DUSTING OFF THE PERCEPTION OF RISK AND RETURNS IN FOREX MARKETS

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Abstract

In this paper, we construct alternative theoretical models for exchange rates by introducing additional risk factors, based on the volatility of macroeconomic fundamentals. The modified flexible-price monetary model is used to characterize the long-run equilibrium of exchange rates, while the modified sticky-price model explains the adjustment towards the long run. Empirically, in a number of OECD countries we find cointegration relationships between the exchange rate and macroeconomic variables and also some evidence for the long-run equilibrium error correction. Macroeconomic uncertainty can significantly explain the variation of the exchange rate from its fundamental-based value. The results lead us to believe that macroeconomic sources of FOREX risk may be a missing factor in the exchange rate study.

JEL Code: E44, F31, G12.

Keywords: flexible-price and sluggish-price exchange rate models, expectation formations, macroeconomic risk, risk premium, asset pricing.

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1 Introduction

After the demise of the Bretton Woods system in early 1973, many industrialized countries turned to a (semi) floating exchange rate regime.[1] Academics try to explain causes of exchange rate fluctuations and search for policy recommendations. There are numerous papers trying to explain the movement of exchange rates.[2] Many theoretical attempts, however, fail to determine exchange rates in practice. Empirical investigations have been carried out to test the exchange rate theories

[1] This articile is partially from Chapter 2 „Modeling Currency Prices“ in a doctoral thesis by Cumperayot (2002).

[2] For example. For the monetary-approach partial equilibrium models Frenkel (1976), Mussa (1976) and Bilson (1978) discuss the flexible-price model, while Dornbusch (1976), Frankel (1979), Mussa (1979) and Buiter and Miller (1982) consider the sticky-price model. The general equilibrium asset pricing models are studied by Stockman (1980), Lucas (1982), Svensson (1985a, b) and Hodrick (1989), and extended into the continuous-time stochastic framework by Bakshi and Chen (1997) and Basak and Gallmeyer (1998).

and the predictability of exchange rates.[3] The empirical support for the theories has been rather weak.

In this paper, a nonlinear model for exchange rates is proposed, based on the monetary exchange rate theory and the theory of financial asset pricing, so as to provide alternative insights about the anomalous behavior of exchange rates. This paper is inspired by the pioneering work of Hodrick (1989), in which the volatility of macroeconomic fundamentals are introduced in the exchange rate model as additional risk factors. Dissimilar to Hodrick (1989), we incorporate macroeconomic risk into the flexible-price and the sluggish-price monetary models, which allow us to examine long-run and short-run effects of the fundamental uncertainty. Moreover, our empirical results are rather striking and supportive compared to Hodrick (1989).

In the long run, we find that an increase in the domestic money supply or a decrease in domestic real income leads depreciation of the domestic currency, and vice versa for the foreign variables. Time-varying conditional variances of the macroeconomic variables, representing macroeconomic risk, can significantly explain the deviation of the exchange rate from its fundamental-based value. Macroeconomic uncertainty influences the perception of FOREX risk and consequently influences market expectations about compensation for risk bearing. Due to risk aversion, high risk is accompanied by high expected future returns, or equivalently a current depreciation of the currency. In the short run, we find evidence for correction of equilibrium errors towards the long-run equilibrium.

We conclude that macroeconomic sources of FOREX risk may be a missing factor in exchange rate studies and that the monetary-approach models could potentially still be usefulness. The next section gives the motivation of our work. In Section 3, we discuss the nonlinear dynamic model. Its econometric results are reported in Section 4, while Section 5 contains conclusions.

2 Motivation for the Model

The monetary approach to model exchange rates has been viewed as one of the most dismal failures in modern economics, see Flood and Rose (1999). Nevertheless, we can hardly deny that for our anticipation of exchange rates we rely on economic fundamentals, and often in the manner predicted by the monetary-based exchange rate models. Inspired by the works of Dornbusch (1976) and Hodrick (1989), we establish a model for exchange rates by reconsidering the expectation assumptions used in the traditional exchange rate models and by exploiting the statistical regularity of time-varying conditional variances of fundamental growth rates. As suggested in Dornbusch (1976), a fundamental change from its equilibrium level may cause a short-run overshooting in the exchange rate.

Volatility in the macroeconomic variables may consequently induce volatility in the exchange rate. As a result, uncertainty in macroeconomic fundamentals may influence the perception of risk in the markets, and subsequently through the risk premium it may price returns on the exchange rate, as stated in Hodrick (1989). This seems a natural idea for explaining the exchange rate risk premium, arising from variation in conditional variances of exchange rate returns, but Hodrick (1989) finds little support for the idea. After more than a decade since his research and almost three decades of floating exchange rate regime, it is timely to reinvestigate the hypothesis in Hodrick (1989).

[3] To name but a few, the empirical studies have been done by Frenkel (1976), Bilson (1978), Hodrick (1978, 1989), Meese and Rogoff (1983, 1988), Backus (1984), Meese (1990), MacDonald and Taylor (1994), Chinn and Meese (1995), Mark (1995) and Flood and Rose (1995, 1999).

In the literature, exchange rates rely on two factors, which are the current fundamental levels, $\widetilde{f}_t$, and the expectation of future exchange rates, $E_t\left[e_{t+1}\right]$.[4] A general framework of the models in the exchange rate literature can be summarized as shown in Cuthbertson (1999)[5],

$$e_t = E_t\left[e_{t+1}\right] - \alpha\widetilde{f}_t, \tag{1}$$

where e_t is the logarithm of the nominal exchange rate, $\widetilde{f}_t$ represents the fundamentals that may differ in each model, and $E_t[\cdot]$ is the conditional expectation operator. Apart from many possible estimation problems[6], as expectations about the future exchange rate are likely to be a self-fulfilling prophecy, the expectation formation deserves considerable attention.

In the context of the present value relation, it is known that persistent movement in an asset's expected return tends to have dramatic effects on the asset price, as it makes the price more volatile than in the case of a constant expected return.[7] This also holds for the currency price, for which the expected return is represented by the expected price change. However, the source of the expectation variation is an unresolved issue. In this paper, we provide an alternative explanation for the expectation formation in the exchange rate models. According to the exchange rate literature, the fundamental solution of the exchange rate is determined by the expected present value of macroeconomic fundamentals, discounted at a constant rate (following from Cuthbertson (1999) in this case is equal to one)[8];

$$e_t = -\sum_{i=0}^{\infty} \alpha E_t[\widetilde{f}_{t+i}]. \tag{2}$$

By comparing equation (2), i.e., $e_t = -\alpha\widetilde{f}_t - \sum_{i=1}^{\infty} \alpha E_t[\widetilde{f}_{t+i}]$, to equation (1), one finds that the expected future fundamentals are used to determine the expected future exchange rate. Nonetheless, in practice the structure of expectation formation is not known and the infinite horizon is not easily specified. It is often assumed that the fundamental processes are a random walk process, $E_t\left[x_{t+1}\right] - x_t = 0$. As a consequence, the models are then left with the current values of the fundamentals as representatives of the expected future fundamentals, see, e.g., Meese and Rogoff (1983). As there is no expected change in the fundamentals, these rational expectation models imply zero expected exchange rate returns. Yet, empirically positive correlations of exchange rate returns are found at short horizons, whereas negative serial correlations are reported at longer horizons, see, e.g., Cuthbertson (1999).

Moreover, there is some evidence for predictability of the exchange rate at long horizons once the fundamentals are brought into the analysis.[9] It is unlikely that

[4] Mathematical applications are partially adopted from Cuthbertson (1999).

[5] This equation is derived from the uncovered interest parity (UIP) and from an assumption corresponding to the monetary models that the interest rate differential depends on the fundamentals $\widetilde{f}_t$:

$$i_t - i_t^* = \alpha\widetilde{f}_t.$$

[6] See a summary in Meese (1990).

[7] See Campbell, Lo and MacKinlay (1997) Chapter 7.

[8] This solution is derived by applying the law of iterated expectations, i.e., $E_t[E_{t+1}[X]] = E_t[X]$, to equation (1). Suppose the discount rate is lower than one, e.g., as it is governed by an interest semi-elasticity to money demand which is said to be smaller than one. The expectation would be assigned lower exponential weight (to the power i) as looking forward (to time $t+i$). From the Limit Theorem, at infinity $T \to \infty$ the bubble term (with a weight to the power $T+1$) vanishes. See also Blanchard and Fischer (1993) Chapter 5.

