a foreign currency, and the mean short rate column (the fifth column in the table) is 0.407 across all countries. Taking only the G10 this correlation rises to 0.696. Not surprisingly, the correlation between next-month mean excess FX returns and mean Level factors across countries is similar, at 0.409 across all countries and 0.654 in the G10. This positive relation between interest rates and foreign currency returns is the main driver of the carry trade. The correlation between mean excess FX returns and the average Term across countries is -0.294, and -0.854 in the G10 countries, indicating that different parts of the yield curve give rise to different patterns in foreign exchange returns.

Figure 2 plots the minimum and maximum short rate for the G10 currencies across time. Our post-1975 sample is characterized by tremendous movement in the early 1980's, coinciding with monetary targeting in the U.S., and the dispersion becomes very wide in the late 1980's and early 1990's. There is also a sharp spike in the late 1990's. Post-2000 the dispersion in short rates is more stable, even during the recent financial crisis. The periods of wide dispersion in the G10 short rates are due to many currencies experiencing periods of crisis or financial stress over the sample. For most of our sample Greece and Italy's interest rate differentials are high and volatile. Australia and New Zealand experienced persistently high interest rate differentials in the late 1980's. In 1992 a financial crisis swept through much of Europe affecting Denmark, Finland, Ireland, Norway, and Sweden particularly hard, but also Spain and France to a lesser extent. The large increase in dispersion in the late 1990's is associated with the introduction of the euro. The regime change in early 2000's with reduced dispersion is often attributed to the adoption of inflation targeting across many countries (see, for example, Bernanke et al., 2001). We are mindful of controlling for these features of the data in designing our portfolio formations and regression specifications.

4 Portfolio Returns

In this section we explore the relation between excess currency returns and yield curve predictors by forming portfolios of currencies. We start in Section 4.1 by examining the standard carry trade which dominates the literature. We use the carry trade as a benchmark for using other predictive variables from the term structure of interest rates, which we examine in Section 4.2. Since the standard carry trade is essentially based on indicator functions, we later consider an alternative portfolio specification that is closer in spirit to running a regression in Section 4.4.

All our portfolio results take the perspective of a U.S. investor. We assume that the investor is able to transact in all developed country currencies at no cost and is able to borrow and deposit at the prevailing interbank rates. Furthermore, we assume that if the investor takes a position in his home currency, he borrows in his home currency and immediately deposits it back in the home currency.

4.1 The Benchmark Carry Trade

The benchmark carry trade ranks currencies by their short rates. The carry trade entails purchasing currencies with high interest rates and selling currencies with low interest rates. Often, currencies with the highest (lowest) one-third values of interest rates are purchased (sold) with equal weights.[11] Hence, if there are ten currencies to choose from, this implementable version of the carry trade buys the highest three interest currencies and sell the lowest three interest rate currencies with equal weights. These portfolios are rebalanced each month.

We report the benchmark carry trade in the row labeled "Short rate" in Table 3. Panel A considers portfolios formed across all 23 developed country currencies while Panel B considers the portfolios formed across only the G10 currencies. When the carry trade is conducted across all developed country currencies, carry strategies average 0.181% per month with a standard deviation of 0.934% per month. This translates to an impressive annualized Sharpe ratio of 0.673. For comparison the Sharpe ratio on the S&P 500 using LIBOR as the risk-free rate is 0.105 per month or 0.362 per annum over our sample. When only the G10 currencies are used the carry strategy produces an annualized Sharpe ratio of 0.567. It is well known that carry trade portfolio returns have negative skewness and are prone to occasional large losses as documented by Jurek (2008), Brunnermeier, Nagel and Pedersen (2009), Farhi et al. (2009), and

[11] For example, this is the strategy used by DBV, an ETF which implements the carry strategy. It is also the basic carry trade return generated by the Bloomberg screen FXFB.

others. Table 3 reports the skewness on the carry trade is -1.106 across all developed markets and -1.012 for the G10.

4.2 Additional Predictors from the Term Structure

We construct long-short portfolio returns for other term structure signals listed in the first column of Table 3. We construct additional currency portfolios in the same manner as the carry trade portfolios. Since these portfolios are zero-cost positions, the returns can be interpreted as profits on purchasing one U.S. dollar worth of high signal currencies and borrowing one U.S. dollar worth of low signal currencies. The correlations of the foreign currency excess returns generated by each of the signals in Table 3 are reported in Table 4.

4.2.1 Changes in Short Rates

The second rows of both panels in Table 3 show the equal-weighted portfolio returns based on changes in short rates. Across all developed countries, this trade has averaged a return of 0.088% per month with a standard deviation of 0.688% per month. This translates to an annualized Sharpe ratio of 0.442, which is higher than the Sharpe ratio of the S&P 500. Moreover, the correlation with carry trade returns is low at 0.040 as reported in Table 4. The Sharpe ratio is slightly lower at 0.350 when only G10 currencies are used. Unlike the carry trade, however, using changes in the short rate results in a portfolio that is not prone to large losses: the skewness is only -0.272 across all countries and only -0.069 for the G10, compared to skewness below -1 for the benchmark carry trade. Clearly short rate changes contain valuable information for forecasting foreign exchange returns that is quite different from the standard short rate levels.

The ability of short rate changes to predict foreign exchange returns immediately implies that there must be more than just one factor driving foreign exchange risk, if risk is the explanation.[12] Our results are consistent with the model of Section 2.2, where interest rates contain a slowly moving long-term conditional mean which affects prices of risk. However, we cannot rule out an under-reaction story, advocated by Burnside, Eichenbaum and Rebelo (2007) and Gourinchas and Tornell (2004), where exchange rates only partially adjust to interest rate changes. An advantage of the no-arbitrage framework is that it can easily explain why multiple term structure variables can predict returns. A behavioral story should simultaneously explain the persistent effect of carry, under-reactions to short rate changes, and as we show below,

[12] Most models of currency returns are one-factor models, such as Verdelhan (2010).

over-reactions to other term structure predictors.

4.2.2 Long Rates

The third and fourth rows in Table 3 show the portfolio returns when long rates are used instead of short rates in both levels and first differences. Using long rates leads to a portfolio with similar negatively skewed characteristics as the carry trade, but a slightly lower Sharpe ratio of 0.462 compared to 0.673 for the carry trade. The correlation of the long rate portfolio's return with the carry trade is very high at 0.900. This is not surprising since short rates and long rates move largely in tandem, which is one reason we also combine both into the "Level" factor.

However, a portfolio based on changes in long rates operates very differently from a portfolio based on changes in short rates. Table 3 shows that returns on the long-short strategy based on long rate changes produces a Sharpe ratio of 0.548, which is slightly greater than that of portfolios based on changes in short rate differentials at 0.442. The correlations with other portfolios are low. Table 4 reports that the correlation of the long rate change strategy has correlations of effectively zero with the short rate and long rate level strategies, at -0.021 and 0.020, respectively. The correlation with short rate changes is only 0.214. While the short rate and long rate tend to move in the same direction over time, shocks to these factors have a large degree of independence. This behavior is consistent with many two-factor models of the yield curve such as the example in Section 2.3. These results on levels and changes of the long rates are similar when only G10 currencies are used in Panel B of Table 3.

4.2.3 Interest Rate Levels and Changes

To summarize the information in the short rate and long rate, and changes in the short rate and long rate, we next examine the "Level" and "Change" variables. These portfolio returns are shown in the fifth and sixth rows of Table 3. Nor surprisingly, foreign exchange portfolio returns created by sorting on Level leads to similar results to the carry trade and the long rate portfolios. The Sharpe ratio of the Level portfolio is large at 0.642, but its portfolio returns are negatively skewed. However, portfolios sorted by Change produce a Sharpe ratio of 0.470 with only slight negative skewness of -0.256. As Table 4 shows, the correlation between the Level and Change portfolio returns is only 0.061.

4.2.4 Term Spreads

The next two rows of Table 3 labeled "Term" and "Δ Term" examines portfolio returns of term spread levels and differences, respectively. The portfolio returns formed by taking long-short positions in term spreads have a negative Sharpe ratio of -0.809 so they should be implemented by taking reverse positions. That is, currencies with low (or negative) term spreads should be purchased and currencies with high slope of the yield curve should be sold. Interestingly, this strategy produces the highest Sharpe ratio in absolute terms of all the signals considered in all developed markets as well as only taking the G10 currencies. Term spreads portfolios, like carry, exhibit highly negative skewness, and have a correlation of 0.728 in absolute value with carry returns. Thus, although term spread portfolios generate impressive returns, they do not seem to be completely different from simple carry strategies.

