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Are Exchange Rates Excessively Volatile? And What Does "Excessively Volatile" Mean, Anyway?

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Abstract

Using data for the major currencies from 1973 to 1994, we apply recent tests of asset price volatility to re-examine whether exchange rates have been excessively volatile with respect to the predictions of the monetary model of the exchange rate and of standard extensions that allow for sticky prices, sluggish money adjustment, and time-varying risk premia. Consistent with previous evidence from regression-based tests, most of the models that we examine are rejected by our volatility-based tests. In general, however, we find that exchange rates have not been excessively volatile relative to movements of their determinants, with respect to the predictions of even the most restrictive version of the monetary model. Alternative measures of "volatility", however, may disguise the cause of rejection as excessive exchange rate volatility.

JEL Classification Numbers:

F31, E41, E51

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Contents

Summary

This paper uses recent volatility-based tests of asset price models to provide new evidence on the ability of some popular exchange rate models to match observed patterns of exchange rate volatilities over the post-Bretton Woods period. The methodology developed by Mankiw, Romer, and Shapiro (1991) in the context of stock price models is applied to 1973-94 data for the eight major currencies to test the textbook flex-price version of the monetary model and other models, including some with sticky prices and sluggish money adjustment.

The tests show that, although these models are broadly rejected by the data, this rejection cannot--in general--be attributed to "excessive" exchange rate volatility, but rather to the inconsistency of the models with the assumed efficiency of currency markets. Hence, the tests confirm the wisdom gained from standard, regression-based tests of these models. However, as these tests possess better statistical properties than previous regression-based tests (in particular, they are unbiased in small samples), they provide even stronger evidence against the joint hypotheses of the monetary model (or its extensions) and market efficiency. Furthermore, because these data explicitly constructed as volatility tests, they help clarify the role played by exchange rate volatility in the models' rejection.

The tests conducted in this paper point to the importance of choosing a meaningful definition of exchange rate volatility, so as to avoid disguising a model's rejection as evidence of excessive volatility. The tests show that, when exchange rate volatility is defined as the average of conditional or unanticipated exchange rate changes, there is no evidence that exchange rates may have been excessively volatile with respect to the predictions of even the most restrictive version of the monetary model. Evidence of excessive exchange rate volatility, however, may emerge on the basis of alternative definitions of volatility.

I. Introduction

Are exchange rate fluctuations justified by changes in their fundamental determinants? In an efficient market with rational investors, exchange rates are forward-looking prices that reflect anticipated changes of relative demands and supplies of two monies. Hence, their volatility should reflect investors' expectations of changes in the determinants of money stocks, such as incomes and interest rates. Given a model of exchange rate determination, market efficiency places restrictions on the relative volatility of exchange rates and of their determinants, which can be tested to yield insight on the validity of the underlying model. A family of such tests is applied in this paper, to assess whether some popular exchange rate models are capable of matching observed patterns of exchange rate volatility over the post-Bretton Woods period.

Our interest in exchange rate volatility is motivated by both analytical and policy concerns. Exhibit A in policy discussions of exchange rate volatility is often represented by a chart such as Figure 1, pointing to the dramatic increase in exchange rate volatility for major currencies since the breakdown of the Bretton Woods system. This evidence is often accompanied by an expression of concern that "private markets may not always anchor their behavior to economic fundamentals, thus making their responses susceptible to contagion and bandwagon effects that may be disruptive and detrimental to economic performance" (Mussa *et al.*, 1994, p. 18). Excessive exchange rate volatility is also often advocated as ground for sand in the wheels of currency markets (see, for instance, Eichengreen, Tobin, and Wyplosz, 1995).

Before policies to inhibit market response be advocated, however, one ought to verify that the volatility of exchange rates does not simply reflect that of their underlying determinants. Also, because these tests are typically joint tests of market efficiency and of a specific exchange rate model, the results must be conditioned on the particular model adopted as their basis.

Given the prominence in research on exchange rates of the monetary model and of its variants, early studies of exchange rate volatility, including Huang (1981), Vander Kraats and Booth (1983), and Wadhwani (1987), followed Shiller's (1981) work on stock price volatility to construct variance bounds tests of the monetary model of the exchange rate. Invariably, these studies found the volatility of exchange rates since the breakdown of the Bretton Woods system to exceed the model's predictions, leading their authors and several commentators (see, for instance, Levich, 1985), to assert either the inefficiency of foreign exchange markets, or the invalidity of the underlying model, or both.

Later studies, however, questioned those results. Diba (1987), for instance, showed that the tests of Huang (1981) and Vander Kraats and Booth (1983) were vitiated by an erroneous transformation of annual semi-

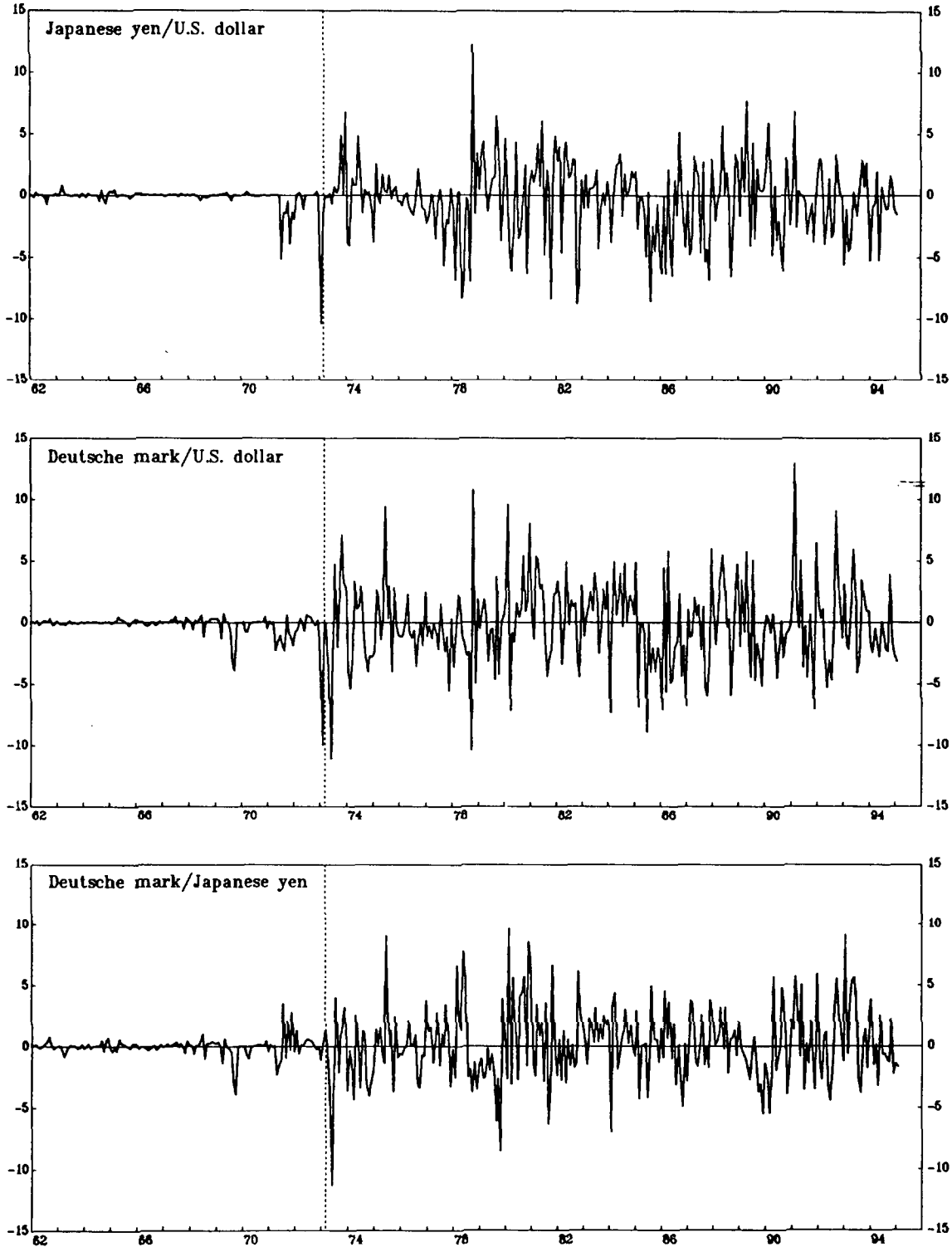
elasticities of money demand to interest rates into their high-frequency counterparts. When correctly calibrated, those tests failed to reject the monetary model's predictions, although that failure was likely to reflect the weak restrictions placed by those tests on the model. Early volatility tests of asset price models were also shown to suffer from serious statistical biases, leading them to reject the underlying model too often in finite samples (see, for instance, Kleidon, 1986, and Marsh and Merton, 1986). To address some of these concerns, Gros (1989) used improved volatility inequalities to present new evidence of excessive exchange rate volatility. His analysis, however, was not based on a formal statistical test, was subject to the same calibration problems pointed out by Diba (1987), and involved measuring exchange rate volatility in a way that was likely to overstate his finding of excessive volatility. In summary, after fifteen years of research, evidence on the ability of the most popular exchange rate models to match the observed variability of exchange rates rests largely on misspecified and weak statistical tests. Not surprisingly, several authors have expressed a perception of futility when reviewing the inconclusive state of research on exchange rate volatility (see, for instance, Frenkel and Meese, 1987, pp. 134-36).