[9] For instance, MacDonald and Taylor (1994) find cointegration between exchange rates and monetary variables in the fundamental exchange rate models. Chinn and Meese (1995), as well as Mark (1995), find evidence that for long horizons the monetary-based exchange rate model

the expected returns are zero. In particular, since the patterns of time variation in the mean and the variance of the fundamental changes have actually been observed. Like exchange rate returns, there is rather strong evidence of time-varying conditional variances of the fundamentals, though it is not well documented.[10] As there exists systematic fundamental volatility, this paper investigates whether the fundamental uncertainty, e.g., through risk premium, can determine expected exchange rate returns and thus, the exchange rate movement.

This doctrine is similar to the well-known theme of asset pricing models, e.g., the Capital Asset Pricing Model (CAPM) developed by Markowitz (1959), Sharpe (1964) and Lintner (1965) and Arbitrage Pricing Theory by Ross (1976). The theory's goal is mainly to quantify assets' equilibrium expected returns from the risk of bearing the assets. To relate exchange rate risk and return, Fama (1984) finds that variation in risk premium in the forward exchange market is more pronounced than the expected depreciation rate, i.e., expected exchange rate return. Frankel and Meese (1987) indicate that changes in conditional variance of the exchange rate have substantial impacts on the level of the exchange rate. Hodrick's (1989) model theoretically predicts that changes in the macroeconomic variances affect risk premia and therefore, exchange rates. Yet, the empirical results are not supportive. Our model is described in the next section.

3 The Model

The present value of the exchange rate for **the flexible-price model** can be written as

$$e_t = \varsigma_0 \sum_{i=0}^{\infty} \varsigma_2^i + \varsigma_1 \sum_{i=0}^{\infty} \varsigma_2^i E_t[\widetilde{f}_{t+i}], \tag{3}$$

where $\widetilde{f}_t = \widetilde{m}_t - (1+\gamma)\widetilde{y}_t$, and $\widetilde{m}_t$ and $\widetilde{y}_t$ are the logarithms of the domestic money supply and real income with respect to the foreign levels. For **the sluggish-price model**, inertia is introduced into the price mechanism and thus, the exchange rate equation. Cuthbertson (1999) shows that with the UIP condition the Dornbusch model gives rise to a form similar to equation (2):

$$e_t = \vartheta_1 e_{t-1} + \lambda \sum_{i=0}^{\infty} \vartheta_2 E_{t-1}[\widetilde{k}_{t+i}]; \ (\vartheta_1, \ \vartheta_2) < 1, \tag{4}$$

where $\widetilde{k}_t \equiv \frac{1}{\varphi}\widetilde{f}_t + \frac{1-\theta}{\theta\varphi}\widetilde{f}_{t-1}$. The exchange rate now depends on $\widetilde{k}_t$, namely current and lagged values of money supply and real income, and its expected future values.[11]

Since the exchange rate is a discounted sum of expected future fundamentals, i.e., equations (2), (3) and (4), if one could specify the expectation of $\widetilde{f}$ (or $\widetilde{k}$ in a case of the sticky-price model), an explicit process of the exchange rate can then be found. A number of methods to incorporate the fundamentals' variances into their expectations are discussed in Appendix C. Here, we assume that the fundamental series can be explained by its historical values and its time-varying second

overcomes the random walk model in predicting exchange rates. Groen (1999) shows that at a pooled time series level, there is cointegration between exchange rates and macroeconomic variables in the monetary model.

[10] The exceptions include the studies by Cragg (1982), Engle (1982, 1983), Obstfeld (1987), Hodrick (1989), Arnold (1996) and Bekaert (1996).

[11] In Appendix B, we provide the derivation (in details) of the reduced-form solutions of the flexible-price and sluggish-price models. It should also be noted that for the sluggish-price model we actually work with a more complex assumption of price inertia. As a result, our solution looks tedious (but similar), compared to equation (4). Importantly, it facilitates our closed-form derivation shown next.

moment.[12] Therefore, the expected future fundamentals do not only depend on the current fundamental levels but also the expected variances of the fundamentals, representing how volatile the fundamentals are. An explicit solution of the flexible-price model can, then, be written as

$$e_t = a_0 + a_1\widetilde{m}_t + a_2\widetilde{y}_t + a_3 h_{\widetilde{m},t} + a_4 h_{\widetilde{y},t}. \tag{5}$$

In addition to the current fundamental values, the exchange rate is determined by time-varying conditional variances of the fundamentals, i.e., h_t.

For the sticky-price model, the closed-form solution is

$$\begin{aligned} e_t \;=\; & b_0 + b_1 e_{t-1} + b_2\widetilde{m}_t + b_3\widetilde{y}_t + b_4\widetilde{m}_{t-1} + b_5\widetilde{y}_{t-1} \\ & + b_6 h_{\widetilde{m},t} + b_7 h_{\widetilde{y},t} + b_8 h_{\widetilde{m},t-1} + b_9 h_{\widetilde{y},t-1}, \end{aligned} \tag{6}$$

in which the present and lagged values of the fundamentals and their time-varying conditional variances are included in the exchange rate determination. The levels of macroeconomic fundamentals are well known to be insufficient for explaining exchange rate movements. In addition to the traditional monetary models, we introduce macroeconomic risk to describe the deviation of the excessive volatile exchange rate relative to the conventional prediction based on economic fundamentals.

In this paper, the expectations of future fundamentals are reformulated by exploiting the systematic pattern of fundamental volatility, instead of assuming a random walk process. Equations (5) and (6) similarly predict that ceteris paribus, an increase in money supply and a decrease in industrial production, relative to the foreign levels, tend to depreciate the domestic currency. Besides, we explain anomalous movements of the exchange rate, relative to the traditional paradigm, by the presence of volatility clusters in the fundamentals.[13] To capture the currency price volatility, time variation in conditional variances of the fundamentals, captured by a GARCH(1,1) model[14], are incorporated to describe expected exchange rate returns.

The modified flexible-price model in equation (5) is used to characterize the long-run equilibrium of exchange rates, while the modified sticky-price model in equation (6) corrects for fundamental disequilibrium. The idea to examine the long-run impacts of macroeconomic risk on the exchange rate may seem controversial at first, as one would think that the exchange rate volatility is considered as a short-term phenomenon and has nothing to do with the long run. In fact, the asset pricing models, e.g., CAPM, are used for the long-run equilibrium price determination. Intuitively, the models say that one who holds risky assets expects to be compensated at least in the long run. Similarly, our paper discusses the expected compensation from holding risky assets in both short run and long run. The next section provides the empirical investigation.

4 Specification and Estimation

With regard to the exchange rate level, although many developments can cause permanent changes in the exchange rate, the cointegration relationship between the spot rates and macroeconomic fundamentals implies that there is some long-run

[12] The argument and derivation are in Appendix D.

[13] The nonlinearity in the model seems to coincide with the idea of nonlinear bubbles. For example, in Froot and Obstfeld (1991) the bubble is a nonlinear function of stock's dividend.

[14] A GARCH(1,1) model (with a student-t distribution, if necessary) is used to capture fundamental uncertainty. The model is considered as a parsimonious model of conditional variance that adequately fits many economic time series, see, e.g., Bollerslev (1987). It suggests a form of heteroskedasticity, in which the variance of next period shocks depends on the size of shocks in this period. Therefore, a turbulent (tranquil) period is likely to be followed by turbulent (tranquil) periods. Alternatively, news has persistent effects in some periods.

equilibrium relation tying the exchange rate to its macroeconomic fundamentals, see Hamilton (1994).[15] Moreover, persistent movements in the fundamental volatility are likely to have larger impacts on exchange rate risk and returns than temporary movements. To model the exchange rate, we are therefore concerned with the cointegration among the variables in equation (5), whereas equation (6) is applied as an error-correction model to explain the adjustment towards the long-run equilibrium.

Like other macroeconomic studies, this empirical study involves nonstationary and trending variables, e.g., exchange rates, money supply and industrial production. Furthermore, some GARCH series, as a proxy of time variation in conditional variances h_t, may appear to be $I(1)$ as the variance process is close to an integrated GARCH model, i.e., IGARCH. There are several ways to manipulate such series, namely to use transformations to reduce them to stationary, e.g., to use a vector autoregressive (VAR) model, or to analyze the relationship between these trending variables. Hodrick (1989) takes first differences to make the series stationary. However, in the existence of a cointegration relationship differencing the data might not be appropriate since counterproductively, it would obscure the long-run relationships between the variables.