Changes in term spreads produce a portfolio with low returns and some skewness risk. With only the G10 currencies, the returns and skewness are close to zero. Interpreting these results based on our motivating models in Section 2 suggests that changing long-run means in term spread factors have little role in explaining currency returns. Term structure estimations show that macro variables like inflation have significantly different prices of risk across country pairs (see, e.g. Dong, 2006) and these macro variables play important roles in explaining the variation of term spreads (see Ang and Piazzes, 2003). One possible interpretation is that the these factors affect term spread levels and are systematic global factors. Any possible changing long-run means of these factors, which would show up in changes in term spreads, are largely idiosyncratic for pricing currency risk. Put another way, the short-run components of term spreads are global and priced in currency markets but the long-term means of these factors are determined by country-specific effects.

4.2.5 Volatilities

The final row of Table 3 reports returns on portfolios sorted on short rate volatilities, labeled "Volatility". The Volatility portfolio has modest returns, at 0.052% per month with an annualized Sharpe ratio of 0.233 across all developed countries in Panel A. Skewness risk is low for Volatility portfolio returns at -0.226. These figures are quantitatively similar taking only G10 currencies in Panel B.[13] This Sharpe ratio is much lower than the Level, Change, and Term strategies. Thus, Volatility risk does not seem to command the same premium as the

[13] We measure interest rate volatilities by taking daily changes in short rate over the past year. We obtain similar results (not reported) computing volatilities using daily data over the past month and past three months.

other term structure variables. The modest Sharpe ratio for Volatility is partly consistent with Collin-Dufresne, Goldstein and Jones (2009) who argue that short rate volatility is not spanned by the yield curve. Since volatility is not priced in long-term bonds, it should not predict foreign exchange rates. While we find a significant Sharpe ratio for Volatility, Table 4 indicates a modest, but significant correlation around 0.35 of Volatility returns with the carry and Level portfolios. Since short rate volatility is well known to be related to interest rate levels, as in a Cox, Ingersoll and Ross (1985) model, this indicates that we need to control for level and slope factors in assessing the independent strength of interest rate volatility's role in predicting foreign exchange returns. We do this in Section 5.

4.3 Cumulative Returns

So far, our results indicate that there are three yield curve variables with strong predictive power for foreign exchange returns: Level, Change, and Term. In order to visualize the returns an investor would have earned through time, we plot cumulative returns on Level, Change, and Term portfolios starting with \$1 invested in January 1975 in Figure 3. The plot of Level generally shows a strong upward trend throughout the sample with a sharp drop in the early 1990's and a very pronounced decline during the recent financial turmoil. However, the Level strategy (carry trade) soon recovered most of its losses soon thereafter. Figure 3 shows that the Term portfolio exhibits the same general pattern but with some exceptions: during the 1980's when carry did poorly the term spread strategy held up robustly; during the Scandinavian banking crisis in the early 1990's when carry did poorly the term spread strategy soared; and most recently during 2009 when the term spread strategy has yet to recover but carry has bounced back.

A very different pattern is observed for the Change portfolio. This portfolio does not have as pronounced drawdowns as the carry trade portfolio and its low correlation with carry is clearly visible in the graph. The financial crisis also impacted the returns of Change and, interestingly, like the Term portfolio, it did not see the same rebound as the Level portfolio in 2009. Part of this could be due to the very low level of interest rates set by policy makers in response to the financial crisis: changes in interest rates when short-term interest rates in most countries are very close to zero do not exhibit much dispersion.

4.4 Signal-Weighted Currency Portfolio Returns

The portfolios constructed so far are based on an indicator function and place no weight on the magnitude of the signals, except to indicate whether it will be held long or short. If three currencies are purchased, they are all given the same weight, even though the highest signal value may be very different from the third-highest signal value, or the fourth-highest signal is very similar to the third-highest. To use information about the magnitude of the signal, we create signal-weighted currency portfolios. These signal-weighted portfolios also alleviate concerns that the truncation of outliers or discreteness of the cut-off point affect our currency portfolio results. Figure 2 shows that we cannot directly use the interest rate levels directly in our analysis as the tremendous time-varying range produces severe distortions in the portfolio weights. The same comment also applies to the other term structure variables.

To maintain zero net positions and constant long and short portfolio weights, we de-mean and rescale the predictors across currencies each month. We rescale the signals in such a way that all positive signal values sum to one and all negative signal values sum to -1. We accomplish this by standardizing the signals to be zero mean and have a constant standard deviation of two. This preserves order and a sense of magnitude. For each currency with a positive (negative) de-meaned and rescaled signal, we purchase (sell) a U.S. dollar amount equal to the adjusted signal. This ensures that the portfolio is long and short an equal amount, total long and total short position sizes are fixed constant across time, and the individual position size is proportional to the de-meaned signal.

The returns on these signal-weighted currency returns are presented in Table 5. Overall, we find similar results as equal-weighted currency returns, but with some differences. We find that the signal-weighted carry trade has an even higher Sharpe ratio, at 0.856 compared to the naïve strategy, which has a Sharpe ratio of 0.673 in Table 3, and is slightly less negatively skewed at -0.964 compared to -1.106. With signal weighting, the Change strategy continues to produce portfolio returns with a high Sharpe ratio of 0.482 and is positively skewed. Again, the currency portfolio based on long rates still looks similar to the carry trade.

The returns on currency portfolios based on Level and Change are also similar when we perform signal weighting. They both continue to produce high Sharpe ratios, of 0.749 and 0.496, respectively. Whereas the Change portfolio was slightly negatively skewed in Table 3 at -0.256 when using equal weights, the signal-weighted Change returns are significantly positively skewed at 0.366. Signal-weighted returns on the currency portfolio based on term spreads are similar to the equal-weighted counterparts. In particular, the Term portfolio still produces the highest Sharpe ratio in absolute value, at 0.907. These signal-weighted portfolio returns can easily be compared to the predictive coefficients in cross-sectional regressions, which we now examine.

5 Cross-Sectional Foreign Exchange Regressions

One difficulty with examining portfolio returns is that it does not allow us to disentangle the effects of one signal from another.[14] In this section, we employ a cross-sectional regression framework that allows us to gauge the strength of the signal and control for other predictive variables.[15]

We maintain direct comparability with our signal-weighted portfolio results in our regression specifications. The dependent variable is the future excess currency return, but we vary the horizon from one month to 12 months. Longer horizon returns are compounded monthly returns, but we express the long-horizon returns in monthly terms to make comparisons across horizons easier. Specifically, we compute the k-month excess currency return of foreign currency i as

$$\Pi^i_{t,k} = \exp\left[\frac{1}{k}\sum_{j=1}^{k}\log\left(1+\Pi^i_{t+j}\right)\right] - 1, \tag{28}$$

where Π^i_{t+1} is the arithmetic one-period FX excess currency return given in equation (27).

Our basic regression specification is a pooled-panel cross-sectional regression run at the monthly frequency with month fixed effects:

$$\Pi^i_{t,k} = c_t + \mathbf{X}^i_t\mathbf{b} + \mathrm{e}^i_t, \tag{29}$$

where c_t is a monthly fixed effect, $\mathbf{X}^i_t$ is a vector of regressors for country i at time t, $\mathbf{b}$ is a vector of coefficients, and e^i_t represent the residuals. The month fixed effects absorb any average time-series variation in excess currency returns. This removes the effect of common U.S. dollar

[14] In portfolio formation with stocks, the traditional way of tackling this problem is by conducting a judicious number of double- or triple-sorted portfolios. The small number of currencies does not permit this analysis.