In this paper we use recent volatility-based tests of asset price models to provide new, clearer evidence on the ability of some popular exchange rate models to match observed patterns of exchange rate volatilities over the post-Bretton Woods period. We apply the methodology developed by Mankiw, Romer, and Shapiro (1991) in the context of stock price models, and use data for the eight major currencies from 1973 to 1994, to test the textbook flex-price version of the monetary model, as well as more general models including some with sticky prices, sluggish adjustment of money stocks, and time-varying risk premia.

Our tests show these models to be broadly rejected by the data, but that this rejection cannot--in general--be attributed to excessive exchange rate volatility, but rather to the inconsistency of these models with the assumed efficiency of currency markets. Hence, our tests confirm the wisdom from standard regression-based tests of these models (see Hodrick, 1987, for a survey). However, since our tests possess better statistical properties than previous regression-based tests (in particular, they are unbiased in small samples), they provide even stronger evidence against the joint hypotheses of the monetary model (or of its extensions) and of market efficiency. Furthermore, because they are explicitly constructed as volatility tests, our tests help clarify the role played by exchange rate volatility in the models' rejection.

Specifically, our tests point to the importance of choosing an economically meaningful definition of exchange rate volatility as a basis for the tests, so as to avoid disguising a model's rejection as evidence of excessive volatility. The tests show that when exchange rate volatility is defined--traditionally--as the average of conditional or unanticipated exchange rate changes, then there is no evidence that exchange rates may have been excessively volatile with respect to the predictions of even the

Figure 1
Germany, Japan, and the United States:
Volatility of Nominal Exchange Rates, January 1962 - September 1994
(Percentage changes from previous month)



Dotted line indicates approximate date of breakdown of the Bretton Woods System.
Source: IMF, International Financial Statistics.

most restrictive version of the monetary model. Evidence of excessive exchange rate volatility, however, may emerge on the basis of alternative definitions of volatility.

Our findings, we hope, will contribute to future research on exchange rate volatility being more clearly defined in its scope and, perhaps, to greater caution when formulating claims of excessive exchange rate volatility. Our imposing on the data the straightjacket of the monetary model should even strengthen our conclusions: if exchange rates do not appear to be excessively volatile even with respect to a framework predicting their close movement with money and income alone, the likelihood that evidence of excess volatility may be uncovered based on more flexible models appears even more remote.

II. Volatility Tests of the Monetary Model

1. The monetary model of the exchange rate

The standard specification of the monetary model involves two equations describing domestic and foreign money demands, a purchasing power parity equation, and an uncovered interest parity equation. Assuming, as is standard, that the domestic and foreign money demand parameters are the same, the model can be written as:

$$m_t - p_t = \beta y_t - \alpha i_t \ , \tag{1}$$

$$m_t^* - p_t^* = \beta y_t^* - \alpha i_t^* \ , \tag{2}$$

$$p_t = s_t + p_t^* \ , \tag{3}$$

$$i_t - i_t^* = E_t[s_{t+1} - s_t] \ , \tag{4}$$

where m_t, p_t, and y_t denote (log) domestic money supply, prices, and real income, respectively, and i_t denotes the interest rate at time t on deposits maturing at time $t+1$. Foreign variables are denoted with an asterisk. The (log) exchange rate, *defined as the domestic price of a unit of foreign* currency, is denoted by s_t, while $E_t[.]$ denotes the rational expectation operator conditional on information available at time t.

Equations (1)-(4) can be collapsed into

$$s_t = \frac{f_t}{1+\alpha} + \frac{\alpha}{1+\alpha} E_t[s_{t+1}], \tag{5}$$

where

$$f_t \equiv (m_t - m_t^*) - \beta(y_t - y_t^*). \tag{6}$$

Equations (5) and (6) express the exchange rate as the sum of current fundamentals, f_t, plus a linear function of its own value at time $t+1$. Solving (5) forward up to time $t+h$, yields

$$s_t = \frac{1}{1+\alpha}\left(\sum_{i=0}^{h-1}\left(\frac{\alpha}{1+\alpha}\right)^i E_t[f_{t+i}]\right) + \left(\frac{\alpha}{1+\alpha}\right)^h E_t[s_{t+h}]. \qquad (7)$$

The standard assumption in the literature is to assume the absence of exchange rate bubbles, i.e., that $\lim_{i\to\infty}\left(\frac{\alpha}{1+\alpha}\right)^i E_t[f_{t+i}]=0$, and solve equation (7) forward solely in terms of fundamentals:

$$s_t = \frac{1}{1+\alpha}\sum_{i=0}^{\infty}\left(\frac{\alpha}{1+\alpha}\right)^i E_t[f_{t+i}]. \qquad (8)$$

The tests considered in this paper, however, are robust to the presence of bubbles, and can be performed directly on (7): if s_{t+h} incorporates a bubble term (i.e., a capital gain that reflects solely the anticipation of a future currency transaction), so does s_t, and equation (7) remains valid. In most of our tests, the investment's holding period h is set at three, as forward markets tend to be most liquid for three-month maturities, and the power of our tests falls when h increases much above three. Tests for different values of h are discussed below.

2. Volatility tests of the monetary model

Let us now define the perfect-foresight (or fundamental) exchange rate, s_t^*, as the value that the exchange rate would take if investors could predict with certainty future fundamentals, as well as the exchange rate at $t+h$. The fundamental exchange rate s_t^* is obtained from equation (7) by dropping the expectation operator:

$$s_t^* = \frac{1}{1+\alpha}\left(\sum_{i=0}^{h-1}\left(\frac{\alpha}{1+\alpha}\right)^i f_{t+i}\right) + \left(\frac{\alpha}{1+\alpha}\right)^h s_{t+h}, \qquad (9)$$

so that, by definition, $s_t = E_t[s_t^*]$ under the assumptions of the monetary model.

We must now choose a benchmark exchange rate, denoted by s_t°, about which to measure the volatility of both market and fundamental exchange rates. The need for a benchmark rate reflects analytical and statistical considerations. First, there is simply not a unique way to define "exchange rate volatility" except with respect to a reference benchmark (be it its sample mean or other variables). Second, the notorious nonstationarity of exchange rates requires measuring exchange rate movements with respect to a specific (stochastic) trend.

There are two main requirements for the choice of s_t°: that it be known to investors at time t, and that the differences $s_t - s_t^\circ$ and $s_t^* - s_t^\circ$ be stationary. There are many alternative ways to choose s_t°, however, so as to satisfy these requirements. For instance, s_t° could be defined as the model's prediction at time t-1 of the exchange rate at time t, which can be obtained by lagging equation (5) once and solving for $E_{t-1}[s_t]$:

$$s_t^\circ \equiv E_{t-1}[s_t] = \left(\frac{1+\alpha}{\alpha}\right)s_{t-1} - \frac{f_{t-1}}{\alpha}. \tag{10}$$

When s_t° is chosen in this fashion, the series $s_t^* - s_t^\circ$ and $s_t - s_t^\circ$ describe fundamental and actual exchange rate *surprises*, based on the predictions of the monetary model.