As mentioned, we favor the latter option so as to distinguish between a long-run relationship, in which the variables drift together at roughly the same rate, and the short-run dynamics that capture the relationship between deviations of the variables from the long-run trend, see Stock and Watson (1988) and Greene (2000). It should also be noted that our analysis involves generated regressors, i.e., estimated conditional variances. According to Pagan (1984), the two-step procedure, i.e., to estimate the conditional variances from the ARCH models and to exogenously use the estimated variances in the OLS regression, can produce consistency in estimated coefficients if the ARCH processes provide consistent estimates of true conditional variances, see also Hodrick (1989). Dissimilar to Hodrick (1989), we use a GARCH(1,1) model with a student-t error distribution to estimate conditional variances h_t.[16]

For the empirical study, we use macroeconomic series from 6 OECD countries, i.e., Canada, France, Italy, Japan, the UK and the US, that coincide with our theoretical constructs, namely exchange rates, money supply and industrial production.[17] To see the role of economic fundamental uncertainty in determining the exchange rate risk and expected returns, we consider the price of a US dollar in terms of the domestic currency, as the US dollar has been recognized as a vehicle currency[18]. The US variables are, thus, considered as the foreign variables in the exchange rate models. According to Hodrick (1989), he finds no evidence for fundamental volatility to price exchange rates because of the weak evidence of ARCH at monthly exchange rates. By expanding the period employed in Hodrick (1989), we find stronger evidence of ARCH in monthly observations.[19] Herein, we reexamine

[15] For empirical results, see, e.g., MacDonald and Taylor (1994) and Groen (1999).

[16] Hodrick (1989) applies the ARCH-LR test and models fundamental volatility by using an ARCH(1) model with a normal distribution.

[17] For more details, the reader is referred to Appendix A. We also study Austria, Germany and the Netherlands. However, there is no evidence of cointegration relationship in the case of the Netherlands, while there are ambiguous cointegration test results between the Johansen (1988) test and the augmented Engle and Granger (1987) test in the case of Austria and Germany.

[18] This definition is given in Krugman and Obstfeld (1997). The US dollar is broadly accepted and held as a financial asset.

[19] There are many studies investigating ARCH properties in the logarithmic changes in exchange rates. At short horizons, strong findings in weekly and daily intervals respectively have been reported by Engle and Bollerslev (1986) and Baillie and Bollerslev (1987), but due to temporal aggregation (see Drost and Nijman (1993)) rather weak evidence for monthly data has been reported by Baillie and Bollerslev (1989) and Hodrick (1989).

Within our sample, we find rather strong evidence of ARCH in monthly exchange rate returns and fundamental growth rates. The results of the ARCH(1)-LM test, the ARMA-GARCH modthe question posed in Hodrick (1989).

To investigate the exchange rate determination based on equations (5) and (6), it should be noted that we look at the domestic and the foreign variables separately, not in relative terms.[20] Thus, the regression equations become

$$\begin{aligned} e_t &= a_0 + a_1 m_t + a_{1,f} m_t^* + a_2 y_t + a_{2,f} y_t^* \\ &\quad + a_3 \widehat{h}_{m,t} + a_{3,f} \widehat{h}_{m^*,t} + a_4 \widehat{h}_{y,t} + a_{4,f} \widehat{h}_{y^*,t}, \end{aligned} \tag{7}$$

and

$$\begin{aligned} e_t &= b_0 + b_1 e_{t-1} + b_2 m_t + b_{2,f} m_t^* + b_3 y_t + b_{3,f} y_t^* \\ &\quad + b_4 m_{t-1} + b_{4,f} m_{t-1}^* + b_5 y_{t-1} + b_{5,f} y_{t-1}^* \\ &\quad + b_6 \widehat{h}_{m,t} + b_{6,f} \widehat{h}_{m^*,t} + b_7 \widehat{h}_{y,t} + b_{7,f} \widehat{h}_{y^*,t} \\ &\quad + b_8 \widehat{h}_{m,t-1} + b_{8,f} \widehat{h}_{m^*,t-1} + b_9 \widehat{h}_{y,t-1} + b_{9,f} \widehat{h}_{y^*,t-1}, \end{aligned} \tag{8}$$

where e is the logarithm of the nominal exchange rate, i.e., the price of a unit of foreign currency in terms of domestic currency, x represents a domestic variable and x^* represents a foreign (US) variable.

The method of investigation is as follows. An augmented Dickey-Fuller test is firstly applied to test the null hypothesis that the variables in equation (7) contain a unit root, i.e., an $I(1)$ series, and whether the series are integrated to the same order. If the variables are integrated to different orders, a cointegration model would not be appropriate. Secondly, the Johansen (1988) test is used to identify the number of cointegration vectors from groups of the variables. Then, by an augmented Engle and Granger (1987) test we check if the error term of the cointegration equation is an $I(0)$ series. Later on, we present the dynamic OLS estimation of equation (7) and the short-run dynamic equation (8).

The first step is to identify the appropriate degree of differencing for each series. Suppose the series of interest is z_t, then the augmented Dickey-Fuller test is based on the regression of the following equation, with or without the presence of a trend t:

$$\chi(L)\Delta z_t = \mu + \tau t + \beta z_{t-1} + v_t,$$

where

$$\chi(L) = \mathbf{I}_n - \chi_1 L - \chi_2 L^2 - \ldots - \chi_p L^p,$$

and v_t is an error term. This augmented specification is then used to test the null hypothesis of a unit root in the series, i.e., $H_0 : \beta = 0$, against $H_1 : \beta < 0$. Table 1 shows the results from the augmented Dickey-Fuller tests of the null hypotheses (1) that the logarithmic level of series is an $I(1)$ series, and (2) that the logarithmic first difference of the series contains a unit root. The table displays $\widehat{\beta}$ and throughout this paper an asterisk, two asterisks and three asterisks indicate significance at the 10%, 5% and 1% level of significance, respectively.

According to Table 1, the economic series are likely to be $I(1)$ series. At the 1% level of significance, first differencing is appropriate to induce stationary in the

eling method and the estimated coefficients of GARCH models are available upon request.

[20] This is due to the fact that in most of the countries (except Canada and the UK) the Wald test can reject the restriction that the coefficients of the domestic and foreign (US) variables are significantly equal in the case of money supply and real income. The test statistics are available upon request.

Table 1: Results of the augmented Dickey-Fuller unit root test

$$\chi(L)\Delta z_t = \mu + \tau t + \beta z_{t-1} + v_t$$

		Canada	France	Italy	Japan	UK	US
Exchange Rate	e	-0.709	-1.933	-1.920	-2.338	-2.560	
	Δe	-7.729***	-6.873***	-6.834***	-7.212***	-7.458***	
Money Supply	m	-1.591	-2.200	-0.965	-3.275*	-3.366*	1.313
	Δm	-10.710***	-10.997***	-12.714***	-12.560***	-9.798***	-7.873***
	$\widehat{h}_m$	-3.185**	-2.400	-8.218***	-3.492***	-4.903***	-4.043***
	$\Delta\widehat{h}_m$	-7.824***	-8.639***				
Industrial Production	y	-2.403	-2.783	-3.143	-1.108	-2.845	-2.915
	Δy	-6.350***	-8.125***	-8.754***	-5.471***	-7.944***	-6.461***
	$\widehat{h}_y$	-3.179**	-5.676***	-6.538***	-3.919***	-4.413***	-5.563***
	$\Delta\widehat{h}_y$	-11.059***					

This table gives the results of the augmented Dickey-Fuller unit root test. The test is based on the augmented equation displayed on top of the table. The specification, with or without a trend t depending on its significance, is used to test the null hypothesis of a unit root in the series, i.e., $H_0 : \beta = 0$, against the alternative hypothesis of no unit root $H_1 : \beta < 0$. The test is applied to the natural logarithmic levels of exchange rate (e), money supply (m) and real income (y), and also to the estimated GARCH series (h) of money growth and income growth. For the series that cannot reject the unit root at the 1% level, the test is also applied to first differences of these series. *, ** and *** indicate significance at the 10%, 5% and 1% level, respectively.

natural logarithms of the exchange rate, money supply and industrial productivity. The estimated GARCH processes of the macroeconomic variables are shown to be $I(0)$, except the estimated series of the French money supply. The estimated GARCH processes of the Canadian money supply and real income exhibit trend stationarity at the 5% significance level. Therefore, the model represented by equation (7) involves the variables that can individually be either $I(0)$ or $I(1)$. The modified exchange rate equation is then tested for a cointegration relationship, i.e., if there exists a stationary linear combination of these variables. The $I(0)$ variables are introduced as exogenous regressors in the cointegration function.