[15] In our cross-sectional regressions we deliberately do not consider underlying macro fundamentals of the yield curve, such as inflation or money supply differentials. Despite a very long history in the literature, these variables have typically little predictive ability (see Engel and West, 2005; Engel, Mark and West, 2007, among many others). More recently Dong (2006), Molodtsova and Papell (2008) and Wang and Wu (2009) have used Taylor (1993) monetary policy rules which build in some macro factors, to forecast exchange rates. These studies do not use term structure information. Ang and Piazzesi (2003) show that the domestic term structure already captures a large part of underlying inflation and output movements.

movements across time relative to other currencies. Finally, to make it easier to convert our results to perspectives from other currencies, we keep the U.S. dollar in our regressions as the currency with zero excess currency returns and zero interest rate differentials.

One advantage of our regression framework in contrast to the portfolio approach is that it allows us to take into account cross-currency correlations. For example, we know that currencies of the euro zone were highly correlated with each other even before they entered the euro. Due to currency convergence, some of these currencies would ex post appear to be redundant and we would want to account for such cross-correlation when we assess the significance of our results. In other words, it may be the case that $\mathrm{E}[\mathrm{e}_t^i \mathrm{e}_t^j] \neq 0$ for $i \neq j$. We control for this by computing standard errors that are clustered by time. In particular, we follow Petersen (2009) and all of our regressions use standard errors that are heteroskedasticity-robust and double-clustered by month and currency. Clustering by currency allows for the additional possibility of auto-correlated shocks in currency returns, $\mathrm{E}[\mathrm{e}_t^i \mathrm{e}_{t+k}^i] \neq 0$ for $k \neq 0$. Heteroskedasticity-robust standard errors allows for variabilities across currencies or across time in the magnitudes of shocks to currency returns, $\mathrm{E}[\mathrm{e}_t^i \mathrm{e}_t^i] \neq \mathrm{E}[\mathrm{e}_{t+k}^j \mathrm{e}_{t+k}^j]$ for $i \neq j$ or $k \neq 0$. In summary, our standard errors account for correlations of currencies at a point in time, account for auto-correlations of currencies, and account for variabilities in currency volatility over time or across currencies.

In Figure 2 we noted the large time-varying dispersion between short rate differentials. The same is true for all the other term structure predictors. To account for the significant time variation in the distribution of the signals across countries, we transform each of our independent variables by cross-sectionally standardizing our regressors to have zero mean and unit variance within each month. This removes the large heteroskedasticity of dispersion across time, but maintains information in the spacing of the predictors relative to each other. For the most part, we consider a sample consisting of all developed countries, but also consider a sample consisting of only G10 currencies for robustness. We standardize our regressors separately for each sample of countries and separately for each variable.

5.1 Base-Case Regression Results

We begin by examining multivariate regressions of future excess currency returns using Level, Change, and Term as our regressors in Panel A of Table 6.[16] This multivariate specification al-

[16] We have also conducted univariate and bivariate regressions to ensure that multi-collinearity is not driving our results. Results based on univariate and bivariate regressions all have quantitatively the same impact as the multifactor regressions reported.

lows us to understand how many different mechanisms are present. Going across the columns, we vary the holding period horizon of currencies as our dependent variable. The positive coefficients on Level is the panel regression equivalent of the carry portfolio returns. This predictability persists up to 12 months. At the one-month horizon, the coefficient of 0.098 on Level, which is significant at the 99% level, implies that a country with an interest rate one cross-sectional standard deviation higher than the sample mean forecasts an expected foreign exchange excess return of 9.8 basis points over the next month, or approximately 1.18% per annum, for investing in that currency. At all horizons we find that predictability remains economically large and statistically very strong. When we put the next 12-month excess foreign exchange rate return as the dependent variable, we find a coefficient estimate of 0.087 on Level, which is very similar to the 0.098 coefficient at the one-month horizon, and also significant at the 99% level.

In the same regression we also place the Change variable. Similar to our portfolio results, Change enters significantly and a positive change in interest rates predicts future currency appreciation. The coefficient of 0.073 on Change at the one-month horizon implies an annualized return of approximately 0.88% for a one standard deviation shock to Change. Predictability is significant at the 95% level at all horizons except at the six-month horizon which is significant at the 90% level. The longer horizon predictability also suggests that portfolio strategies based on changes in interest rates can be constructed in a way that portfolio turnover is not as high as the naïve rebalancing strategies we employed in the previous section.[17]

The regressions in Panel A of Table 6 also include term spreads. Consistent with the portfolio results in Section 4, the Term strongly negatively predicts future foreign exchange returns, and is significant at the 99% level at all horizons. The coefficient of -0.126 on Term implies an annualized return of about 1.51% for a one standard deviation flattening of the yield curve. Importantly, both Level and Term remain statistically significant, even though they are correlated with each other, which suggests that both contain independent information.

In Panel B of Table 6, we repeat the analysis in Panel A but with the addition of short rate volatility. The coefficients on Level, Change, and Term are largely unchanged when Volatility is added. Furthermore, consistent with our portfolio results that find a much weaker relation between short rate volatility and foreign exchange returns, we find that the coefficients on Volatil-

[17] Since interest rates are very persistent, past studies such as Campbell (1991) and Hodrick (1992) have taken interest rates relative to a recent average. In an unreported robustness test, we construct interest rate changes as the difference between current short rates and their 12-month moving averages, and find very similar results. This is consistent with constructing an estimator of long-run conditional means of interest rates in Section 2.2, which ideally uses longer lags of past interest rates than just the previous month.

ity is close to zero at all horizons. Thus, interest rate volatility is not a significant determinant of future currency returns after controlling for other interest rate variables.

Since developing countries include many countries that entered the euro and currencies that are closely tied to the U.S. dollar or the euro, we check the robustness of our main results using just the G10 currencies in Panel C. Compared to Panel A with all developed markets, we continue to find that each of these predictors come in with stronger economic significance in the G10 sample. The one-month horizon coefficients on Level, Change, and Term for the G-10 currencies are 0.106, 0.128, and -0.132, respectively, compared to 0.098, 0.073, and -0.126, in Panel A for all developed markets. However, the statistical significance is slightly reduced, since only about half of the observations are available in this reduced panel. Nevertheless, we find that these three predictors continue to remain statistically significant for the most part at the 95% level.

In summary, we find that three yield curve predictors come in with statistical and economic significance: Level, Change, and Term. Level and Change carry positive signs whereas the coefficient on term spreads is negative. The portfolio results showed that each of these comes in significantly by itself, but even in a multivariate setting where we allow these variables to compete against each other, we continue to find that they remain individually and jointly significant. This predictability remains significant for all variables at longer horizons up to 12 months. Overall, it appears that there is more predictive information in the yield curve than just levels of interest rates, or carry.

5.2 Additional Currency Risk Factors

It is well known among practitioners and formally shown by Bhojraj and Swaminathan (2006) and Asness, Moskowitz and Pedersen (2009) that there are both momentum effects and value effects in currency markets. We extend the panel regressions of Table 6 and control for currency momentum and value effects in Table 7. We define foreign exchange momentum (FX momentum) as the past three-month cumulative excess foreign exchange return.[18] Following Asness, Moskowitz and Pedersen (2009), we define foreign exchange value (FX value) by the past five

[18] Momentum can also be defined using raw foreign exchange returns, instead of excess returns, and our results are largely unchanged. Others in the literature typically use 12 months of past returns to define momentum. If anything, our momentum measures produces the strongest momentum results and gives it the best chance of reducing predictability by Level, Change, and Term. We have also experimented with using foreign exchange rates relative to the Purchasing Power Parity exchange rates published by the OECD, which produces a weaker effect for FX value than the one we use.

years of cumulative foreign exchange returns. Table 7 includes FX momentum and FX value as additional predictors along with Level, Change, and Term. As with our earlier regression specifications, each regressor is standardized each month to zero mean and unit variance. When we regress all five variables together, we find that only three of the variables are statistically significant: Change, Term, and FX momentum. Thus, FX momentum seems to subsumes the basic carry effect (Level).