Alternatively, exchange rate volatility could be measured by setting $s_t^\circ = s_{t-L}^\circ$, where L is a suitable lag. For instance, it is customary to focus on *conditional volatilities*, defined, with L=1, as the volatility of the first difference of exchange rates, $s_t - s_{t-1}$. Our task, in this case, would be to assess the consistency of the model's predictions of market and fundamental exchange rate changes from the last known realization of the exchange rate.

Yet another possibility would be to choose s_t° as some "naive" exchange rate forecast, for instance as the value that the exchange rate would take if investors expected fundamentals to evolve as a random walk. Under this assumption, solving Equation (7) forward with $E_t[f_{t+i}] = f_t$, as implied by the random walk hypothesis, yields $s_t = f_t$, i.e., the exchange rate itself should follow a random walk under the assumptions of the monetary model. Note that this "naive" forecast need not be a rational one (although there is, indeed, a considerable amount of evidence that exchange rates may be well approximated by random walks): as long as $s_t = f_t$ is known to investors at time t, and $s_t - s_t^\circ$ and $s_t^* - s_t^\circ$ are stationary, then $s_t^\circ \equiv f_t$ is an acceptable benchmark for our volatility tests. Indeed, Mankiw, Romer, and Shapiro (1985, 1991) have suggested a very similar benchmark when testing for excess stock price volatility, by assuming stock dividends to follow a random walk. Gros (1989) followed their lead, measuring exchange rates with respect to a random walk benchmark. These issues, and their implications for the volatility tests performed in this paper, are further discussed in the following.

Now, with rational expectations, the forecast error $s_t^* - E_t[s_t^*] = s_t^* - s_t$ should be uncorrelated with variables known at time t, including s_t and s_t°. This implies that we should have

$$E_t\left[(s_t^* - s_t)(s_t - s_t^\circ)\right] = 0. \tag{11}$$

Therefore, squaring both sides of the identity

$$s_t^* - s_t^\circ \equiv (s_t^* - s_t) + (s_t - s_t^\circ), \tag{12}$$

taking expectations, and using equation (11), yields

$$E_t[(s_t^* - s_t^\circ)^2] = E_t[(s_t^* - s_t)^2] + E_t[(s_t - s_t^\circ)^2], \tag{13}$$

or

$$q_t \equiv E_t[(s_t^* - s_t^\circ)^2] - E_t[(s_t^* - s_t)^2] - E_t[(s_t - s_t^\circ)^2] = 0. \tag{14}$$

Therefore, the monetary model implies the testable restriction $q_t = 0$, and hence the restriction $E[q_t] = 0$: the sample mean of the q_t's, $\bar{q}$, should be close to zero if the model describes correctly the dynamics of exchange rates. As noted above, this test is robust to the presence of exchange rate bubbles, since if the market exchange s_t incorporates a bubble term, so do s_t^* and s_t°, and equation (14) remains valid.

Thus, we can construct a test of the monetary model as follows. First, we can compute the fundamental exchange rate, s_t^*, and the benchmark exchange rate, s_t°, from (9) and (10), after calibrating the money demand parameters α and β. Then we can use an asymptotic distribution of the sample mean $\bar{q}$ and reject the model when $\bar{q}$ is significantly different from zero. A Generalized Method of Moments distribution of $\bar{q}$ (see Bollerslev and Hodrick, 1992) is a normal distribution

$$\bar{q} \sim N\left(0 , \frac{V}{T}\right), \tag{15}$$

with variance estimated by $\hat{V} = C(0) + 2\sum_{j=1}^{h-1} C(j)$, where $C(j) = \frac{h-j}{h}\sum_{t=j+1}^{T} \frac{q_{t+h} q_{t+h-j}}{T}$, which is robust to serial correlation and heteroskedasticity in the error terms.

Equation (13) also implies

$$E\left[(s_t^* - s_t)^2\right] \leq E\left[(s_t^\circ - s_t^*)^2\right], \tag{16A}$$

$$E\left[(s_t - s_t^\circ)^2\right] \leq E\left[(s_t^\circ - s_t^*)^2\right], \tag{16B}$$

where the expectations are now taken unconditionally. Should either one of these inequalities be violated, then $E_t[q_t] < 0$ (although the opposite is not necessarily true), thus suggesting to use (16A-B) as diagnostics for the model. Inequality (16A), in particular, states that the market exchange rate, s_t, should forecast the behavior of the fundamental rate, s_t^*, better than the benchmark rate, s_t°, in terms of the usual mean-square error

criterion. Inequality (16B) states that the market exchange rate should be less volatile around the benchmark rate than the fundamental rate. This latter inequality provides an 'excess volatility' test of the model, and its intuition is simple: the fundamental exchange rate should deviate from the benchmark rate by as much as the market rate does, *plus* a forecast error $s_t^*-s_t$. If markets are efficient and the monetary model correctly describes exchange rate dynamics, this forecast error should not be systematically related to information available to investors. The volatility of the fundamental exchange rate around the benchmark rate, therefore, should exceed that of the market rate.

3. Relation to alternative tests of the model

Two points should be noted about the test procedure just outlined. First, there is a close relationship between the volatility-based tests presented here and previous regression-based tests (see Hodrick, 1987, for a survey). Recall that the starting point of our analysis is the condition that $s_t^*-s_t$ and $s_t-s_t^\circ$ should be uncorrelated if exchange rates reflect information available to market participants and the monetary model correctly describes the dynamics of exchange rates. Using regression analysis, the natural test of this hypothesis would be to regress $s_t^*-s_t$ on $s_t-s_t^\circ$, and test if the regression coefficient

$$\hat{\pi}_1 = \left(\frac{1}{T}\sum_t (s_t-s_t^\circ)(s_t^*-s_t)\right) \div \left(\frac{1}{T}\sum_t (s_t-s_t^\circ)^2\right), \tag{17}$$

is zero. A non-zero $\hat{\pi}_1$ implies that the prediction error $s_t^*-s_t$ can be forecast at time t. This, among other things, implies that $s_{t+1}-E_t[s_{t+1}]$ is forecastable, since $s_t^*-s_t = \frac{\alpha}{1+\alpha}(s_{t+1}-E_t[s_{t+1}])$, i.e., that there is a systematic bias between exchange rate predictions and realizations.

In comparison with (17), the volatility tests implemented in this paper reject the model when the mean of the q_t's is zero. Now, since $\bar{q}$ can be written as

$$\bar{q} = \frac{1}{T}\sum_t (s_t-s_t^\circ)(s_t^*-s_t) \cdot 2, \tag{18}$$

a link between the regression-based and the volatility-based methods is apparent. Both methods involve testing whether $\frac{1}{T}\sum (s_t-s_t^\circ)(s_t^*-s_t)$, suitably standardized, is significantly different from zero, and both tests provide--when statistically significant--evidence of excess returns' forecastability, i.e., that either markets are inefficient, or the assumed exchange rate model is invalid, or both. There are two main differences between the two methods, however.

The first difference is that the test used in this paper is directly linked to measures of exchange rate volatility and to corresponding volatility inequalities. These inequalities allow testing whether

"excessive" volatility (suitably defined) is indeed a cause of failure of the model.

The second difference is more technical: the volatility-based tests used here have been shown to exhibit better statistical properties than the corresponding regression-based tests. Specifically, Mankiw, and Shapiro (1986) and Mankiw, Romer, and Shapiro (1991) present Montecarlo simulations showing that the finite-sample distribution of a sample-mean $\overline{q}$ is well approximated by its asymptotic distribution, namely, that the volatility-based test tends to reject the underlying model *on average the right number of times*. In contrast, the finite-sample distribution of the regression coefficient $\hat{\pi}_1$ is poorly approximated by its asymptotic distribution. In particular, if the dependent and the independent variables are correlated, and the independent variable is itself serially correlated--which is certainly the case in our tests, where the same "fundamentals" drive both the dependent and independent variables--then regression-based tests are systematically biased, tending to reject the underlying model too often in finite samples.