Second step is to examine if there is any cointegration relationship among these $I(1)$ series, i.e., if there exists any linear combinations of these $I(1)$ variables that are $I(0)$. The Johansen (1988) test is used to serve this purpose. We apply Johansen's (1988) method and estimate the coefficient matrix in an unrestricted VAR form, then test whether one can reject the restrictions implied by the reduced rank of the matrix.[21] To test for cointegration, only $I(1)$ variables are investigated against the null hypothesis that the cointegration rank is r or lower.[22] Table 2 reports the number of significant cointegration vectors. The likelihood ratio (LR) test can reject the null hypothesis of no cointegration in every country. At the 5% significance level, the LR test indicates 1 cointegration relationship for France, Italy and Japan, and 2 cointegration relationships in the case of Canada and the UK.

As the Johansen test predicts cointegration relationship(s) for every country, an alternative method by Engle and Granger (1987) is furthermore used to assess

[21] For more details, the reader is referred to Hamilton (1994) and Greene (2000).

[22] The results are based on the statistics in reference to the critical values for the reduced rank test given by Osterwald-Lenum (1992). As the critical values reported by EViews do not account for the inclusion of exogenous variables, only $I(1)$ variables are tested.

Table 2: Results of the Johansen cointegration test

$$e_t = a_0 + a_1 m_t + a_{1,f} m_t^* + +a_2 y_t + a_{2,f} y_t^*$$
$$+ a_3 \widehat{h}_{m,t} + a_{3,f} \widehat{h}_{m^*,t} + a_4 \widehat{h}_{y,t} + a_{4,f} \widehat{h}_{y^*,t}$$

	Canada	France	Italy	Japan	UK
Hypothesised no. of ranks	2**	1**	1**	1**	2**

This table gives the results of the Johansen cointegration test for the group of the $I(1)$ variables in the modified flexible-price model (as shown on top of the table). The test is conducted under the null hypothesis that the cointegrating rank is r or lower. The table shows the number of cointegrating vectors, that cannot be rejected. *, ** and *** indicate significance at the 10%, 5% and 1% level, respectively.

Table 3: Results of the augmented Engle and Granger cointegration test

$$\Delta\varepsilon_t = \phi_0 \varepsilon_{t-1} + \phi_1 \Delta\varepsilon_{t-1} + ... + \epsilon_t$$

	Canada	France	Italy	Japan	UK
$\widehat{\phi}_0$	-3.415**	-4.904***	-3.722***	-3.129**	-4.522***

This table gives the results of the augmented Engle and Granger cointegration test on the equilibrium error ε_t. It is to test the significance of the null hypothesis that the error series contains a unit root, i.e., $H_0 : \phi_0 = 0$, $H_1 : \phi_0 < 0$. If the null hypothesis cannot be rejected, there is no cointegrating relationship. *, ** and *** indicate significance at the 10%, 5% and 1% level, respectively.

whether linear combinations, based on the flexible-price model in equation (7), appear to be stationary. From equation (7), one may rewrite the model for the exchange rate that is suitable for the regression analysis as follows;

$$\begin{aligned} e_t &= \widehat{a}_0 + \widehat{a}_1 m_t + \widehat{a}_{1,f} m_t^* + \widehat{a}_2 y_t + \widehat{a}_{2,f} y_t^* \\ &\quad + \widehat{a}_3 \widehat{h}_{m,t} + \widehat{a}_{3,f} \widehat{h}_{m^*,t} + \widehat{a}_4 \widehat{h}_{y,t} + \widehat{a}_{4,f} \widehat{h}_{y^*,t} + \varepsilon_t, \end{aligned} \tag{9}$$

where ε_t is an error term. In equation (9), the cointegration function represents the long-run movement of exchange rates. OLS estimation is applied because it has been proved to yield asymptotically superconsistent estimators when estimating cointegration relationships, see Greene (2000). The Engle and Granger (1987) two-step procedure test is applied to examine the stationarity of the residual term ε_t.

To correct for autocorrelation in the equilibrium error series, an augmented Engle and Granger test is based on estimating

$$\Delta\varepsilon_t = \phi_0 \varepsilon_{t-1} + \phi_1 \Delta\varepsilon_{t-1} + ... + \epsilon_t,$$

under the Newey-West approach. If one cannot reject the null hypothesis of a unit root in the residual series ($H_0 : \phi_0 = 0$, $H_1 : \phi_0 < 0$), there is no cointegration relationship between the variables in the model. Table 3 shows $\widehat{\phi}_0$. Asterisks indicate that the null hypothesis of unit root can be rejected at the 5% significance level for Canada and Japan, and at the 1% level for France, Italy and the UK. Table 2 and 3 demonstrate the evidence of cointegration in these countries.

To test our assumption regarding the expectation formation that incorporates macroeconomic uncertainty, we firstly deal with the modified flexible-price model, and then the modified sluggish-price model. The Stock and Watson (1993) dynamic OLS estimation method is employed to regress the logarithm of the exchange rate against the logarithms of money supply and industrial production, and the estimated conditional variances (from a GARCH(1,1) model) of the growth rates of money supply and industrial production. The US variables are used as the foreign variables. Although the OLS estimation has been proved to asymptotically yield superconsistent estimates, due to the possibility that the explanatory variables are contemporaneously correlated with the disturbance term, the OLS regression coefficients are likely to be inconsistent.[23] The dynamic OLS procedure, on the other hand, is robust to small sample size and simultaneity bias.

To eliminate the effects of these correlations, we apply the Stock and Watson (1993) dynamic OLS approach by adding the one period leads and lags of the first differences of the regressors mentioned above.[24] The method is also known for being a robust single equation that corrects for stochastic-regressor endogeneity. According to equation (7), the dynamic OLS equation is

$$\begin{aligned} e_t \quad = \quad & \widehat{a}_0 + \widehat{a}_1 m_t + \widehat{a}_{1,f} m_t^* + \widehat{a}_2 y_t + \widehat{a}_{2,f} y_t^* \\ & + \widehat{a}_3 \widehat{h}_{m,t} + \widehat{a}_{3,f} \widehat{h}_{m^*,t} + \widehat{a}_4 \widehat{h}_{y,t} + \widehat{a}_{4,f} \widehat{h}_{y^*,t} + \widehat{a}_5 \Delta m_{t+1} + \widehat{a}_{5,f} \Delta m_{t+1}^* \\ & + \widehat{a}_6 \Delta y_{t+1} + \widehat{a}_{6,f} \Delta y_{t+1}^* + \widehat{a}_7 \Delta \widehat{h}_{m,t+1} + \widehat{a}_{7,f} \Delta \widehat{h}_{m^*,t+1} + \widehat{a}_8 \Delta \widehat{h}_{y,t+1} \qquad (10) \\ & + \widehat{a}_{8,f} \Delta \widehat{h}_{y^*,t+1} + \widehat{a}_9 \Delta m_{t-1} + \widehat{a}_{9,f} \Delta m_{t-1}^* + \widehat{a}_{10} \Delta y_{t-1} + \widehat{a}_{10,f} \Delta y_{t-1}^* \\ & + \widehat{a}_{11} \Delta \widehat{h}_{m,t-1} + \widehat{a}_{11,f} \Delta \widehat{h}_{m^*,t-1} + \widehat{a}_{12} \Delta \widehat{h}_{y,t-1} + \widehat{a}_{12,f} \Delta \widehat{h}_{y^*,t-1} + \xi_t, \end{aligned}$$

where ξ_t denotes the error term. Table 4 contains the estimated parameters from equation (10), $\widehat{a}_i$ and $\widehat{a}_{i,f}$ when $i = 1, .., 4$. An asterisk, two asterisks and three asterisks indicate significance at the 10%, 5% and 1% level of significance, respectively.

Apart from allowing us to examine the long-run impacts of macroeconomic risk on exchange rates, adding the estimated macroeconomic risk into a cointegration equation may help reduce the problem of omitted variables.[25] From Table 4, the estimated coefficients of money supply and real income have signs as expected in the literature. In the long run, an increase in the domestic money supply or a decrease in the foreign money supply tends to depreciate the domestic currency, except for Canada. Higher domestic output or lower foreign output is likely to appreciate the domestic currency (though there are exceptions for Canada and Japan).

For Canada and the UK, at the 5% significance level the Wald test cannot reject the null hypothesis that the coefficients of domestic and foreign macroeconomic variables, like money supply and real income, are significantly equal. When we restrict the domestic and foreign coefficients of money supply and real income to be equal in these countries, in relative to the US levels higher money supply or lower

[23] However, if the explanatory variables and the disturbance term are not independent but they are contemporaneously uncorrelated, the OLS retains its desirable properties, see Dougherty (1992).

[24] According to Hamilton (1994), the similar method has been suggested by Saikkonen (1991) and Phillips and Loretan (1991).