In Table 8 we report betas with respect to several risk factors for the portfolio returns formed on the various foreign exchange strategies (reported in each column). We take k-month long-short currency portfolio returns defined as $\Pi_{t,k}^{\text{FX}} = \sum_i \omega_i \Pi_{t,k}^i$, where the weights, ω_i, sum to zero and are equal weighted and $\Pi_{t,k}^i$ are the k-month excess returns of currency i defined in equation (28). We go long the highest one-third and short the lowest one-third separately ranking on Level, Change, Term, Volatility, FX momentum, and FX value. We then regress each of these portfolio returns separately onto a single explanatory variable, Z_{t+k}:

$$\Pi_{t,k}^{\text{FX}} = c + \beta \mathrm{Z}_{t+k} + u_{t+k}. \tag{30}$$

The explanatory variable varies across panels and the standard errors, u_{t+k}, are heteroskedasticity robust and include 12 Newey-West (1987) lags. Note that both the right-hand side and left-hand side variables are contemporaneous.

Panel A of Table 8 regresses currency portfolio returns on the return to the contemporaneous carry trade portfolio formed by ranking on short rates, which we constructed in the first row of Table 3. We use a horizon of $k = 1$ month. The constant term in Panel A can be interpreted as a risk-adjusted currency return where the carry trade is treated as a risk factor. By construction, we find that Level portfolio returns have a loading on the carry trade portfolio that is close to one (0.951) and have risk-adjusted returns which are essentially zero. Consistent with our earlier results, we find that currency returns based on Change and Term remain large and significant after computing a carry trade beta. Portfolio returns on Change have close to a zero loading of 0.025 on carry trade profitability and risk-adjusted returns remain economically significant at 9.0 basis points per month, which is statistically significant at the 95% level. Interestingly, while portfolio returns on Term load strongly on carry trade profits with a coefficient of -0.655, absolute risk-adjusted returns remain large at 7.8 basis points per month, which is also statistically significant at the 95% level. This supports our interpretation that term spreads contain additional information beyond the levels of interest rates. Consistent with our earlier results, we find little risk-adjusted profitability for the Volatility portfolio controlling for carry. Finally, the FX momentum and FX value have low carry trade betas and the FX momentum profits are particularly high after adjusting for covariation with carry returns, at 19.3 basis points per month.

In the remaining panels of Table 8, we regress these currency portfolio returns on U.S. macroeconomic variables that have been shown to be potential sources of currency risk factors in the literature. In these panels, we do not report the constant terms because they cannot be interpreted as alphas or excess returns. We begin with the monthly change of implied volatility index from S&P 500 index options (VIX) in Panel B, which we refer to as ΔVIX. We again use a horizon of $k = 1$ month and in this panel, our sample is slightly shortened due to data availability. Consistent with Bhansali (2007), Lustig, Roussanov and Verdelhan (2009), Angelo, Christiansen and Söderlind (2009), Jorda and Taylor (2009), and others, the Level portfolio returns are negatively related to ΔVIX with a statistically significant coefficient of -0.070. However, the coefficient on ΔVIX of Change portfolio returns is insignificantly different from zero. When we regress Term returns on ΔVIX, we find a coefficient of 0.034, which is lower in absolute value than the coefficient of the Level portfolio, with only marginal statistical significance. We find that ΔVIX has little covariation with the other foreign currency portfolios based on Volatility, FX momentum, and FX value.

We examine the relation between currency returns and real percentage changes in U.S. nondurable and durable goods consumption growth rates in Panels C and D. We use year-on-year consumption growth rates so our dependent variables are 12-month cumulative percentage returns on currency portfolios (equation (30) with $k = 12$). Both consumption growth rates and portfolio returns are available at the monthly frequency, so we use overlapping observations and control for serial correlations in our estimates of standard errors. To maintain comparability with other panels, we express our returns in monthly units. Overall, we find that currency portfolio returns based on Level, Change, and Term do not have any significant loadings on U.S. consumption growth rates. If anything, we observe significantly negative loadings on portfolio returns based on Volatility and FX momentum, and a slightly positive consumption beta for FX value. In order for covariation with consumption growth rates to explain these portfolio returns, we would expect to see consumption betas with the opposite signs.

The weak relation with consumption and the foreign currency returns we report in Table 8 is surprising given the large role consumption plays in explaining carry trade profitability in Lustig and Verdelhan (2007). However, Lustig and Verdelhan's approach is cross sectional and they work with eight currency portfolios whereas we use time-series regressions in Panels C and D. Our sample period ends in 2009 and encompasses the most recent financial crisis and we restrict our sample to developed markets. In contrast, Lustig and Verdelhan's sample period includes emerging markets, ends in 2002, and goes back further than 1975 and thus encompasses the period of fixed exchange rates under Bretton Woods.

6 Conclusion

By far the vast majority of academic studies have focused on using differentials in interest rate levels, commonly known as carry, to predict exchange rate risk premiums. We find there is significant information that is useful for predicting excess foreign exchange returns in foreign countries' yield curves beyond just carry. We find that changes in interest rate levels and term spreads between long-term and short-term rates contain additional predictive power for foreign exchange returns independent of carry. In particular, currencies with large changes in interest rate levels tend to appreciate and currencies where the term spread is steep tend to depreciate. Exploiting these term structure variables results in portfolio strategies with high Sharpe ratios, returns that are less negatively skewed, and have relatively low correlations with carry strategies. The predictability persists up to 12 months and is robust to controlling for other currency risk factors.

Predictability of foreign exchange rate risk premiums by information in the term structure is consistent with a no-arbitrage framework. Any variable which affects the prices of domestic bonds can potentially predict exchange rates. Term structure models with a time-varying long-run mean factor, which could arise from shifting agents' expectations of monetary policy and inflation, would give rise to changes in interest rates predicting foreign currency returns. The foreign exchange predictability by term spreads is consistent with multifactor term structure models employing a price of risk factor which determines time-varying risk premiums of long-term bonds. Of course, the no-arbitrage pricing kernels leave open what types of economic mechanisms underlie the factor dynamics. Our work points to the need to consider multiple factors other than just carry and shows the importance of multifactor models in understanding foreign exchange risk premiums.

Appendix

A Estimation of the Time-Varying Long-Term Mean Model

This appendix describes the estimation of the conditional long-term mean model in equation (15). For reference, we restate this model here:

$$r_{t+1} = \theta_{t+1} + \rho r_t + \sigma_r \varepsilon_{t+1}, \tag{A-1}$$

with the long-term mean, θ_{t+1}, following

$$\theta_{t+1} = \theta_0 + \phi\theta_t + \sigma_\theta v_{t+1}. \tag{A-2}$$

We specify ε_{t+1} and v_{t+1} to be IID $N(0,1)$ and uncorrelated at all leads and lags.

We estimate equations (A-1) and (A-2) by a Gibbs sampling Bayesian algorithm and treat $\{\theta_{t+1}\}$ as a latent factor estimated by data augmentation. A textbook reference for these types of econometric models is Robert and Casella (1999).

We iterate over the following conditional distributions in the Gibbs sampler:

1. $p(\{\theta_t\}|\rho, \theta_0, \phi, \sigma_r, \sigma_\theta)$
   We use the forward-backward algorithm of Carter and Kohn (1994) to draw $\{\theta_t\}$. Equation (A-2) represents a state equation while equation (A-1) is a measurement equation in a Kalman filter system with an exogenous variable ρr_t. The algorithm works by running the Kalman filter forward through the sample and then sampling backwards following Carter and Kohn (1994).
2. $p(\rho, \sigma_r|\{\theta_t\}, \theta_0, \phi, \sigma_\theta)$
   Given the latent factor $\{\theta_t\}$, equation (A-1) is simply a regression and we can draw these parameters using a conjugate normal-inverse gamma distribution. We assume a diffuse normal prior for ρ yielding a normal posterior and an uninformative inverse gamma prior for σ_r^2 yielding a inverse gamma posterior.
3. $p(\phi, \sigma_\theta|\{\theta_t\}, \rho, \sigma_r)$
   Given $\{\theta_t\}$, equation (A-2) is also a standard regression Normal-Inverse Gamma draw for ϕ, and σ_θ.

In the estimation we impose stationarity and discard any draws of ρ and ϕ greater than one. We also do not directly draw θ_0 and instead set it to $\mu = \bar{r}(1-\phi)$, where $\bar{r}$ is the sample mean of the short rate so that we match the sample mean of the short rate in each iteration. We estimate the system with 10,000 burn-in draws and 100,000 iterations.