Next, the ability of the test to reject the model, as well as the interpretation of the test results, depend crucially on the particular choice of s_t°. While it impinges on the model to pass tests with respect to *all suitable* $s_t^\circ s$, the usefulness of the test depends on s_t° being a useful benchmark for the measurement of exchange rate volatility. Establishing the best benchmark is a task that goes well beyond the scope of this paper, particularly since different benchmarks are bound to be useful in different contexts. In welfare analysis, for instance, the appropriate definition of "exchange rate volatility" will depend on agents' attitudes toward risk, the nature of adjustment costs, etc. Nevertheless, it is clear that the usefulness of a particular benchmark is likely to depend on whether exchange rates tend to gravitate, in some loose sense, around it. Few scientists seem to find useful a description of stars' and planets' position in space with respect to the moon, nor to find useful the (formally correct) statement that the sun is more volatile than the earth *about the moon*.

As the issue of choosing a suitable benchmark cannot be resolved in a statistical context--only on the basis of a well specified economic model--in our statistical analysis we follow an eclectic approach. We present results for a variety of choices of s_t°, drawing from common usage in research and policy analysis, in order to highlight the implications of alternative definitions of "exchange rate volatility." We focus, in particular, on the conditional volatility of exchange rates and on the volatility of their unanticipated movements. We present tests that use the model's one-period-ahead prediction of the exchange rate as a benchmark (see equation (10)), to test whether *unanticipated* changes in exchange rates are consistent with movements in their determinants. We also present tests that use the lagged exchange rate as a benchmark, to test whether *total* changes in exchange rates are justified by movements in their determinants. Finally, we present tests where the benchmark rate is set at the value that the exchange rate would take if investors believed fundamentals to behave as

random walks. The tests can be applied in a straightforward way to other definitions of s_t°.

Though our tests' dependence on the benchmark s_t° may seem unfortunate, this dependence simply reflects the intrinsic ambiguity of the concept of "exchange rate volatility": there is simply no unique way to measure exchange rate volatility--just as there is no unique way to measure a planet's movements--except with respect to a specific benchmark. This is the main point we wish to emphasize in this paper, that this ambiguity should be explicitly recognized.

III. More General Specifications of the Model

The test procedure described in the previous section can be applied to a variety of exchange rate models. We discuss here some extensions of the monetary model that allow for slow adjustment of prices and money holdings, and for violations of the interest parity conditions. The point here is not to insist on the empirical accuracy of these specifications, although we draw from the empirical literature in calibrating our models. The aim, rather, is to illustrate the flexibility of the testing procedure, and to provide preliminary evidence of the robustness of our results. Our qualitative findings turn out to be rather robust, suggesting that greater effort to incorporate empirically accurate models, while welcome, is unlikely to overturn our main results.

1. Sticky prices

Following Mussa (1985) and Gros (1989), we adopt a sticky-price version of Purchasing Power Parity (PPP), much along the lines of the standard Dornbusch model. In this model, the real exchange rate $s_t+p_t^*-p_t$ moves toward its PPP value at the rate θ, as in

$$s_{t+1}+p_{t+1}^*-p_{t+1}=(1-\theta)(s_t+p_t^*-p_t)\,. \tag{19}$$

In equation (19), when $\theta=0$ the real exchange rate follows a random walk with no tendency to revert to PPP. When $\theta=1$ the exchange rate converges to its PPP value in a single period.

Replacing Equation (3) with Equation (19) in the model, some tedious but straightforward algebra yields the 'fundamental' sticky-price exchange rate, solved forward up to time $t+h$:

$$s_t^*=\bar{s}_t^*-\frac{(1-\gamma^h)(1-\theta)}{1+\alpha\theta}(p_{t-1}-p_{t-1}^*-s_{t-1})\,, \tag{20}$$

where $\gamma = \frac{(1-\theta)\alpha}{1+\alpha}$, and $\tilde{s}_t^*$ denotes the fundamental exchange rate for the flex-price model[1] (see equation (9)). The expectation at t-1 of the market exchange rate at time t is

$$s_t^e = s_{t-1} - \frac{f_{t-1}}{\alpha} + \frac{p_{t-1} - p_{t-1}^*}{\alpha}. \tag{21}$$

For θ=1, the sticky-price model degenerates into the flex-price model; for smaller values of θ, the sticky-price model predicts greater volatility of exchange rates in response to changes in their determinants. Except for this redefinition of variables, the test procedure remains the same as described in the previous section.

2. Slow money adjustment

We can also relax the assumption that real money balances adjust instantaneously to their equilibrium value. Partial adjustment equations of the form

$$m_t - p_t = \lambda\gamma + \lambda\beta y_t - \lambda\alpha i_t + (1-\lambda)(m_{t-1} - p_t), \tag{22}$$

$$m_t^* - p_t^* = \lambda\gamma + \lambda\beta y_t^* - \lambda\alpha i_t^* + (1-\lambda)(m_{t-1}^* - p_t^*), \tag{23}$$

have been widely used in the literature on money demand functions. The terms $(1-\lambda)(m_{t-1}-p_t)$ and $(1-\lambda)(m_{t-1}^*-p_t^*)$ include lagged money terms and contemporaneous price terms, reflecting an adjustment process of money balances specified in nominal terms. Alternatively, the adjustment term could have been specified as $(1-\lambda)(m_{t-1}-p_{t-1})$ (and similarly for the foreign equation), if the assumed slow response were of *real* money balances. We use the former specification because it allows the familiar forward solution of the exchange rate in terms of fundamentals, and because of its superior empirical performance (see Fair, 1987). 1/

Thus, the coefficients β and α in (22) and (23) describe the long-run income elasticity and long-run interest semi-elasticity of money demand, respectively; λ measures the speed of adjustment of real money balances to their steady state, and takes values between zero and one: when λ=1, real money balances adjust immediately to their steady state; when λ=0, money

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1/ We limited our exploration of money demand equations to specifications with instantaneous or partial adjustment of money stocks. Recent literature has considered buffer-stock and error-correction models that imply even greater departure from the standard specification of the monetary model (see Boughton, 1992, for a survey). These specifications are difficult to integrate in equilibrium exchange rate models, due to their data-dependent parameterization, and their tendency to involve lags of interest rates at different maturities and to predict long-run price non-homogeneity.

demand does not respond to interest rates and income, and the model has no steady-state solution.

Replacing (1) and (2) with (22) and (23) yields

$$f_t \equiv \frac{(m_t - m_t^*) - (1-\lambda)(m_{t-1} - m_{t-1}^*)}{\lambda} - \beta (y_t - y_t^*) . \qquad (24)$$

Except for this redefinition, the test procedure remains the same as described above.

3. Time-varying risk premia

Finally, we can allow for a time-varying residual, x_t, in the interest parity equation (4):

$$i_t - i_t^* = E_t[s_{t+1} - s_t] + x_t , \qquad (25)$$

For our purposes, an *ex post* estimate of the residual x_t can be obtained by detrending $i_t - i_t^* - (s_{t+1} - s_t)$, i.e., $(1+\alpha) s_t - \alpha s_{t+1} - (m_t - m_t^*) + \beta (y_t - y_t^*)$ with a Hodrick-Prescott filter. The test procedure then remains the same as that described in Section 3, with "fundamentals" redefined as

$$f_t \equiv (m_t - m_t^*) - \beta (y_t - y_t^*) + x_t . \qquad (26)$$

One possible interpretation of x_t is as a risk-premium and, for simplicity, we shall use this label in our discussion. Nevertheless, our simple treatment must be viewed only as an *ad hoc* way to relax the interest parity equation, not as a structural model of a risk premium. Our aim, once again, is not to provide a satisfactory exchange rate model, but only to verify the robustness of our results to relaxation of the basic assumptions of the monetary model. 1/ Hence, in our tests we have used a variety of values for the Hodrick-Prescott smoothing coefficient, ρ, summarized by the choices ρ=14,400 (which, following the literature, equals 100 times the square of the sample frequency), and ρ=1,600, a lower value that allows the model to better fit the data.

1/ In particular, since we use all the model's equations to obtain an *ex post* estimate of x_t, the model would be identically satisfied (i.e., $s_t^* \equiv s_t$) by setting the Hodrick-Prescott smoothing coefficient, ρ, at zero. The model specified with (25) imposes restrictions on the data only to the extent that the filtered residual is required to be smooth over time.

IV. Empirical Results

1. Data and calibration of the tests

The full sample covers data for the United States, Japan, Germany, France, the United Kingdom, Italy, Canada, and Switzerland during the period January 1973-September 1994. We use the same proxies for the monetary model's variables used in previous studies: monthly data for narrow and broad money supply, GDP, industrial production, consumer price indices, and exchange rates against the U.S. dollar (end-of-period data). All data are from the IFS of the IMF, except for a few incomplete IFS series that were obtained from the Current Economic Indicator data-base of the IMF.