[25] It should also be stressed that this approach is not exposed to the simultaneity bias. To avoid the simultaneity bias (or other violation of the fourth Gauss-Markov condition, e.g., from stochastic regressors or measurement errors), we use instrumental variables that are highly correlated with the regressors but not correlated to the error terms. In this paper, rather than using the true conditional variances, whose random components may be correlated with error terms in the exchange rate equation, we use the predicted values of the endogenous explanatory variables, i.e., the GARCH forecast of volatility. By using the forecasts which are functions of the squared lagged residual and the estimated variances from the previous period, we eliminate the random components in the fundamentals' conditional variances.

Table 4: Parameters of the modified flexible-price model

$$e_t = \widehat{a}_0 + \widehat{a}_1 m_t + \widehat{a}_{1,f} m_t^* + +\widehat{a}_2 y_t + \widehat{a}_{2,f} y_t^*$$
$$+ \widehat{a}_3 \widehat{h}_{m,t} + \widehat{a}_{3,f} \widehat{h}_{m^*,t} + \widehat{a}_4 \widehat{h}_{y,t} + \widehat{a}_{4,f} \widehat{h}_{y^*,t} + ...$$

	Canada	France	Italy	Japan	UK
$\widehat{a}_0$	-3.128***	6.740***	6.210***	7.472***	3.868***
$\widehat{a}_1$	-0.116	0.753***	0.929***	0.774***	0.321**
$\widehat{a}_{1,f}$	0.155**	-0.580***	-0.666***	-1.101***	0.097
$\widehat{a}_2$	0.535**	-1.886***	-2.056***	0.538**	-1.266**
$\widehat{a}_{2,f}$	0.076	0.479*	0.693***	-1.444***	0.029
$\widehat{a}_3$	116.328***	-530.64***	-497.51*	-224.703*	-877.01**
$\widehat{a}_{3,f}$	1356.045**	-3185.05**	-4555.66**	-1840.97	-6340.388***
$\widehat{a}_4$	178.947***	376.15**	46.59**	270.166*	-172.19*
$\widehat{a}_{4,f}$	-25.750	6.369	-433.14	-555.754**	-777.12***

This table gives the estimation results of the modified flexible-price model, based the Stock and Watson (1993) dynamic OLS approach. It contains the estimated parameters, $\widehat{a}_i$ and $\widehat{a}_{i,f}$ when $i = 1, .., 4$. An asterisk, two asterisks and three asterisks indicate significance at the 10%, 5% and 1% level of significance, respectively.

real income tends to depreciate the domestic currencies, while the coefficients of macroeconomic risk are similar to Table 4.[26]

Significantly, an increase in the money supply volatility, regardless of domestic and foreign sources, depreciates the Canadian dollar, while appreciates other currencies. For uncertainty in real income, the results significantly show that an increase in the domestic volatility depreciate the domestic currency (except the UK), whereas an increase in the foreign volatility appreciate the domestic currency. Higher uncertainty in the US real income or the US money supply raises the expected future returns on the US dollars by pushing down the current US dollar price. It consequently causes the domestic currency to appreciate (except Canada). By the same argument, uncertainty in the domestic real income is positively related to the US dollar exchange rates. It leads to an upward bias in the variation of actual exchange rates from the prediction of the traditional model.

From the table, macroeconomic uncertainty, represented by the conditional variances of money supply and real income, can explain the deviation of the exchange rate from its fundamental-based value. Uncertainty about the economy seems to lower the demand for the currency and subsequently depreciate its currency, relative to the fundamental benchmark value. From an asset pricing perspective, higher risk should be accompanied by higher expected future returns, leading to a current depreciation of the currency.

However, the opposite impact can also be observed in some cases. For every

[26] The regression result for Canada is;

$$e_t = 0.889^{***} + 0.343^{***}\widetilde{m}_t - 0.304\widetilde{y}_t$$
$$+149.477^{***}\widehat{h}_{m,t} + 1739.14^{**}\widehat{h}_{m^*,t} + 141.418^{***}\widehat{h}_{y,t} - 440.945^{***}h_{y^*,t} + \xi_t.$$

The regression result for the UK is;

$$e_t = 0.320 + 0.119\widetilde{m}_t - 0.566^{*}\widetilde{y}_t$$
$$-1500.33^{***}\widehat{h}_{m,t} - 5263.13^{***}\widehat{h}_{m^*,t} - 315.254^{***}\widehat{h}_{y,t} - 341.454h_{y^*,t} + \xi_t.$$

country except Canada, higher volatility in the domestic money supply tends to increase the domestic currency prices. This might be because a volatile domestic monetary policy, e.g. central bank intervention to stabilize the economy, can provide a positive outlook on the domestic currency. Due to these positive aspects of macroeconomic risk (intervention), economic agents prefer to hold their local currencies and are willing to pay a higher price. The case of the UK also reveals a strong preference for the domestic currency, which is parallel to the Equity Home Bias that has been long studied in finance.[27] On the other hand, for Canada the country that moves along with the US there exists a negative risk premium towards the US dollar which shows a trust in the volatile US monetary policy.

The modified sticky-price model extends the cointegration relationship between the exchange rate and its fundamentals by adding the long-run equilibrium error adjustment. By rearranging equation (8) , one obtains a form of the error-correction model

$$\begin{aligned}\Delta e_t &= \widehat{b}_0 + \widehat{b}_2 \Delta m_t + \widehat{b}_{2,f} \Delta m_t^* + \widehat{b}_3 \Delta y_t + \widehat{b}_{3,f} \Delta y_t^* \\ &\quad + \widehat{b}_6 \Delta \widehat{h}_{m,t} + \widehat{b}_{6,f} \Delta \widehat{h}_{m^*,t} + \widehat{b}_7 \Delta \widehat{h}_{y,t} + \widehat{b}_{7,f} \Delta \widehat{h}_{y^*,t} \\ &\quad + (\widehat{b}_1 - 1) \left\{ \begin{array}{c} e_{t-1} - \widehat{c}_1 m_{t-1} - \widehat{c}_{1,f} m_{t-1}^* - \widehat{c}_2 y_{t-1} - \widehat{c}_{2,f} y_{t-1}^* \\ -\widehat{c}_3 \widehat{h}_{m,t-1} - \widehat{c}_{3,f} \widehat{h}_{m^*,t-1} - \widehat{c}_4 \widehat{h}_{y,t-1} + \widehat{c}_{4,f} \widehat{h}_{y^*,t-1} \end{array} \right\} + \nu_t,\end{aligned}$$

where $\widehat{c}_1 = -(\widehat{b}_4 + \widehat{b}_2)/(\widehat{b}_1 - 1)$, $\widehat{c}_{1,f} = -(\widehat{b}_{4,f} + \widehat{b}_{2,f})/(\widehat{b}_1 - 1)$, $\widehat{c}_2 = -(\widehat{b}_5 + \widehat{b}_3)/(\widehat{b}_1 - 1)$, $\widehat{c}_{2,f} = -(\widehat{b}_{5,f} + \widehat{b}_{3,f})/(\widehat{b}_1 - 1)$, $\widehat{c}_3 = -(\widehat{b}_8 + \widehat{b}_6)/(\widehat{b}_1 - 1)$, $\widehat{c}_{3,f} = -(\widehat{b}_{8,f} + \widehat{b}_{6,f})/(\widehat{b}_1 - 1)$, $\widehat{c}_4 = -(\widehat{b}_9 + \widehat{b}_7)/(\widehat{b}_1 - 1)$ and $\widehat{c}_{4,f} = -(\widehat{b}_{9,f} + \widehat{b}_{7,f})/(\widehat{b}_1 - 1)$. Provided that a stable relationship between the exchange rate and the fundamentals exists, the set of coefficients c in this equation is equivalent to the set of coefficients a in the modified flexible-price model. Thus, in fact we test the short-run dynamic equation

$$\begin{aligned}\Delta e_t &= \widehat{b}_0 + \widehat{b}_2 \Delta m_t + \widehat{b}_{2,f} \Delta m_t^* + \widehat{b}_3 \Delta y_t + \widehat{b}_{3,f} \Delta y_t^* \\ &\quad + \widehat{b}_6 \Delta \widehat{h}_{m,t} + \widehat{b}_{6,f} \Delta \widehat{h}_{m^*,t} + \widehat{b}_7 \Delta \widehat{h}_{y,t} + \widehat{b}_{7,f} \Delta \widehat{h}_{y^*,t} \\ &\quad + (\widehat{b}_1 - 1)\varepsilon_{t-1} + \nu_t.\end{aligned}$$

It should also be noted that as first differencing is sufficient to produce stationary series and as there exists a cointegration relationship shown in Table 2 and 3, the residual term ν_t is an $I(0)$ series.

