

Crash Risk in Currency Returns: Internet Appendix

Not intended for publication

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August 30, 2017

Abstract

We review related literature; provide a list of all estimated jumps and macro-economic events associated with them; provide a detailed solution of the Long-Run Risk models used in the main text as examples; discuss implications for UIP regressions, characterize alternative modeling approaches; compute the expected future variance and derive entropy. Finally, we describe our estimation and inference methodology.

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I Related Literature

We limit our discussion of related literature to papers that highlight the importance of jumps for understanding the properties of exchange rate returns. One exception is the work of Brandt and Santa-Clara (2002) and Graveline (2006). These papers are early antecedents of our paper in terms of methods and research questions. These authors also estimate a time-series model of exchange rates using the time-series of FX and implied variance. However, they do not allow for jumps.

A number of early papers provide parametric evidence of constant arrival rate jumps in exchange rates, but not in their variance (Akgiray and Booth, 1988; Boothe and Glassman, 1987; Jorion, 1988; Nieuwland, Verschoor, and Wolff, 1994; Tucker and Pond, 1988; Vlaar and Palm, 1993). Methodologically, these papers cannot estimate jump times and magnitudes. Thus, they cannot relate jumps to news. Johnson and Schneeweis (1994) is the only exception as they explicitly associate jumps in exchange rates with macro announcements. A more recent literature uses high-frequency data to disentangle jumps from normal shocks and to subsequently relate them to news (Chatrath, Miao, Ramchander, and Villupuram, 2014 and references therein). These papers take a non-parametric approach, which does not deliver asset-pricing implications.

Yet another branch of the literature measures surprises of macro announcements by the standardized difference between survey-based expectation and the realization of a particular macro variable. These surprises are related to the magnitude of changes in exchange rates (see Neely, 2011 for a review and references therein). Our analysis is complimentary and is tied to our specific models. We first use a model to detect days when jumps took place and then check if macro or political announcements took place on these days.

Our paper is related to recent empirical papers that investigate whether high currency returns can be explained as compensation for jump, or crash, risk. Brunnermeier, Nagel, and Pedersen (2008) provide evidence consistent with the hypothesis that large exchange rate moves are related to funding constraints of speculators engaged in carry trades. In particular, they relate the sign and magnitude of skewness of various exchange rates relative to the USD to those of the respective interest rate differentials. Jurek (2014) analyzes the returns on carry trade portfolios in which the exposure to currency crashes is hedged with options. He concludes that exposure to currency crashes account for 15% to 35% of the excess returns on unhedged carry trade portfolios. Burnside, Eichenbaum, Kleshchelski, and Rebelo (2011) investigate whether carry trade returns reflect a “peso problem” (i.e., a low probability event that did not occur in the sample). They use carry returns hedged with options to argue that any such peso event must be a modest negative return on the carry trade combined with an extremely large value of the stochastic discount factor (i.e., the marginal utility of a representative investor must be very high in the, as yet, unobserved peso state). Jordà and Taylor (2012) propose to manage the risk of carry positions by conditioning on macro information instead of options, but the resulting strategy still yields a very high Sharpe ratio. The common thread in these papers is that they provide indirect evidence on the magnitude of jump

risk. Our paper aims to complement this previous work with a formal statistical model and analysis.

Our paper is also related to the option pricing literature, which has focused on modeling the risk-adjusted (risk-neutral) distribution of exchange rates. By construction, these papers do not consider risk premiums. However, the shock structures under the risk-adjusted and actual (true) distributions are usually modeled to be similar. In this respect, this work is complimentary to our analysis. Bates (1996) considers option prices on the Deutsche Mark and is the earliest paper that argues for the inclusion of jumps in currencies. He considers a single normally distributed jump in FX with a constant probability. Carr and Wu (2007) distinguish jumps up and down in FX and also allow for time-varying jump probabilities controlled by unobservable states. Bakshi, Carr, and Wu (2008) extend the Carr-Wu model to a triangle of currencies (GBP, JPY, and USD) and estimate it using 2.25 years of data on exchange rates and option prices. Our analysis provides additional economic intuition, as time variation in jump probabilities are driven by observable interest rates. None of these papers consider jumps in variance or estimate jump times and sizes. Farhi, Fraiberger, Gabaix, Ranciere, and Verdelhan (2009) do not have explicit time-varying states, but allow risk-adjusted parameters to change every period in a nonparametric fashion. Jurek and Xu (2013) have time-varying states only. Their values are calibrated to achieve the best fit to the daily cross-section of option prices.