We calibrated our tests using parameters estimated in previous empirical studies, choosing wide ranges to encompass both estimated and plausible values for each parameter.

Most estimates of the annualized semi-elasticity of money demand to short term interest rates, for money demand functions with instantaneous adjustment, fall in the range 1 to 4 (see, for instance, Bilson, 1978, and Laidler, 1993). Estimated exchange rate models tend to yield smaller values of α (see, for instance, Flood, Rose, and Mathieson, 1991), while money demand equations with partial adjustment tend to yield somewhat higher values of α (see, for instance, Fair, 1987, and Goldfeld and Sichel, 1990). We took the values α=0.1 and α=6 (to be multiplied by 12 in monthly tests) as spanning the plausible range of α, using α=1 as a baseline.

Most estimates of the income elasticity of money demand, β, range from about 0.5 to about 1.5, independently of the assumed speed of money adjustment (see, for instance, Fair, 1987, and Goldfeld and Sichel, 1990). We begin by considering the values β=0.2 and β=2, and then fix β at unity for the rest of the analysis.

The speed of adjustment of money stocks to their steady state, λ, is more difficult to calibrate. Annualized estimates of λ from pre-1974 (quarterly) data typically range around 0.3 - 0.5, suggesting a half-life of money shocks between 6 and 18 months--already a surprisingly slow response. In fact, estimates from post-1974 data typically yield near-zero estimates λ, implying no response of money demand to changes in its determinants, and a breakdown of the steady-state solution of the model. It is now well understood that the estimated unstable behavior of money balances from post-1974 data reflects more the difficulty of capturing with simple dynamic specifications the financial innovations and institutional changes that occurred since 1974, than an implausibly low speed of portfolio adjustment (see Goldfeld and Sichel, 1990, and Boughton, 1992, for a discussion). We report results for the baseline case of instantaneous adjustment, λ=1, and for the cases of λ=0.5 and λ=0.1 (corresponding to monthly values of about λ=.06 and λ=.01). We also present results of tests conducted over split

samples, as a preliminary check of robustness of our inference to structural breaks.

Estimated half-lives of price shocks in PPP equations range anywhere from one to six years, depending on currency and sample (see, for instance, Hakkio, 1992, and Lothian and Taylor, 1993). Hence, (annualized) values of θ should range between 0.1 and 0.5. We report tests with θ set at 0.3; results for tests calibrated with θ=0.5 and θ=0.1 were very similar.

Finally, "fundamental" data for output, money, and prices must be normalized. First, data are reported only in index number form. Second, econometricians can only guess which macro-aggregates best capture "output", "money", and "prices" in theoretical money demand functions, suggesting allowance for a degree of freedom in scaling raw data. Upon allowing for a multiplicative factor in raw data (i.e., for an additive constant in log-transformed data), the model suggests a logical way to normalize the series: by scaling raw data so that the model holds on average over the sample (i.e., so that $\overline{s}_t^* = \overline{s}_t$).

2. Results

Tables 1-3 report a sample of the volatility tests that we implemented. 1/

Table 1 reports results of tests of the textbook flex-price instantaneous-money-adjustment version of the monetary model, for different values of the elasticities β and α. Several important features are apparent from these results.

First, the model is strongly rejected in almost all cases, with test statistics often exceeding their 99 percent critical values of ±2.57. The rejection is strong when $s_t^\circ \equiv E_{t-1}[s_t]$ is used as a benchmark, and is due to the occurrence of a positive test statistic. This positive sign reflects a positive correlation between the forecast error, $s_t^* - s_t$, and the exchange rate surprise at time t, $s_t - E_{t-1}[s_t]$. That is, on average, either $s_t^* > s_t > E_{t-1}[s_t]$ or $s_t^* < s_t < E_{t-1}[s_t]$. Hence, these tests indicate that market exchange rates tend to stay closer to their one-period-ahead forecasts than predicted by the monetary model, confirming evidence from regression-based tests that the joint hypothesis of the monetary model and of market efficiency are mutually exclusive, as systematic profit opportunities would have persisted in the major currency markets over the sample period. The tests also show, however, that "excessive" exchange rate volatility is not a cause of rejection, as inequality (16B) (a violation of which is marked "B" in Tables 1-3) is never violated when $s_t^\circ = E_{t-1}[s_t]$ is used as a benchmark: the

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1/ A more complete set of tests is available from the authors, together with the data and a copy of the GAUSS program used for the tests, upon receipt of a stamped self-addressed envelope and a formatted 3½" high-density disk.

Table 1. Flexible Price Model

	$s_t^\circ = E_{t-1}[s_t]$				$s_t^\circ = s_{t-1}$				$s_t^\circ = f_t$			
	α=.1		α=6		α=.1		α=6		α=0.1		α=6	
	β=0.2	β=2	β=0.2	β=2	β=0.2	β=2	β=0.2	β=2	β=0.2	β=2	β=0.2	β=2
Pound sterling	4.56	4.70	2.52	2.58	-0.39	-0.25	2.29	2.24	-4.60 AB	-4.74 AB	-2.07 B	-2.52 B
French franc	3.62	4.22	2.83	2.84	-0.25	0.33	2.76	2.79	-3.69 AB	-4.36 AB	-2.19 B	-2.28 B
Deutsche mark	4.09	4.44	2.76	2.96	-0.30	-0.24	2.58	2.63	-4.14 AB	-4.47 AB	-2.23 B	-2.43 B
Italian lira	3.98	4.33	2.53	2.42	-0.37	-0.86 A	2.37	2.32	-4.01 AB	-4.65 AB	-1.38 B	-1.12 B
Swiss franc	5.41	4.74	2.78	2.93	-0.18	0.09	2.59	2.61	-5.46 AB	-4.79 AB	-1.87 B	-2.40 B
Canadian dollar	4.88	4.95	2.41	2.75	0.94	1.17	1.76	1.83	-4.92 AB	-5.01 AB	-3.00 B	-3.65 B
Japanese yen	5.09	4.14	2.63	2.45	-1.25 A	-1.43 A	2.05	2.07	-5.07 AB	-4.15 AB	-2.14 B	-1.64 B

Notes: The reported values are the standard normal statistics for the null hp. that $\bar{q}_t = 0$, where q_t is defined by equation (14) in the text. Newey-West standard errors, with a lag truncation of $6 \cdot (n/255)^{1/4}$, where n is the number of observations, were used. A superscript A indicates that inequality (16A) is violated, while a superscript B indicates that inequality (16B) is violated. Monthly data for broad money and industrial production are used in these tests. The sample goes from April 1973 to September 1994. The number of observations is 255.

Table 2. Baseline, Sluggish Money Adjustment, and Sticky Prices

	$s_t^o = E_{t-1}[s_t]$				$s_t^o = s_{t-1}$				$s_t^o = f_t$			
	Baseline $\lambda=1$	$\lambda=0.5$	$\lambda=0.1$	Sticky Prices	Baseline $\lambda=1$	$\lambda=0.5$	$\lambda=0.1$	Sticky prices	Baseline $\lambda=1$	$\lambda=0.5$	$\lambda=0.1$	Sticky Prices
Pound sterling	3.80	4.00	3.48	3.60	0.88	0.71	-0.14	0.84	-4.35 B	-4.51 B	-4.11 B	-4.23 B
French franc	2.90	2.96	2.78	2.51	1.81	2.14	2.52	2.04	-3.33 B	-3.65 B	-4.60 B	-2.97 B
Deutsche mark	3.74	3.76	3.43	3.59	1.28	1.11	0.16	1.36	-4.11 B	-4.07 B	-2.44 B	-3.68 B
Italian lira	2.91	3.17	3.17	2.37	1.33	1.72	2.46	1.73	-3.60 B	-3.93 B	-4.74 B	-3.07 B
Swiss franc	4.13	4.14	3.02	3.13	1.63	2.23	2.41	1.49	-4.82 B	-4.13 B	-2.21 B	-4.32 B
Canadian dollar	4.37	3.86	2.46	4.32	1.44	1.17	0.33	1.21	-4.81 B	-4.55 B	-4.43 B	-4.90 B
Japanese yen	4.54	4.64	3.02	2.98	0.18	0.44	1.04	0.47	-4.57 B	-4.75 B	-4.49 B	-3.77 B

Notes: The reported values are the standard normal statistics for the null hp. that $\bar{q}_t = 0$, where q_t is defined by equation (14) in the text. Newey-West standard errors, with a lag truncation of $6 \cdot (n/255)^{1/4}$, where n is the number of observations, were used. A superscript A indicates that inequality (16A) is violated, while a superscript B indicates that inequality (16B) is violated. Monthly data for broad money and industrial production are used in these tests. The baseline model uses $\alpha=1$, $\beta=1$, $\lambda=1$, $\theta=1$; the sticky price model uses $\theta=.3$. The sample goes from April 1973 to September 1994. The number of observations is 255.