As stated in Greene (2000), the movement of the exchange rate from the previous period associates with the changes in the fundamentals along the long-run equilibrium corrected for the previous deviation from the long-run equilibrium. This equation contains an equilibrium relationship in the first two lines and an adjustment for the deviation from the previous equilibrium in the last line. Table 5 shows that there exists a correction mechanism of equilibrium errors towards the long-run equilibrium, as $(\widehat{b}_1 - 1)$ is significantly negative, except in the case of Italy. The error correction term, ε_{t-1}, is significantly negative at the 5% significance level in the case of Canada and at the 1% significance level for France, Japan and the UK. In the case of Italy, counter-intuitively, at the monthly horizon there is no significant adjustment towards long-run equilibrium. Furthermore, in the short run the exchange rate can be significantly explained by changes in the US real income. Yet, other macroeconomic fundamentals as well as their uncertainty fail to explain the exchange rate in the short run.

[27] For example, see Levy and Sarnat (1970) and Solnik (1974).

Table 5: Parameters of the modified sticky-price model

$$\Delta e_t = \widehat{b}_0 + (\widehat{b}_1 - 1)\varepsilon_{t-1} + \widehat{b}_2 \Delta m_t + \widehat{b}_{2,f} \Delta m_t^* + \widehat{b}_3 \Delta y_t + \widehat{b}_{3,f} \Delta y_t^*$$
$$+ \widehat{b}_6 \Delta \widehat{h}_{m,t} + \widehat{b}_{6,f} \Delta \widehat{h}_{m^*,t} + \widehat{b}_7 \Delta \widehat{h}_{y,t} + \widehat{b}_{7,f} \Delta \widehat{h}_{y^*,t} + \nu_t$$

	Canada	France	Italy	Japan	UK
$\widehat{b}_0$	0.001	2.37E-4	0.003	-0.002	0.001
$(\widehat{b}_1 - 1)$	-0.023**	-0.056***	-0.027	-0.063***	-0.087***
$\widehat{b}_2$	0.042	-0.024	-0.083	0.021	-0.067
$\widehat{b}_{2,f}$	-0.055	-0.071	0.040	-0.189*	0.003
$\widehat{b}_3$	0.070	-0.109	0.009	-0.050	-0.078
$\widehat{b}_{3,f}$	0.207**	0.502**	0.481**	0.084	0.675***
$\widehat{b}_6$	9.119	-10.505	-56.871	75.438	-159.643*
$\widehat{b}_{6,f}$	138.630	33.414	59.534	-210.013	-229.840
$\widehat{b}_7$	17.408	22.570	-3.041	12.068	-10.498
$\widehat{b}_{7,f}$	-28.122	-75.073	-4.561	-21.820	-42.507

This table gives the estimation results of the modified sticky-price model, based the linear OLS regression. An asterisk, two asterisks and three asterisks indicate significance at the 10%, 5% and 1% level of significance, respectively.

5 Conclusion

The expectations regarding macroeconomic circumstances may influence the exchange rate in the manner predicted by the monetary models. Yet, the random walk assumption might be too naive for the market expectations. In this paper, we propose an alternative expectation formation process for the macroeconomic variables by introducing additional risk factors, based on the volatility of the macroeconomic fundamentals. As the fundamentals empirically exhibit a mean-reverting process with persistent memory in the standard deviation (representing the adjustment and speed towards the mean), a nonlinearity in the expectation formation process is present. To capture the exchange rate volatility, in addition to the traditional fundamentals, like money supply and real income, time variation in the second moments of these fundamentals are incorporated to describe the expected exchange rate returns.

We find significant cointegration between the variables in the modified flexible-price monetary model, while there is evidence for the correction of equilibrium errors towards the long-run equilibrium in the modified sticky-price model. In the long run, an increase in the domestic money supply or a decrease in the foreign money supply tends to depreciate the domestic currency. Higher domestic output or lower foreign output is likely to appreciate the domestic currency. The impacts of macroeconomic sources of risk are also significant. Uncertainty about the economy lowers the demand for the currency and subsequently depreciates the currency, relative to the fundamental-based value. From an asset pricing perspective, increased risk is accompanied by increased expected future returns, leading to a current depreciation of the currency. Our findings indicate that macroeconomic sources of FOREX risk seem to be a missing factor in exchange rate studies, and strongly suggest that the monetary exchange rate models are still potentially useful.

Appendix A: Data Sources

The data applied in this paper are monthly observations of exchange rates, money supply and industrial production, starting from June 1973 (after the breakdown of the Bretton Woods system) to December 1998. There are six OECD countries studied, which are Canada, France, Italy, Japan, the United Kingdom (UK) and the United States (US). Both European and non-European countries, with possible different economic mechanisms, are selected based on the availability of the required data. The US dollar is used as a vehicle currency and the US variables are used in the paper as the foreign variables.

The main data source is the IMF International Financial Statistics (IFS), except for M1 of the US. This time series is from the United States Federal Reserve Bank at St. Louis. It is compared with available quarterly series from the IFS and they are very similar. The US dollar exchange rates (domestic currency prices per one US dollar) from the IFS are coded 'AE'. Monetary aggregation is represented by seasonally unadjusted M1 data from IFS coded 34, except for the UK. According to purpose of the paper, liquidity under the central bank's controllability is preferable. For the UK, we decide to use M_0, coded 59, instead of another available choice M_4. Seasonally adjusted industrial production, coded 66, is used as a proxy for real income. If necessary, an additive seasonal moving average approach is used for the seasonal adjustment.

Appendix B: The Reduced-form Solutions of the Exchange Rate Models

The flexible-price model is derived from the simple quantity equation $M_tV_t = P_tY_t$. In logarithms, the quantity equation reveals

$$m_t + v_t = p_t + y_t \tag{11}$$

where m_t, v_t, p_t and y_t are the logarithms of the money supply, the money velocity, the price level and the real income at period t respectively. We assume further that purchasing power parity (PPP) and uncovered interest parity (UIP) hold.

The stochastic PPP assumption, which is a more specific version of the no-arbitrage assumption, is defined as

$$p_t = \tau + p_t^* + e_t + \omega_t. \tag{12}$$

In equation (12), e_t, p_t and p_t^* are the logarithms of the nominal exchange rate, i.e., the price of a unit of foreign currency, the domestic price level and the foreign price level respectively. An asterisk denotes a foreign variable, i.e., in this case a US variable. While τ is a constant and ω_t represents a stationary, zero mean disturbance term, sometimes referred to as the real exchange rate.

According to the UIP condition, the interest rate differential between domestic and foreign assets is supposed to be equal to the expected rate of depreciation of the domestic currency. The expected change in currency price that satisfies equilibrium in the capital markets can, thus, be written as

$$E_t\left[e_{t+1}\right] - e_t = i_t - i_t^*, \tag{13}$$

where i_t and i_t^* are the domestic interest rate and the foreign interest rate respectively. $E_t[\cdot]$ is the conditional expectation operator.

The velocity of money circulation is presumed to be a stable function of real income and the interest rate. The logarithm of money velocity is linearly specified as a decreasing function of the logarithm of real income and an increasing function of the interest rate, i.e.,

$$v_t = \theta - \gamma y_t + \varphi i_t + \varpi_t \tag{14}$$

where θ is a constant and ϖ_t is a stationary, zero mean disturbance.

Suppose that (11) holds at home and in foreign countries with an identical income elasticity, γ, and interest semi-elasticity, φ. Combine (11) with (12), (13) and (14) and rework for the foreign country, one finds

$$e_t = -\tau + \frac{1}{1+\varphi}\widetilde{m}_t - \frac{(1+\gamma)}{1+\varphi}\widetilde{y}_t + \frac{\varphi}{1+\varphi}E_t\left[e_{t+1}\right] + \varepsilon_t, \tag{15}$$

where $\widetilde{x}_t = x_t - x_t^*$ and $\varepsilon_t = \varpi_t - \varpi_t^* - \omega_t$.