B Data Sources

For each of our currencies, we take one-month LIBOR or equivalent interbank offered rates at the end of the month. If an interbank offered rate is not available for a currency, we supplement the data with that country's three-month government bill rate, also obtained from Global Financial Data (GFD). The G10 currencies for which we used three-month government bill rates to increase sample length are AUD, CAD, JPY, NZD, and SEK. We also used three-month government bill rates for the following non-G10 developed currencies: ATS, BEF, ESP, GRD, ITL, NLG, PTE, and SGD.

We also take 10-year government bond rates for each of our currencies. If the 10-year government bond rate is not available, we use the five-year government bond rate. The G10 currencies for which we used five-year government bond rates are AUD, CAD, CHF, NZD, and SEK. Among non-G10 developed countries, we used five-year government bond yields for ATS, BEF, DKK, FRF and GRD. For CHF, we also supplement the long-term bond rate with a generic "long-term bond yield" with the maturity not specified in GFD.

We use interest rate differentials relative to their U.S. equivalents. We take USD LIBOR, denoted as r_t, and U.S. 10-year constant maturity government bond rates, which we denote as y_t. The country i counterparts we denote as r_t^i and y_t^i, respectively. If we use an alternative data for an interest rate (such as a government bill rate or a five-year bond rate), we use its U.S. dollar equivalent. The portfolio strategies below takes zero positions in the U.S. dollar and all of our regression specification includes time fixed effects. Therefore, subtracting the U.S. interest rate at each month from all currencies does not have any impact on our analysis.

Finally, we also collect some U.S. macroeconomic data. We collect monthly levels of Chicago Board Options Exchange Volatility Index ("VIX"), which is an index of the implied volatility of S&P 500 index options calculated and disseminated by the Chicago Board Options Exchange. We also collect U.S. consumption growth rates at a monthly frequency. We take real seasonally adjusted year-on-year changes in non-durable and durable goods components of personal consumption expenditures calculated by the U.S. Bureau of Economic Analysis.

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Table 1: Variable Definitions

Variable	Description	Notation
Short rates	One-month interbank rates	r_t
Δ Short rate	Changes in short rates	$\Delta r_t = r_t - r_{t-1}$
Long rates	10-year bond rates	y_t
Δ Long rate	Changes in long rates	$\Delta y_t = y_t - y_{t-1}$
Level	Interest rate levels	$(y_t + r_t)/2$
Change	Changes in interest rate levels	$\Delta(y_t + r_t)/2 =$ $(y_t + r_t)/2 - (y_{t-1} + r_{t-1})/2$
Term	Difference between 10-year bond rates and one-month interbank rates	$y_t - r_t$
Δ Term	Changes in term spreads	$\Delta(y_t - r_t) =$ $(y_t - r_t) - (y_{t-1} - r_{t-1})$
Volatility	Annualized standard deviation of daily short rate changes over the past 12 months	

Table 2: Summary Statistics

		Excess FX Return		Differential Short Rate		Differential Long Rate		Differential Level		Differential Term		Sample Period	
		Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Start	End
Panel A: G10 Currencies													
Australia	AUD	0.153	3.201	0.214	0.232	0.160	0.132	0.187	0.176	-0.054	0.135	1975:01	2009:07
Canada	CAD	0.142	1.982	0.098	0.155	0.055	0.075	0.076	0.110	-0.043	0.104	1980:12	2009:07
Switzerland	CHF	0.010	3.601	-0.261	0.275	-0.275	0.189	-0.268	0.219	-0.014	0.174	1975:01	2009:07
Germany/Euro	DEM/EUR	0.069	3.269	-0.113	0.232	-0.093	0.140	-0.103	0.180	0.020	0.136	1975:01	2009:07
United Kingdom	GBP	0.144	3.102	0.190	0.231	0.109	0.137	0.149	0.169	-0.081	0.172	1975:01	2009:07
Japan	JPY	0.096	3.412	-0.242	0.219	-0.237	0.124	-0.239	0.161	0.005	0.150	1975:01	2009:07
Norway	NOK	0.123	3.000	0.121	0.318	0.082	0.145	0.102	0.220	-0.039	0.223	1975:01	2009:07
New Zealand	NZD	0.277	3.504	0.321	0.358	0.178	0.198	0.250	0.270	-0.143	0.207	1978:05	2009:07
Sweden	SEK	0.034	3.193	0.123	0.278	0.099	0.135	0.111	0.192	-0.024	0.207	1975:01	2009:07
United States	USD	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1975:01	2009:07
Panel B: Non-G10 Developed Countries													
Austria	ATS	0.173	3.362	0.006	0.216	-0.069	0.146	-0.031	0.164	-0.075	0.170	1975:01	1998:12
Belgium	BEF	0.114	3.361	0.065	0.218	0.036	0.076	0.050	0.139	-0.029	0.170	1975:01	1998:12
Denmark	DKK	0.201	3.220	0.133	0.309	0.192	0.254	0.163	0.242	0.059	0.293	1975:01	2009:07
Spain	ESP	0.149	3.239	0.433	0.407	0.298	0.135	0.365	0.247	-0.135	0.351	1975:01	1998:12
Finland	FIM	0.129	3.204	0.169	0.357	0.147	0.176	0.158	0.256	-0.022	0.231	1978:02	1998:12
France	FRF	0.113	3.231	0.163	0.314	0.106	0.112	0.135	0.193	-0.058	0.273	1975:01	1998:12
Greece	GRD	-0.014	3.413	0.808	0.710	0.572	0.362	0.690	0.472	-0.236	0.614	1981:02	2000:06
Hong Kong	HKD	-0.005	0.171	-0.004	0.118	0.048	0.099	0.022	0.099	0.052	0.092	1994:10	2009:07
Ireland	IEP	0.126	3.165	0.253	0.354	0.225	0.176	0.239	0.227	-0.028	0.328	1975:01	1998:12
Italy	ITL	0.151	3.154	0.444	0.337	0.367	0.184	0.405	0.239	-0.077	0.260	1975:01	1998:12
Netherlands	NLG	0.023	3.368	-0.111	0.262	-0.074	0.132	-0.093	0.182	0.037	0.198	1975:01	1998:12
Portugal	PTE	0.311	3.227	0.569	0.381	0.464	0.256	0.517	0.304	-0.104	0.227	1983:03	1998:12
Singapore	SGD	-0.014	1.536	-0.157	0.113	-0.166	0.087	-0.161	0.084	-0.008	0.112	1988:01	2009:07

Note to Table 2

This table reports means, standard deviations, and sample ranges of variables used. Panel A shows the statistics for G10 currencies and Panel B shows the statistics for non-G10 developed countries. All variables are reported in percentage terms per month. The excess FX return is the next one-month holding period return on buying a currency and depositing the proceeds at the one-month foreign interbank deposit rate, and borrowing U.S. dollars at one-month LIBOR. The short rate, long rate, levels, and term spread are all differentials relative to the U.S. The short rate differential is the monthly rate of foreign one-month interbank deposit rates minus USD one-month LIBOR rate. If an interbank deposit rate is unavailable, the one-month or three-month government bill rate is used instead. The long rate differential is the monthly foreign country 10-year government bond yield (or five-year bond yield) minus the U.S. 10-year constant-maturity government bond rate (or five-year bond rate). The Level factor is the average of the short rate and the long rate and the term spread is the difference between the long rate and the short rate.

Table 3: Returns on Equal-Weighted Currency Portfolios

	Mean (per month)	Stdev (per month)	Sharpe Ratio (Annualized)	Skewness
Panel A: All Developed Countries				
Short rate ("carry")	0.181	0.934	0.673	-1.106
Δ Short rate	0.088	0.688	0.442	-0.272
Long rate	0.116	0.870	0.462	-1.280
Δ Long rate	0.111	0.702	0.548	0.610
Level	0.169	0.913	0.642	-1.243
Change	0.094	0.694	0.470	-0.256
Term	-0.196	0.841	-0.809	0.847
Δ Term	-0.032	0.655	-0.169	0.447
Volatility	0.052	0.771	0.233	-0.226
Panel B: G10 Currencies Only				
Short rate ("carry")	0.217	1.327	0.567	-1.012
Δ Short rate	0.100	0.993	0.350	-0.069
Long rate	0.143	1.269	0.390	-0.796
Δ Long rate	0.159	1.060	0.519	0.328
Level	0.172	1.339	0.445	-0.897
Change	0.132	1.015	0.449	0.006
Term	-0.219	1.137	-0.667	0.492
Δ Term	0.007	1.030	0.024	-0.098
Volatility	0.063	1.039	0.209	-0.370

This table reports summary statistics on returns on equal-weighted long/short currency portfolios. Each portfolio is formed according to a single signal and rebalanced each month. We construct portfolio returns by going long currencies with the highest one-third value of a signal and shorting currencies with the lowest one-third value of a signal. The equal-weighted portfolio based on short rates are also called the "carry" trade. Returns are computed net of lending and borrowing at the interbank rate. Panel A reports results for all developed countries and Panel B reports results for only the G10 currencies. The Sharpe ratios are annualized by multiplying by $\sqrt{12}$ and all other statistics are reported at the monthly frequency with returns in percentages. The sample is from 1975:01 to 2009:07.