Table 3. Time-Varying Risk Premia and Various Subsamples

	$s_t^o = E_{t-1}[s_t]$				$s_t^o = s_{t-1}$				$s_t^o = f_t$			
	Variable Risk Premia		1973.04 to 1983.12	1984.01 to 1994.09	Variable Risk Premia		1973.04 to 1983.12	1984.01 to 1994.09	Variable Risk Premia		1973.04 to 1983.12	1984.01 to 1994.09
	$\rho=14{,}400$	$\rho=1{,}600$			$\rho=14{,}400$	$\rho=1{,}600$			$\rho=14{,}400$	$\rho=1{,}600$		
Pound sterling	2.18	1.53	2.22	2.83	1.07	0.36	1.17	0.88	-3.53 B	-2.63 B	-2.62 B	-3.38 B
French franc	2.58	1.53	2.35	2.18	1.29	0.41	0.98	1.33	-3.13 B	-1.66	-3.36 B	-2.59 B
Deutsche mark	2.51	1.20	2.73	3.05	0.91	-0.13	0.78	1.31	-3.37 B	-2.31	-3.53 B	-3.41 B
Italian lira	2.18	1.11	2.28	2.46	1.07	0.36	0.29	1.32	-2.87 B	-1.48	-3.20 B	-2.98 B
Swiss franc	2.51	1.20	3.12	2.45	1.09	0.13	1.07	1.32	-2.88 B	-1.96	-3.55 B	-2.93 B
Canadian dollar	0.61	-0.75	3.03	3.85	-1.26	-1.94	0.11	1.58	-3.20 B	-2.65 B	-3.68 B	-4.09 B
Japanese yen	2.17	0.79	2.09	2.89	0.71	-0.40	0.44	0.76	-2.35 B	-1.44	-2.68 B	-3.39 B

Notes: The reported values are the standard normal statistics for the null hp. that $\bar{q}_t = 0$, where q_t is defined by equation (14) in the text. Newey-West standard errors, with a lag truncation of $6 \cdot (n/255)^{1/4}$, where n is the number of observations, were used. A superscript A indicates that inequality (16A) is violated, while a superscript B indicates that inequality (16B) is violated. Monthly data for broad money and industrial production are used in these tests. The coefficient ρ is the smoothing coefficient for the Hodrick-Prescott filter. The sample goes from April 1973 to September 1994 unless mentioned. The number of observations in the four samples is 255, 255, 128, and 126, respectively.

sample volatility of market exchange rates around the model's prediction at time t-1, $\hat{E}[(s_t - s_t^\circ)^2]$, is smaller than that of fundamental rates around the same benchmark, $\hat{E}[(s_t^* - s_t^\circ)^2]$. Market exchange rates at time t also appear to forecast fundamental rates better than the model's predictions at time t-1, as required by inequality (16A) (a violation of which is marked "A" in the tables). Thus, both inequalities (16A) and (16B) are satisfied. These inequalities are only necessary--not sufficient--conditions for model acceptance, however, and their fulfillment does not prevent the model from being rejected on grounds of forecastability of excess returns.

There is also no evidence of "excessive" exchange rate volatility when the lagged exchange rate is used as a benchmark ($s_t^\circ \equiv s_{t-1}$): *conditional* volatilities of major exchange rates do not exceed the predictions of even the most restrictive version of the monetary model over the post-Bretton Woods period. Inequality (16A) is violated for the Japanese yen at low values of α, and for the Italian lira at low values of α and large values of β. Interestingly, it is much more difficult to reject the model when $s_t^\circ \equiv s_{t-1}$ than when $s_t^\circ \equiv E_{t-1}[s_t]$: exchange rate innovations, $s_t - s_{t-1}$, appear as largely random in the data--particularly at short horizons--and only for high values of α is the model rejected with confidence. These are intuitive results: as α falls, the discount rate implicit in the model rises, so that the weights attached by the test to events in the near future rise. As exchange rates are usually difficult to distinguish from random walks at very short horizons, the test cannot reject the hypothesis that $s_t - s_{t-1}$ is pure noise.

Setting $s_t^\circ \equiv f_t$ causes inequality (16B) to be violated for all currencies and parameter values, and $\bar{q}$ to be significantly negative: market exchange rates are too volatile around $s_t^\circ = f_t$ to be consistent with the predictions of the monetary model. Inequality (16A) is also violated, though only for very low values of α. Violation of (16B) is consistent with the evidence presented by Gros (1989) who, following Mankiw, Romer, and Shapiro's (1985) work on stock prices, stationarized exchange rates around a random walk benchmark. The meaning of this evidence, and the caveats discussed in Section 2, can be clarified with reference to Figures 2-4.

Figures 2-4 plot $s_t - s_t^\circ$ and $s_t^* - s_t^\circ$ for all seven exchange rates, for the three alternative choices of s_t°, based on a baseline set of parameters, $\alpha = \beta = \lambda = \theta = 1$. It is visually apparent in Figures 2 and 3 that when $s_t^\circ = E_{t-1}[s_t]$ or $s_t^\circ = s_{t-1}$, respectively, then s_t° tracks s_t more closely then it tracks s_t^*, for all currencies. In contrast, when $s_t^\circ = f_t$ (see Figure 4), then s_t° tracks s_t^* more closely then it tracks s_t. As a result, s_t is *not* excessively volatile in Figures 2 and 3, but *is* excessively volatile in Figure 4, for all currencies and acceptable parameter values. Evidence of "excessive" volatility when stationarizing exchange rates around a "random walk" benchmark is therefore formally correct, though most researchers (including ourselves) would argue this to be a finding of little usefulness. Loosely speaking, what would be viewed as "excessively volatile" for most purposes would be the benchmark itself, not the exchange rate. Indeed, when exchange rates are measured with respect to common benchmarks (the value predicted by

the underlying model based on last period's information, or the last value in the public's information), then there is no evidence that major exchange rates may have been too volatile in the post-Bretton Woods period, with respect to the predictions of even the most restrictive version of the monetary model.

Tables 2 and 3 confirm the previous discussion for alternative specifications of the model.

Table 2 presents results for the baseline set of parameters ($\alpha=\beta=\lambda=\theta=1$), for the model with partial adjustment of money stocks ($\lambda=0.5$ and $\lambda=0.1$), and for the sticky price model. Predictably, the models with sluggish money and price adjustment can be rejected with somewhat less confidence than the baseline model. 1/ More careful modeling of the money and price processes is likely to weaken the evidence against the model even further. For the purpose of the present study, however, suffice to note that these extensions tend to move the test statistics in the "right" direction, while not affecting the volatility inequalities: there is no evidence of "excess" volatility when exchange rates are measured with respect to their lagged values or with respect to the trends anticipated by the model; there is evidence of "excess" volatility, however, when exchange rates are measured with respect to a random walk benchmark.

Table 3 presents test results for the model with time-varying risk premia and for the baseline model over two half-samples. Allowing for violations of the interest parity condition sharply weakens the overall evidence against the model, particularly when the Hodrick-Prescott parameter ρ is set to such a low value ($\rho=1,600$), that much of the interest parity residuals are incorporated into fundamentals. While these tests are clearly skewed in favor of the model (little structure is imposed on the premia x_t, except that they should be smooth over time), our previous discussion of the volatility inequalities (16A-B) requires little change. Indeed, these results suggest that more accurate modeling of the interest parity condition is likely to weaken the evidence of excess volatility even based on a random walk benchmark.