To solve this linear equation with rational expectation, we apply the law of iterated expectations, see Samuelson (1965) and Blanchard and Fischer (1993). For simplicity, we rewrite equation (15) as

$$e_t = \varsigma_0 + \varsigma_1 \widetilde{f}_t + \varsigma_2 E_t\left[e_{t+1}\right] + \varepsilon_t, \tag{16}$$

where $\varsigma_0 = -\tau$, $\varsigma_1 = \frac{1}{1+\varphi}$, $\varsigma_2 = \frac{\varphi}{1+\varphi}$, and $\widetilde{f}_t = \widetilde{m}_t - (1+\gamma)\widetilde{y}_t$. Note that $\varsigma_2 = 1 - \varsigma_1$ and that ς_1 and $\varsigma_2 \in (0,1)$ as $0 < \varphi < 1$, see Flood, Rose and Mathieson (1991) and Flood and Rose (1995). Equation (16) implies that the exchange rate depends on its expected rate for the next period, $E_t\left[e_{t+1}\right]$, and on the current fundamentals, $\widetilde{f}_t$, with the weights summing up one. According to the law of iterated expectations, we have

$$e_t = \varsigma_0 \sum_{i=0}^{T} \varsigma_2^i + \varsigma_1 \sum_{i=0}^{T} \varsigma_2^i E_t[\widetilde{f}_{t+i}] + \varsigma_2^{T+1} E_t[e_{t+T+1}] + \sum_{i=0}^{T} \varsigma_2^i E_t[\varepsilon_{t+i}]. \tag{17}$$

We then assume further that as the horizon T increases, the exchange rate at $T+1$ periods from now becomes negligeable, or equivalently the rational bubble shrinks to zero and that $E_t[\varepsilon_{t+i}] = 0$.

As T tends to infinity,

$$\lim_{T\to\infty} \varsigma_2^{T+1} E_t[e_{t+T+1}] = 0, \tag{18}$$

and the solution becomes:

$$e_t = \varsigma_0 \sum_{i=0}^{\infty} \varsigma_2^i + \varsigma_1 \sum_{i=0}^{\infty} \varsigma_2^i E_t[\widetilde{f}_{t+i}]. \tag{19}$$

This equation is comparable to equation (2), and implies that the elasticity of the exchange rate with respect to its expected fundamentals declines as looking further into the future, as

$$\lim_{t\to\infty} {\varsigma_2}^t = 0. \tag{20}$$

Moreover, for equation (18) to converge it requires that the logarithm of fundamentals, $\widetilde{f}$, grows at rate lower than $\varsigma_1/(1-\varsigma_1)$, i.e., $1/\varphi$, otherwise the solution (19) would be explosive.

The sluggish-price model is an extension of the flexible-price model with inertia introduced into the price mechanism, instead of relying on perfectly flexible prices. Empirically, there are deviations from purchasing power parity in equation (12), in which ω_t are large and persistent. There is also strong correlation between nominal and real exchange rates. In Dornbusch's (1976) sluggish-price model, the expected exchange rate return is formed as the discrepancy between the long run rate $\bar{e}$, to which the economy will eventually converge, and the current spot rate e. Mathematically,

$$E[e] - e = \delta(\bar{e} - e),\ 0 < \delta < 1.$$

To allow for sticky prices, the Phillips curve equation is substituted in the place of purchasing power parity in equation (12), see, e.g., Obstfeld and Rogoff (1984), Frankel and Rose (1994) and Flood and Rose (1995). It is conventional to assume that in addition to the PPP condition, prices respond to the lagged excess demand in the good markets, $y_t - \overline{y}_t$, and shocks to the good markets, g_t:

$$p_{t+1} - p_t = \mu(y_t - \overline{y}_t) + g_t + E_t[\widehat{p}_{t+1} - \widehat{p}_t],\ 0 < \mu < 1, \tag{21}$$

where $\overline{y}$ is the long-run output level, g_t has zero mean and constant variance, and $\widehat{p}_t$ is the price level at time t if prices were flexible and the good markets cleared.

$$y_t - \overline{y}_t = \Theta(e_t + p_t^* - p_t) + \Phi r_t. \tag{22}$$

The excess demand is defined as an increasing function of real exchange rate, $\Theta > 0$, and a decreasing function of the ex ante expected real interest rate, i.e., $r_t \equiv i_t - E_t[p_{t+1} - p_t]$, $\Phi < 0$. Thus, by substituting equation (22) into equation (21) one gets

$$p_{t+1} - p_t = \mu\left[\Theta(e_t + p_t^* - p_t) + \Phi r_t\right] + g_t + E_t[\widehat{p}_{t+1} - \widehat{p}_t]. \tag{23}$$

Equation (23) displays the long-run equilibrium (when the purchasing power parity holds and thus, the left-hand-side (LHS) is equal to the last term on the right-hand-side (RHS)) and its short-run dynamics (represented by deviations from the purchasing power parity by the first and the second terms on the RHS).

As in the long run $\widehat{p} = p$, $\widehat{p}$ can be defined by

$$\mu\left[\Theta(e_t + p_t^* - \widehat{p}_t) + \Phi r_t\right] + g_t = 0,$$

and thus,

$$\begin{aligned} p_{t+1} - p_t &= \mu\left[\Theta(e_t + p_t^* - p_t) + \Phi r_t\right] + g_t + E_t\left[p_{t+1}^* - p_t^*\right] \\ &\quad + E_t\left[e_{t+1} - e_t\right] + \frac{\Phi}{\Theta}E_t\left[r_{t+1} - r_t\right] + \frac{1}{\mu\Theta}E_t\left[g_{t+1} - g_t\right]. \end{aligned}$$

Therefore, instead of using the purchasing power parity condition in equation (12) we substitute this price equation,

$$\begin{aligned} \widetilde{p}_t &= p_t - p_t^* = e_t + \frac{1}{\Theta\mu}E_t\left[e_{t+1} - e_t\right] + \frac{1}{\Theta\mu}E_t\left[p_{t+1}^* - p_t^*\right] - \frac{1}{\Theta\mu}\left(p_{t+1} - p_t\right) \\ &\quad + \frac{1}{\mu}\frac{\Phi}{\Theta^2}E_t\left[r_{t+1} - r_t\right] + \frac{\Phi}{\Theta}r_t + \frac{1}{\mu^2\Theta^2}E_t\left[g_{t+1} - g_t\right] + \frac{1}{\Theta\mu}g_t, \end{aligned} \tag{24}$$

into the money demand equation, derived from the quantity equation (11) and the assumption of money circulation (14):

$$\widetilde{p}_t = \widetilde{m}_t - (1+\gamma)\,\widetilde{y}_t + \varphi\widetilde{i}_t + \widetilde{\varpi}_t.$$

Hence,

$$\begin{aligned} e_t &= \widetilde{m}_t - (1+\gamma)\,\widetilde{y}_t + \varphi\widetilde{i}_t + \widetilde{\varpi}_t \\ &\quad - \frac{1}{\Theta\mu}E_t\left[e_{t+1} - e_t\right] - \frac{1}{\Theta\mu}E_t\left[p_{t+1}^* - p_t^*\right] + \frac{1}{\Theta\mu}\left(p_{t+1} - p_t\right) \\ &\quad - \frac{1}{\mu}\frac{\Phi}{\Theta^2}E_t\left[r_{t+1} - r_t\right] - \frac{\Phi}{\Theta}r_t - \frac{1}{\mu^2\Theta^2}E_t\left[g_{t+1} - g_t\right] - \frac{1}{\Theta\mu}g_t. \end{aligned} \tag{25}$$

To present the model in a common form as in equation (2), we assume the UIP condition (13) and the price process in equation (24). As a consequence, the exchange rate equation becomes

$$\begin{aligned} e_t &= \widetilde{k}_t + E_t\left[e_{t+1}\right] \\ &+ \frac{(1-\theta)\varphi - \theta}{\theta\varphi} E_{t-1}\left[e_t\right] - \frac{(1-\theta)\varphi - \theta + 1}{\theta\varphi} e_{t-1} + \psi_t. \end{aligned} \tag{26}$$

where $\widetilde{k}_t = \frac{1}{\varphi}\widetilde{f}_t + \frac{1-\theta}{\theta\varphi}\widetilde{f}_{t-1}$, $\psi_t = \frac{1}{\varphi}p_t^* - \frac{1}{\varphi}E_{t-1}\left[p_t^*\right] - \frac{\Omega}{\varphi}E_{t-1}\left[r_t\right] - \frac{(1-\theta\Omega)}{\theta\varphi}r_{t-1} - \frac{1}{\varphi}g_{t-1} - \frac{\theta}{\varphi}E_{t-1}\left[g_t - g_{t-1}\right]$ and the fundamental $\widetilde{f}_t$ is defined as $\widetilde{f}_t = \widetilde{m}_t - (1+\gamma)\widetilde{y}_t$. The coefficients are assigned by $\theta = \frac{1}{\Theta\mu}$ and $\Omega = \frac{\Phi}{\Theta}$. To apply the law of iterated expectations to this second order difference equation, we define $A_t = e_t + \frac{(1-\theta)\varphi - \theta + 1}{\theta\varphi}e_{t-1}$. Equation (26) can, then, be rewritten as

$$A_t = \widetilde{k}_t + E_{t-1}\left[A_{t+1}\right] - \frac{1}{\theta\varphi}E_{t-1}\left[e_t\right] + \kappa_t + \psi_t, \tag{27}$$

in which $\kappa_t = E_t\left[e_{t+1}\right] - E_{t-1}\left[e_{t+1}\right]$.