Table 4: Correlations of Returns on Equal-Weighted Currency Portfolios

	Short rate	Δ Short rate	Long rate	Δ Long rate	Level	Change	Term	Δ Term
Short rate	1.000							
Δ Short rate	0.040	1.000						
Long rate	0.900	0.034	1.000					
Δ Long rate	-0.021	0.214	0.020	1.000				
Level	0.973	0.063	0.933	-0.011	1.000			
Change	0.033	0.781	0.043	0.503	0.061	1.000		
Term	-0.728	-0.164	-0.562	0.090	-0.698	-0.106	1.000	
Δ Term	-0.047	-0.697	-0.029	0.227	-0.061	-0.389	0.114	1.000
Volatility	0.340	-0.144	0.390	-0.032	0.351	-0.120	-0.090	0.110

This table reports correlations of returns on equal-weighted long-short currency portfolios using all developed countries. The portfolios are formed according to a single signal and rebalanced each month. The portfolios go long currencies with the highest one-third value of a signal and go short currencies with the lowest one-third value of a signal. Portfolio returns are net of lending and borrowing at the interbank rate. The sample is from 1975:01 to 2009:07.

Table 5: Returns on Signal-Weighted Currency Portfolios

	Mean (per month)	Stdev (per month)	Sharpe Ratio (Annualized)	Skewness
Panel A: All Developed Countries				
Short rate	0.245	0.992	0.856	-0.964
Δ Short rate	0.116	0.833	0.482	0.171
Long rate	0.156	0.973	0.554	-1.458
Δ Long rate	0.067	0.804	0.287	-0.379
Level	0.214	0.989	0.749	-1.096
Change	0.117	0.815	0.496	0.366
Term	-0.241	0.920	-0.907	0.341
Δ Term	-0.075	0.785	-0.331	-0.138
Volatility	0.117	0.878	0.463	-0.297
Panel B: G10 Currencies Only				
Short rate	0.235	1.342	0.606	-0.865
Δ Short rate	0.133	1.073	0.431	0.164
Long rate	0.155	1.376	0.391	-1.022
Δ Long rate	0.134	1.154	0.403	-1.181
Level	0.207	1.363	0.527	-0.919
Change	0.163	1.055	0.536	0.257
Term	-0.233	1.171	-0.691	0.483
Δ Term	-0.046	1.103	-0.146	-0.491
Volatility	0.076	1.142	0.231	-0.413

This table reports summary statistics on returns on equal-weighted long/short currency portfolios. Each portfolio is formed according to a single signal and rebalanced each month. We rescale the signals so that all positive signal values sum to one and all negative signal values sum to -1. by standardizing the signals to to have zero mean and a constant standard deviation of two. For each currency with a positive (negative) demeaned and rescaled signal, we purchase (sell) a U.S. dollar amount equal to the adjusted signal. Portfolio returns are net of lending and borrowing at the interbank rate. Panel A reports results for all developed countries and Panel B reports results for only the G10 currencies. The Sharpe ratios are annualized by multiplying by $\sqrt{12}$ and all other statistics are reported at the monthly frequency in percentages. The sample is from 1975:01 to 2009:07.

Table 6: Currency Predictability Regressions Using Level, Change, and Term

	Excess FX Return Horizon (Months)					
	1	2	3	6	9	12
Panel A: Level, Change, and Term						
Level	0.098**	0.100**	0.096**	0.087**	0.086**	0.087**
	(0.029)	(0.023)	(0.021)	(0.017)	(0.016)	(0.016)
Change	0.073**	0.060**	0.044*	0.020+	0.040**	0.038**
	(0.028)	(0.021)	(0.018)	(0.011)	(0.014)	(0.015)
Term	-0.126**	-0.105**	-0.099**	-0.089**	-0.083**	-0.086**
	(0.030)	(0.029)	(0.030)	(0.027)	(0.024)	(0.027)
Panel B: Level, Change, Term, and Volatility						
Level	0.093**	0.099**	0.096**	0.088**	0.093**	0.099**
	(0.035)	(0.029)	(0.027)	(0.022)	(0.021)	(0.021)
Change	0.080**	0.066**	0.048**	0.023*	0.042**	0.040**
	(0.027)	(0.021)	(0.018)	(0.011)	(0.014)	(0.014)
Term	-0.121**	-0.098**	-0.093**	-0.085**	-0.077**	-0.080**
	(0.031)	(0.029)	(0.030)	(0.026)	(0.024)	(0.026)
Volatility	0.025	0.016	0.010	0.003	-0.010	-0.019
	(0.042)	(0.040)	(0.038)	(0.032)	(0.032)	(0.032)
Panel C: G-10 Currencies Only						
Level	0.106*	0.108*	0.104**	0.096**	0.092**	0.090**
	(0.052)	(0.042)	(0.039)	(0.030)	(0.031)	(0.031)
Change	0.128**	0.082**	0.068*	0.024	0.066**	0.057*
	(0.041)	(0.030)	(0.026)	(0.016)	(0.019)	(0.023)
Term	-0.132*	-0.116*	-0.112*	-0.108*	-0.095*	-0.103*
	(0.057)	(0.049)	(0.049)	(0.044)	(0.042)	(0.046)

This table reports pooled-panel multivariate regressions of future excess foreign currency (FX) returns on yield curve predictors:

$$\Pi^i_{t,k} = c_t + \mathbf{X}^i_t \mathbf{b} + \mathrm{e}^i_t.$$

Dependent variables, $\Pi^i_{t,k}$, are cumulative excess FX returns over one-month to 12-month horizons expressed in percentage terms per month. Independent variables, $\mathbf{X}^i_t$, are standardized each month to have zero mean and unit variance. Regressions include unreported month fixed-effects, c_t. Standard errors are heteroskedasticity robust and double-clustered by month and currency, following Petersen (2009). Double asterisk (**), asterisk (*) and plus (+) represent statistical significance at the 99%, 95%, and 90% confidence levels, respectively. The number of observations is up to 7581, spans 415 months and represents 23 currencies in all developed countries. The number of observations in Panels A and B is up to 7581, spans 415 months and represents 23 currencies in all developed countries. The number of observations in Panel C is up to 4039, spans 415 months and represents 10 currencies in only G10-currency countries.

Table 7: Controlling for Currency Momentum and Value

	Excess FX Return Horizon (Months)					
	1	2	3	6	9	12
Level	0.039	0.047	0.042	0.036	0.033	0.040
	(0.048)	(0.041)	(0.039)	(0.034)	(0.032)	(0.033)
Change	0.082**	0.068**	0.050**	0.024*	0.047**	0.044**
	(0.028)	(0.021)	(0.018)	(0.011)	(0.014)	(0.014)
Term	-0.117**	-0.101**	-0.100**	-0.099**	-0.082**	-0.089**
	(0.032)	(0.031)	(0.033)	(0.032)	(0.026)	(0.030)
FX Momentum	0.152**	0.112**	0.084*	0.032	0.091**	0.058+
	(0.049)	(0.042)	(0.037)	(0.022)	(0.027)	(0.030)
FX Value	-0.074	-0.072	-0.080	-0.084	-0.076	-0.073
	(0.067)	(0.061)	(0.061)	(0.056)	(0.052)	(0.055)

This table reports pooled-panel multivariate regressions of future excess foreign currency (FX) returns on yield curve predictors:

$$\Pi^i_{t,k} = c_t + \mathbf{X}^i_t \mathbf{b} + \mathrm{e}^i_t.$$

Dependent variables, $\Pi^i_{t,k}$, are cumulative excess FX returns over one-month to 12-month horizons expressed in percentage terms per month. Independent variables, $\mathbf{X}^i_t$, are standardized each month to have zero mean and unit variance. Currency momentum is based on past three-month cumulative excess currency returns. Currency value is based on past five-year cumulative currency returns. Regressions include unreported month fixed-effects, c_t. Standard errors are heteroskedasticity robust and double-clustered by month and currency, following Petersen (2009). Double asterisk (**), asterisk (*) and plus (+) represent statistical significance at the 99%, 95%, and 90% levels, respectively. The number of monthly observations is 7581, spans 415 months, and represents 23 currencies in all developed countries.