Finally, overall evidence against the model remains strong when the tests are performed over split samples, and the qualitative aspects of the excess volatility tests are also unchanged.

A variety of alternative specifications of the tests, for which results are available upon request, gave very similar results. We relaxed the assumption of long-run PPP by allowing for a time-varying trend in the real exchange rate (estimated, as in the case of a time-varying risk premium, by passing $s_t+p_t^*-p_t$ through a Hodrick-Prescott filter); we performed tests with

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1/ Given the existing econometric evidence on money demand equations, it is also not surprising that the data favor an extremely low value of λ. See the discussion in Section 4.1.

Figure 2

Volatility of Market and Fundamental Exchange Rates around Benchmarks

$$s_t^o \equiv E_{t-1}[s_t]$$

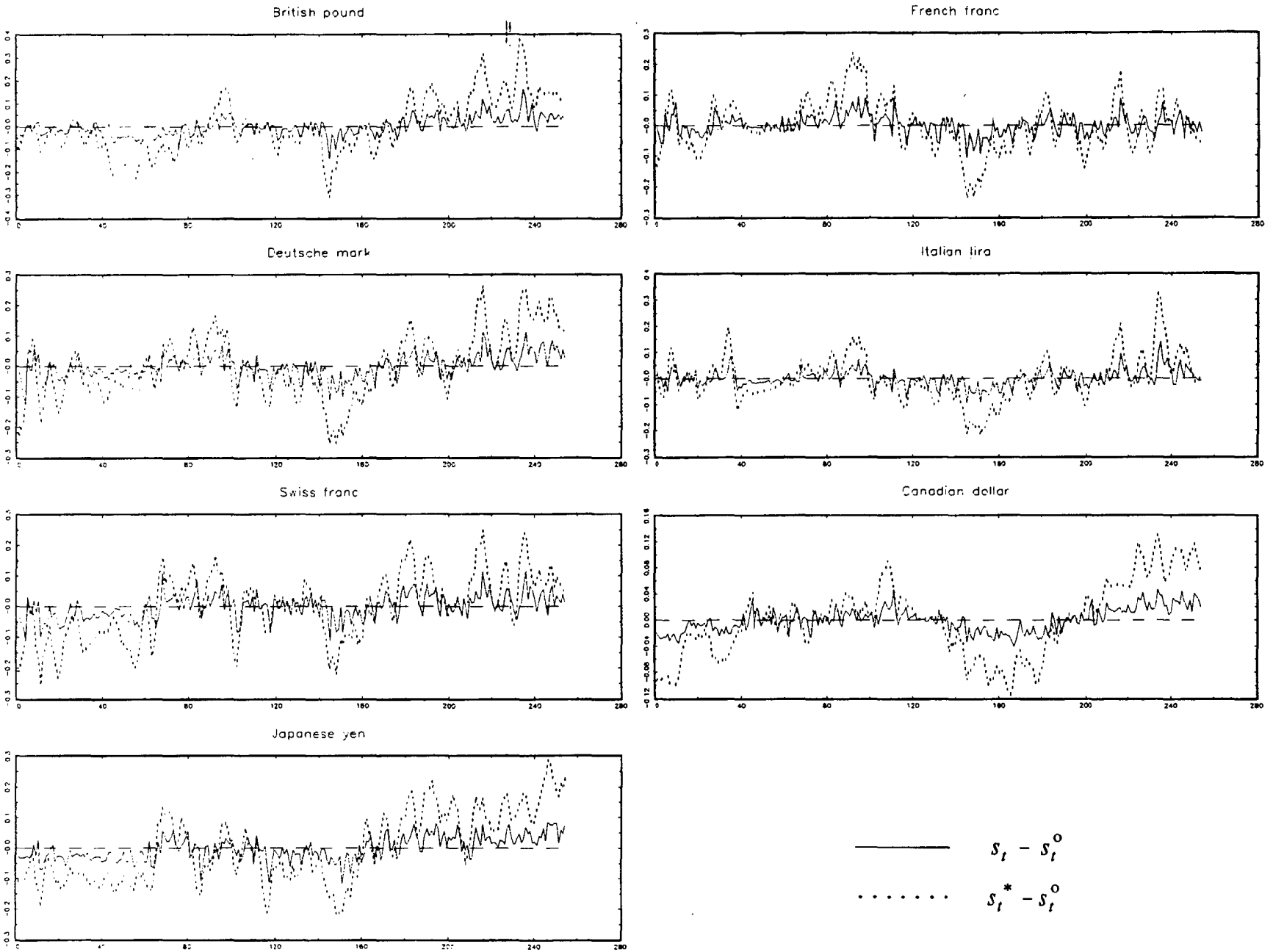


Figure 3

Volatility of Market and Fundamental Exchange Rates around Benchmarks

$$s_t^o \equiv s_{t-1}$$

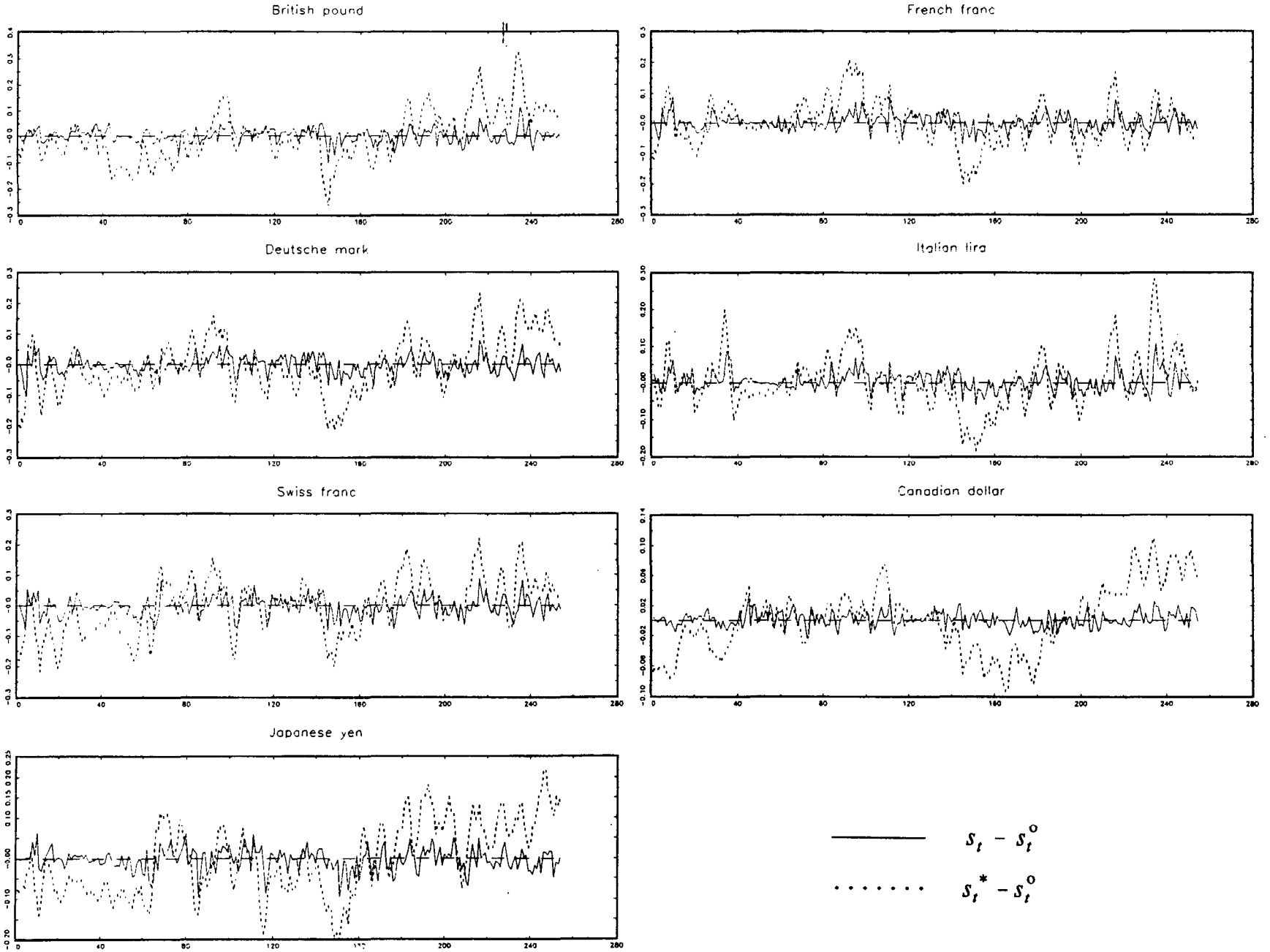
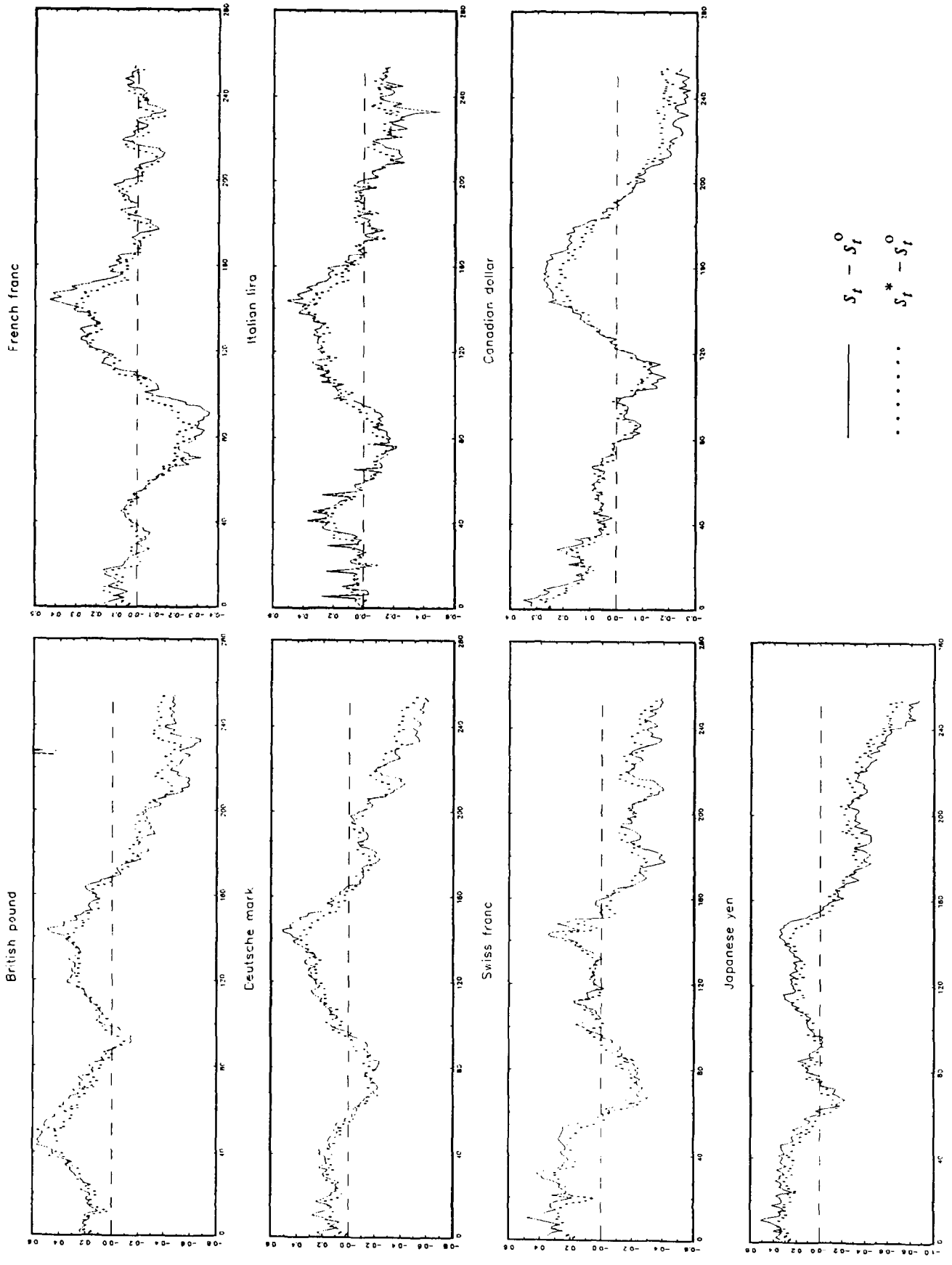


Figure 4

Volatility of Market and Fundamental Exchange Rates around Benchmarks

$s_t^o \equiv f_t$



narrow money instead of broad money as the monetary variable, using moving averages rather than the Hodrick-Prescott filter to filter the data, using quarterly (instead of monthly) data and, in this case, using real GDP instead of industrial production data; we measured exchange rates with respect to the deutsche mark rather than the dollar; we considered different holding periods, h, in the definition of the fundamental exchange rate, and different lags, L, in the definition of the benchmark exchange rate. Our volatility-based tests continued to provide evidence against the model as a whole (more precisely: evidence of excess returns forecastability), but no evidence of excess volatility--except with respect to a random walk benchmark. 1/

V. Concluding Remarks

The volatile behavior of exchange rates since the breakdown of the Bretton Woods system has led scholars and policymakers to question the consistency of exchange rate fluctuations with movements in their underlying determinants, with complaints of unjustified (or "irrational") market turbulence rising loud during episodes of exchange rate instability. Several previous studies have presented evidence that exchange rates since 1973 have been excessively volatile with respect to the predictions of a variety of popular exchange rate models. However, for reasons ranging from calibration errors, small-sample biases, and lack of a proper testing procedure, these studies failed to present convincing evidence of the inability of these models to match the observed pattern of exchange rate volatilities over the post-Bretton Woods period.

This paper has tried to provide more solid evidence on the ability of a popular family of exchange rate models to match observed patterns of exchange rate changes, by applying recent tests of asset price volatility. Two main points have emerged from the analysis.