By the law of iterated expectations one may get

$$\begin{aligned} A_t &= \widetilde{k}_t + \sum_{i=1}^{T} E_{t-1}[\widetilde{k}_{t+i}] - \frac{1}{\theta\varphi}\sum_{i=0}^{T} E_{t-1}[e_{t+i}] + E_{t-1}[A_{t+T+1}] \\ &+ \sum_{i=0}^{T} E_{t-1}[\kappa_{t+i}] + \sum_{i=0}^{T} E_{t-1}[\psi_{t+i}]. \end{aligned}$$

For simplicity, we presume that the expected exchange rate in any one period, i.e., $E_{t-1}[A_{t+T+1}]$, is only a small component in determining the current spot rate, and it becomes negligeable as the horizon T rises. Furthermore, when $i \geq 0$, $E_{t-1}[\kappa_{t+i}] = E_{t-1}[\psi_{t+i}] = 0$. As a consequence, as T tends to infinity the solution becomes

$$e_t = \frac{(1+\varphi)(\theta-1)}{\theta\varphi}e_{t-1} + \widetilde{k}_t + \sum_{i=1}^{\infty} E_{t-1}[\widetilde{k}_{t+i}] - \frac{1}{\theta\varphi}\sum_{i=0}^{\infty} E_{t-1}[e_{t+i}]. \tag{28}$$

Equation (28) is like equation (19) in the flexible-price model, except there is inertia in the exchange rate equation. The exchange rate now depends on $\widetilde{k}_t$, namely current and lagged values of money supply and income, and its expected future fundamentals. Additionally, equation (28) is also rather similar to the sticky-price concept stated earlier and also a solution (4) from Cuthbertson (1999).

Appendix C: Adding Stochastic Volatility to the Fundamental Expectations

There may be many ways to incorporate the second moments of the fundamentals into their expectations. In this appendix, we show a few possible ways. In developing an explicit solution for the exchange rate, Hodrick (1989) assumes a conditionally lognormal data generating process for the fundamentals, and applies the fact that if x has a lognormal distribution with $\log(x) \sim N(\mu, \sigma^2)$, its expectation reads $E[x] = e^{\mu + \frac{1}{2}\sigma^2}$. Hence, by loglinearization of his general equilibrium model one gets $\log(E[x]) = \mu + \frac{1}{2}\sigma^2$, which is exploited in Hodrick (1989).

One could equivalently adopt the modified form of uncovered interest parity (UIP) that adjusts for a risk premium and specify a risk premium as a function of time-varying fundamental variances. This is alike the portfolio balance model, in which the UIP condition incorporates the risk premium as a function of relative asset holding in domestic and foreign bonds. By combining equation (15) with a modified version of UIP that has a time-varying risk premium ρ_t, and applying the law of iterated expectations, the exchange rate can be expressed as

$$e_t = E_t\left[\widetilde{m}_{t+i}\right] - \beta E_t\left[\widetilde{y}_{t+i}\right] + \alpha E_t\left[\rho_{t+i}\right].$$

From the equation above, the exchange rates are determined by two components, which are the expectation regarding the future fundamental values and the expectation regarding risk from holding the currency. Intuitively, a deviation from its expected fundamental value needs an extra compensation. Accordingly, through a risk premium one can characterize risk in the FOREX markets by macroeconomic uncertainty.

Another technical approach is to apply Taylor's theorem. To make our point, we consider money supply process based on Lucas (1982) and Obstfeld (1987). Suppose $m_t = w_t + m_{t-1}$, where m_t is the logarithmic level of money supply and w_t is the stochastic growth rate of money supply. Obstfeld (1987) assumes that w_t exhibits a jump process, i.e., $w_t = d_t\mu_t$, where d_t represents a dummy variable indicating an occurrence of Poisson event, and μ_t denotes the volume of change. To describe money growth w_t, there are a number of possible Poisson processes, ranging from the simplest one with a constant probability to the one with unstable probability behavior where d_t is a Markov Chain with an unabsorbing state.

Yet, in practice we know that the logarithmic first difference of the fundamentals, $m_t - m_{t-1} = \Delta m_t = d_t\mu_t$, is likely to be mean reverting. Hence, to proxy the movement of the variable Δm_t around its mean one may apply Taylor's theorem to an arbitrary function, see Chiang (1984). If the mean is close to zero, one might use Maclaurin's series by expanding the function around the point $\Delta x = 0$. To include the variance term in the fundamental expectation, one may expand the series to the second degree, which is rather conventional for Taylor's expansion. As a result, one can proxy the expected movement of the macroeconomic series by a nonlinear function.

Appendix D: The Closed-form Solutions

To introduce time-varying conditional variances of the macroeconomic variables into the exchange rate model, we assume that there is a relationship between the first and the second moments of the fundamentals. The fundamentals are assumed to have somewhat similar to ARCH-in-Mean (ARCH-M) processes. The ARCH-M model, initiated by Engle, Lilien and Robins (1987), is originally used to describe the risk and return relationship of assets, as suggested in finance theory. For macroeconomic variables, there is rather weak evidence of ARCH-M process.[28] An approximate linear relationship between the fundamental expectation and its variance is, however, intuitive.

Similar to the ARCH-M model, suppose the whole sequence of future fundamentals can be represented by its current value and its variance. If x_t is the time series of interest, the model may read

$$x_{t+1} = \gamma_0 + \gamma_1 x_t + \gamma_2 h_{t+1} + u_{t+1}, \tag{29}$$

where x represents a macroeconomic variable, h is the conditional variance of the variable x, presumably time varying, and u is a residual term. As the fundamentals empirically exhibit mean-reverting processes with persistent memory in standard deviations, time variation in the conditional variance may represent the adjustment and speed towards the mean.

In equation (29), the first component is like a random walk or an AR(1) process, which is often assumed for macroeconomic variables. The second component

[28] For example, in our data set only Canada and the UK show weak evidence of this feature.

shows that macroeconomic uncertainty plays a role in the fundamental expectation formations. For example, the fundamental variances may represent economic circumstances, i.e., whether the economy is in volatile or tranquil periods, in which the expectations may be different. In turmoil (disequilibria), the monetary variables, e.g., money supply and interest rates, may be altered more often, and the state variables, e.g., income, unemployment rate and inflation rate, may be more volatile than in regular periods.

To capture time-varying conditional variances, for simplicity we use a GARCH (1,1) model, i.e.,

$$h_{t+1} = \lambda_0 + \lambda_1 u_t^2 + \lambda_2 h_t.$$

A GARCH (1,1) model is often used to capture time-varying conditional variances of economic variables, see Bollerslev (1987). By using the law of iterated expectations, the expected future fundamentals can be described as

$$\begin{aligned} E_t[x_{t+i}] &= \gamma_0 \sum_{s=0}^{i-1} \gamma_1^s + \gamma_1^i x_t + \gamma_2 \sum_{s=0}^{i-1} \gamma_1^s E_t[h_{t+i-s}], \\ \text{while } E_t[h_{t+i-s}] &= \lambda_0 \sum_{k=0}^{i-s-1} (\lambda_1 + \lambda_2)^k + (\lambda_1 + \lambda_2)^{i-s} h_t. \end{aligned} \tag{30}$$

Reorganizing gives a process of x as a function of its current value and its conditional variance as follows:

$$E_t[x_{t+i}] = \alpha_0 + \alpha_1 x_t + \alpha_2 h_t, \tag{31}$$

where

$$\begin{aligned} \alpha_0 &= \sum_{s=0}^{i-1} \gamma_1^s \left[\gamma_0 + \gamma_2 \lambda_0 \sum_{k=0}^{i-s-1} (\lambda_1 + \lambda_2)^k \right], \\ \alpha_1 &= \gamma_1^i, \\ \text{and } \alpha_2 &= \gamma_2 \sum_{s=0}^{i-1} \gamma_1^s \left[(\lambda_1 + \lambda_2)^{i-s} \right]. \end{aligned}$$

Substitute the expectations for money supply and real income into equation (19) and rework with inertia in equation (28), one obtains equations (5) and (6), respectively.

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