Table 8: Currency Portfolio Betas with Various Risk Factors

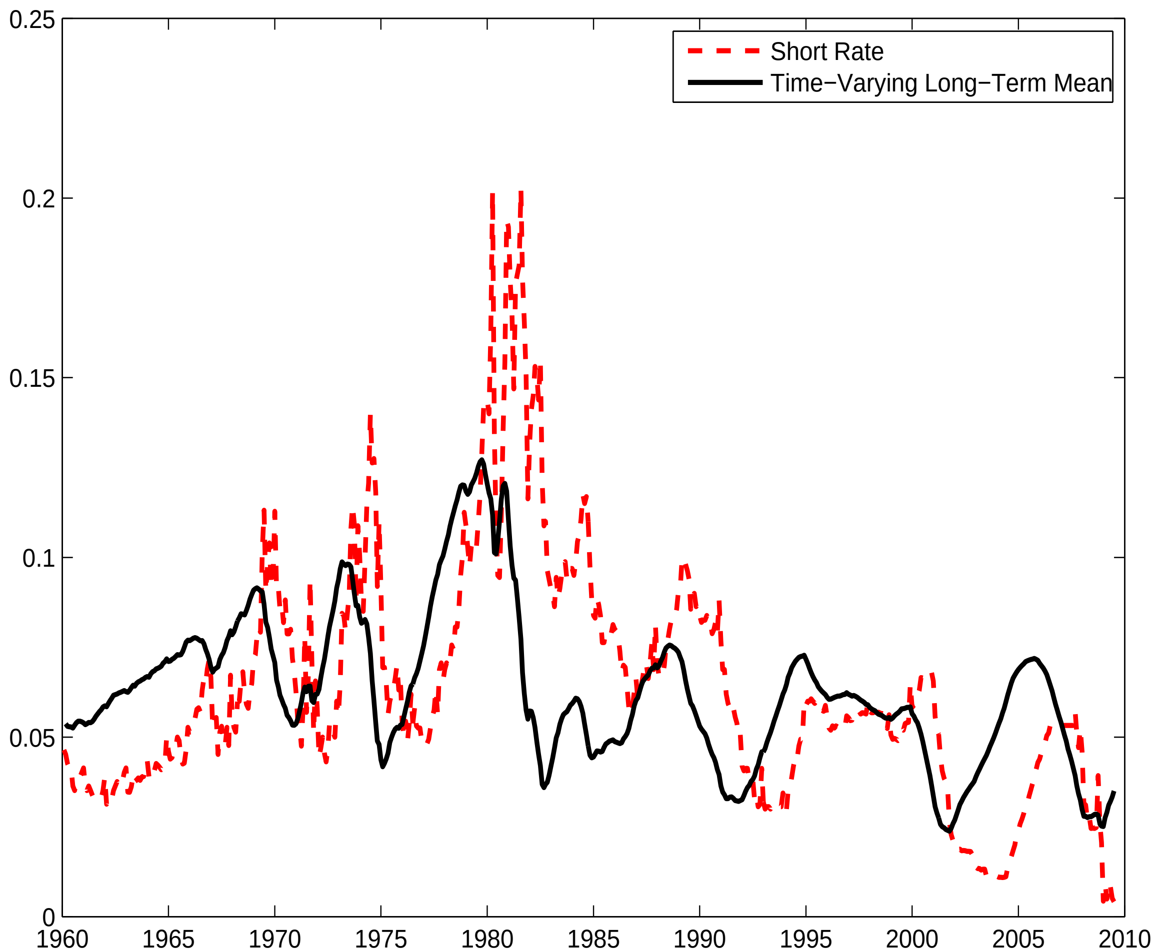
	Level	Change	Term	Volatility	FX Momentum	FX Value
Panel A: Carry Trade						
Constant	-0.003	0.090*	-0.078*	0.001	0.193**	-0.064
	(0.010)	(0.036)	(0.031)	(0.036)	(0.059)	(0.059)
Carry Trade	0.951**	0.025	-0.655**	0.281**	0.034	-0.225+
	(0.013)	(0.061)	(0.050)	(0.069)	(0.130)	(0.122)
Panel B: ΔVIX						
ΔVIX	-0.070**	-0.008	0.034+	-0.022+	0.017	0.008
	(0.020)	(0.008)	(0.020)	(0.012)	(0.026)	(0.024)
Panel C: Real U.S. Non-Durable Consumption Growth						
Consumption Growth	0.023	0.006	-0.036	-0.022*	-0.037*	0.032
(Non-Durables)	(0.034)	(0.015)	(0.039)	(0.011)	(0.017)	(0.022)
Panel D: Real U.S. Durable Goods Consumption Growth						
Consumption Growth	0.001	-0.004	-0.002	-0.010**	-0.009**	0.008+
(Durables)	(0.008)	(0.004)	(0.009)	(0.003)	(0.003)	(0.005)

This table reports univariate time-series regressions of long-short currency portfolio returns on various explanatory variables:

$$\Pi^{\text{FX}}_{t,k} = c + \beta \text{Z}_{t+k} + u_{t+k},$$

where the dependent variable $\Pi^{\text{FX}}_{t,k}$ is the long-short currency portfolio return over horizon k and Z_{t+k} are explanatory variables in each panel. In Panels A and B, the portfolios are formed across all developed countries, held for one month ($k = 1$), and rebalanced each month. In Panels C and D, dependent variables are 12-month cumulative currency portfolio returns ($k = 12$). Each panel has a different right-hand side variable. The carry trade return in Panel A is the long-short currency portfolio returns formed according to short rate levels, reported in the first row of Table 3. Panel B uses monthly changes in VIX (ΔVIX), which is an index of the implied volatility of S&P 500 index options. In Panels C and D, U.S. consumption growth rates are real seasonally adjusted year-on-year changes in non-durable (Panel C) and durable goods (Panel D) components of personal consumption expenditures. The constant terms are not reported in panels B-D. Standard errors, u_t are heteroskedasticity robust and include 12 Newey-West (1987) lags. Double asterisk (**), asterisk (*) and plus (+) represent statistical significance at the 99%, 95%, and 90% levels, respectively. The sample is from 1975:01 to 2009:07 in Panels A, C and D, and is from 1986:01 to 2009:07 in Panel B.

Figure 1: Estimates of Time-Varying Long-Term Mean Model for the U.S.