There is also an important literature that attempts to explain the behavior of exchange rates in macro-founded equilibrium.¹ Our paper is silent about the prices of risk (with the exception of the limited option calibration exercise), but it has implications for how to best model the fundamentals in an equilibrium setting. Gourio, Siemer, and Verdelhan (2013), Guo (2007) and Ready, Roussanov, and Ward (2013) propose production-based models, where productivity is allowed to experience a disastrous decline. Farhi and Gabaix (2015) consider a pure exchange economy and a similar assumption of a disaster in consumption. Disasters are modeled as jumps down, and all papers, with the exception of Ready, Roussanov, and Ward (2013), allow unobservable time-varying processes to drive disaster probabilities. Exchange rates inherit these properties. Our results suggest that it may also be important to allow for jumps in the volatility of these processes and for the process driving probability of jumps in consumption to be related to interest rates in equilibrium.

Our results also speak to the frictions-based equilibrium model of Plantin and Shin (2011). These authors focus on endogenously generated dynamics of a carry trade. A carry trade gets started in a high-liquidity environment, such as accommodative monetary policy. It is self-enforcing because of the speculators' belief that others will join the trade. The trade crashes when the speculators hit funding constraints. As a result, extended periods of slow appreciations of a high interest rate currency are randomly interrupted by endogenous crashes. Because our analysis is implemented at the daily frequency, we are able to capture, in reduced form, related phenomena.

¹Examples include, but not limited to Bekaert (1996); Backus, Gavazzoni, Telmer, and Zin (2010); Bansal and Shaliastovich (2013); Colacito (2009); Colacito and Croce (2013).

II Jumps and News

For each day a currency has experienced a jump according to our model, we search Factiva if there were significant news explicitly attributed to large moves in the FX market in the press. Tables 1 - 5 display a detailed account of this news.

III Long-Run Risk models with identical risk premium implications

In this section we provide two examples of models with critically different shocks to the respective endowment processes that, nonetheless, yield the same functional dependence of currency excess returns on observable variables. We rely on the Long-Run Risk framework of Bansal and Yaron (2004) and use various modeling elements inspired by Bansal and Shaliastovich (2013); Benzoni, Collin-Dufresne, and Goldstein (2011); Drechsler and Yaron (2011); Wachter (2013).

We neither make any claims about realism of these models nor attempt to distinguish them empirically. In fact, we try to construct the simplest models possible that deliver risk premiums dependent on the interest rate differential and the variance of changes in the exchange rate. Moreover, the models have implications for real exchange rates while we are studying the empirical behavior of nominal exchange rates. Thus, these models serve for pure illustrative purposes.

We use recursive preferences and define utility from date t on

$$(1) \quad U_t = [(1 - \beta)c_t^\rho + \beta\mu_t(U_{t+1})^\rho]^{1/\rho},$$

and certainty equivalent function,

$$\mu_t(U_{t+1}) = [E_t(U_{t+1}^\alpha)]^{1/\alpha}.$$

In standard terminology, $\rho < 1$ captures time preference (with intertemporal elasticity of substitution $1/(1 - \rho)$) and $\alpha < 1$ captures risk aversion (with coefficient of relative risk aversion $1 - \alpha$). The time aggregator and certainty equivalent functions are both homogeneous of degree one, which allows us to scale everything by current consumption. If we define scaled utility $u_t = U_t/c_t$, equation (1) becomes