First, consistent with previous regression-based tests of the monetary model, our volatility-based tests strongly reject the monetary model in its textbook flex-price format and in more general versions that allow for sluggish price and money adjustments: excess returns in currency markets appear to be too forecastable for these markets to be efficient *and* exchange rates being governed by the rules of the monetary model. As the volatility-based tests that we employ have been shown to possess better statistical properties that previous regression-based tests, our evidence against the

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1/ Exceptions included moving to quarterly data, which caused most tests to become insignificant, likely as a result of a drastic fall in the degrees of freedom; and increasing the holding period beyond six months and the lag L in $s_t^o \equiv s_{t-L}$ beyond three months, which also caused many of the tests to become insignificant. Replacing broad money with narrow money tended to increase the confidence of rejection.

monetary model should be viewed as stronger than that previously available in the literature. Nevertheless, rejection of the monetary model is hardly a novelty, and this negative outcome would be, on its own account, of secondary interest.

Second, and more interesting, our tests highlight the ambiguity of the concept of exchange rate volatility, and the implications of this ambiguity for claims of "excess" exchange rate volatility. Measuring exchange rate deviations with respect to different benchmarks leads to different conclusions on whether major currencies' exchange rates have been "excessively" volatile over the post-Bretton Woods period. While we have made no attempt to resolve this ambiguity, we have showed that based on certain (odd, in our view) definitions of exchange rate volatility, claims that major exchange rates may have been too volatile over the post-Bretton Woods period may be formally justified. However, based on definitions of exchange rate volatility common in the exchange rate literature (which focus on the volatility of exchange rate surprises, and on the conditional volatility of exchange rates), major exchange rates over the post-Bretton Woods period do not appear to violate the predictions of even the most restrictive version of the monetary model: their volatility is consistent with the anticipated volatility of their determinants.

Our results should lead to greater skepticism against future claims of "excessive" exchange rate volatility, and our focus on a model as restrictive as the monetary model should reinforce this skepticism: models that do not tie down exchange rate movements to those of a such narrow set of macroeconomic variables (for instance, portfolio balance models with imperfect substitutability, asset-price models with variable rates of discount, etc.) should provide even less evidence of excess volatility. (Formally, for a perfectly-fitting model, $s_t^* \equiv s_t$, $\overline{q} \equiv 0$, and both (16A) and (16B) would be satisfied.) The technique applied in this paper to test for excess exchange rate volatility is simple and general, and future research is bound to subject this conjecture to a direct test.

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