This plot shows estimates from the conditional time-varying long-term mean model in equation (15). The short rate is given by

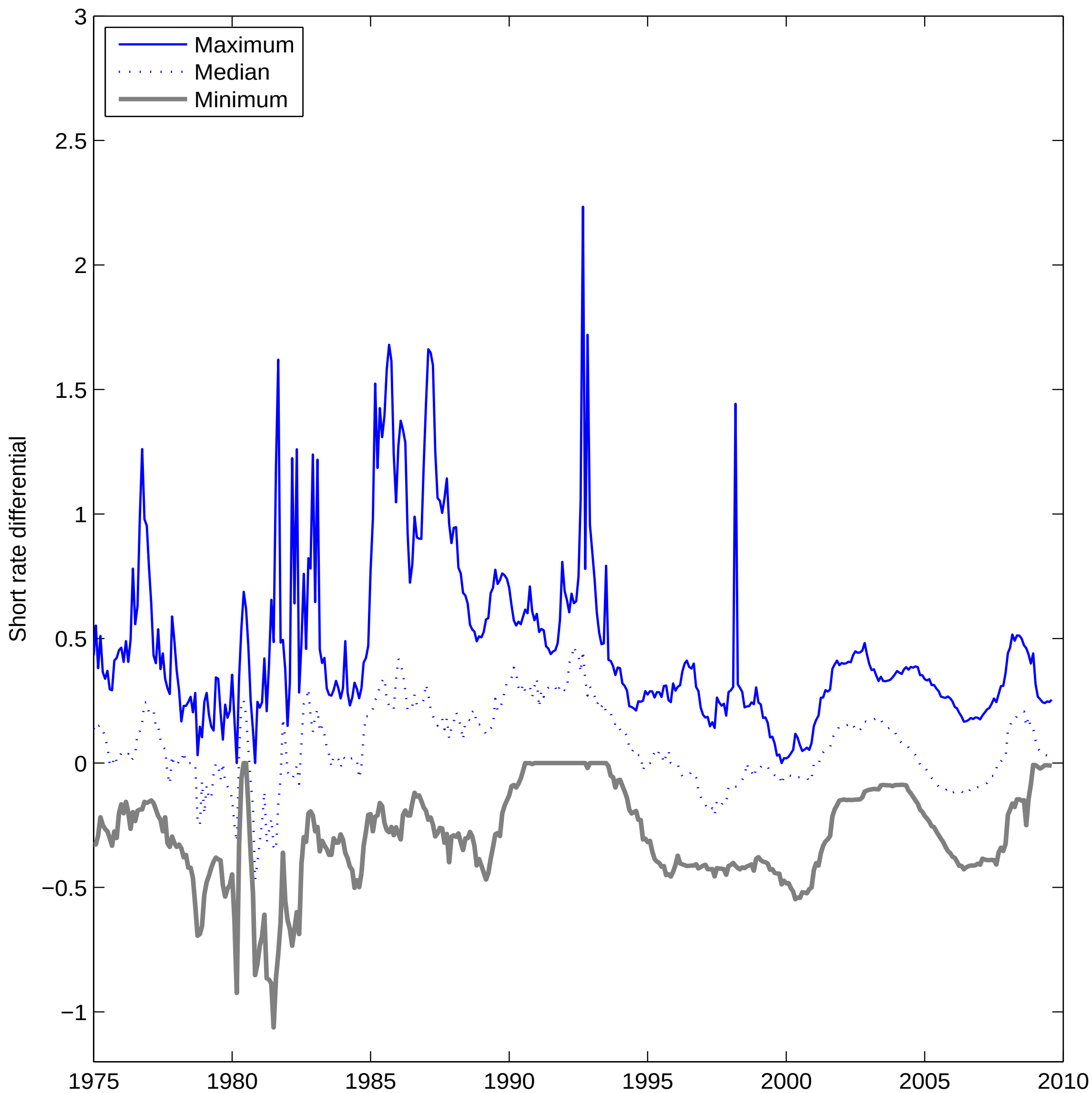
$$r_{t+1} = \theta_{t+1} + \rho r_t + \sigma_r \varepsilon_{t+1},$$

with the long-term mean following

$$\theta_{t+1} = \theta_0 + \phi\theta_t + \sigma_\theta v_{t+1}.$$

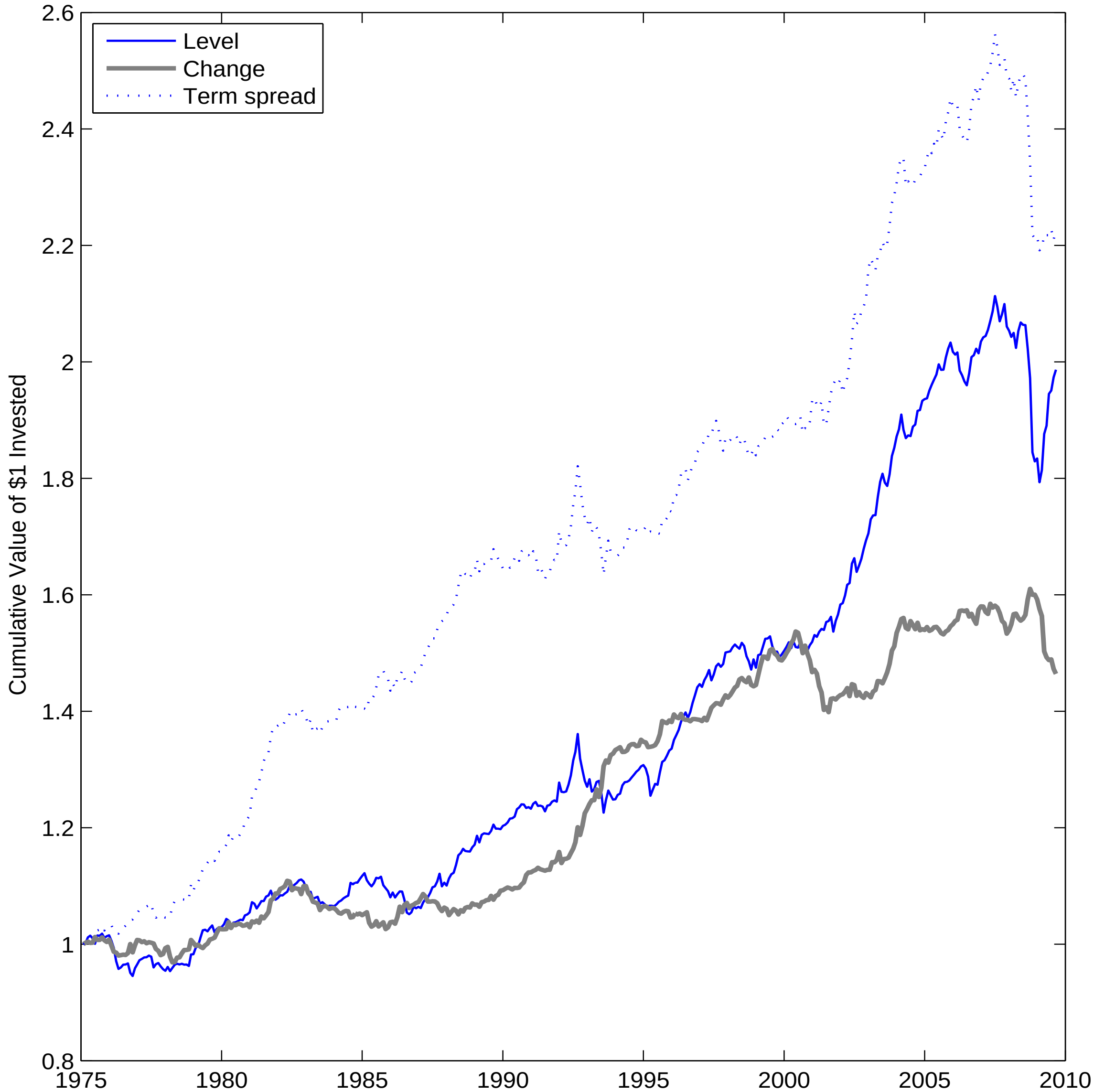
The model is estimated using a Gibbs sampling Bayesian algorithm described in the Appendix. The dotted line is the observed U.S. short rate (one-month LIBOR). The solid line is the estimated time-varying conditional long-run mean of the short-rate, which we plot as $\theta_t/(1-\rho)$ to have the same annualized units as the short rate.

Figure 2: Short Rate Differentials



This plot shows the distribution of short-term interest rate differentials in time-series. Short-term interest rate differential is the monthly rate of foreign 1-month interbank deposit rates minus the U.S. dollar 1-month LIBOR rate. If an interbank deposit rate is unavailable, one-month or three-month government bill rates are used instead. At each point in time, the plot shows the maximum, the median and the minimum short-term interest rate differentials from among the G10 currencies. The sample is from 1975:01 to 2009:07.

Figure 3: Cumulated Returns of Currency Portfolios



This plot shows the cumulative returns on equal-weighted long/short currency portfolios based on on average interest rate levels, on average changes in interest rates, and on term spreads shown in Table 3. Each portfolio is formed according to a single signal and rebalanced each month. The portfolio goes long currencies with the highest one-third value of a signal and goes short currencies with the lowest one-third value of a signal. Portfolio returns are net of lending and borrowing at the interbank rate. The sample includes all developed countries and is from 1975:01 to 2009:07.