$$(2) \quad u_t = [(1 - \beta) + \beta\mu_t(g_{t+1}u_{t+1})^\rho]^{1/\rho},$$

where $g_{t+1} = c_{t+1}/c_t$ is consumption growth. The pricing kernel is

$$\begin{aligned} m_{t+1} &= \beta(c_{t+1}/c_t)^{\rho-1} [U_{t+1}/\mu_t(U_{t+1})]^{\alpha-\rho} \\ &= \beta g_{t+1}^{\rho-1} [g_{t+1}u_{t+1}/\mu_t(g_{t+1}u_{t+1})]^{\alpha-\rho}. \end{aligned}$$

The relationship (2) serves, essentially, as a Bellman equation. Its loglinear approximation

$$\begin{aligned}
\log u_t &= \rho^{-1} \log [(1 - \beta) + \beta \mu_t (g_{t+1} u_{t+1})^\rho] \\
&= \rho^{-1} \log [(1 - \beta) + \beta e^{\rho \log \mu_t (g_{t+1} u_{t+1})}] \\
(3) \quad &\approx b_0 + b_1 \log \mu_t (g_{t+1} u_{t+1})
\end{aligned}$$

gives us transparent closed-form expressions for pricing kernels (Hansen, Heaton, and Li, 2008). The last line is a first-order approximation of $\log u_t$ in $\log \mu_t$ around the point $\log \mu_t = \log \mu$, with

$$\begin{aligned}
b_1 &= \beta e^{\rho \log \mu} / [(1 - \beta) + \beta e^{\rho \log \mu}] \\
b_0 &= \rho^{-1} \log [(1 - \beta) + \beta e^{\rho \log \mu}] - b_1 \log \mu.
\end{aligned}$$

The equation is exact when $\rho = 0$, in which case $b_0 = 0$ and $b_1 = \beta$. We focus on this case for the simplicity sake and to avoid the debate on the accuracy of the log-linear approximation as this subject is not the focus of our paper.

We extend this setting to two countries that we refer to as home (US) and foreign. The representative agents in each country have different risk aversion: $1 - \alpha$ and $1 - \tilde{\alpha}$, respectively. Similarly, all other foreign-country-specific objects, such as consumption growth, or pricing kernel are denoted by tilde $\tilde{\cdot}$.

III.A Model 1: Stochastic Variance

Guess the domestic value function:

$$\log u_t = \log u + p_x x_t + p_{\sigma g} \sigma_{g,t}^2 + p_{\sigma x} \sigma_{x,t}^2.$$

Compute:

$$\begin{aligned}
\log(u_{t+1} g_{t+1}) &= \log u g + x_t + k \sigma_{g,t} \eta_{t+1} + p_x x_{t+1} + p_{\sigma g} \sigma_{g,t+1}^2 + p_{\sigma x} \sigma_{x,t+1}^2 \\
&= \log u g + p_{\sigma g} (1 - \nu_g) v_g + p_{\sigma x} (1 - \nu_x) v_x + (1 + p_x \gamma) x_t + p_{\sigma g} \nu_g \sigma_{g,t}^2 + p_{\sigma x} \nu_x \sigma_{x,t}^2 \\
&\quad + k \sigma_{g,t} \eta_{t+1} + p_x \sigma_{x,t} e_{t+1} + p_{\sigma g} \sigma_{gw} \sigma_{g,t} w_{g,t+1} + p_{\sigma x} \sigma_{xw} \sigma_{x,t} w_{x,t+1}, \\
\log \mu_t (u_{t+1} g_{t+1}) &= [\log u g + p_{\sigma g} (1 - \nu_g) v_g + p_{\sigma x} (1 - \nu_x) v_x] + (1 + p_x \gamma) x_t \\
&\quad + (p_{\sigma g} \nu_g + \alpha k^2 / 2 + \alpha p_{\sigma g}^2 \sigma_{gw}^2 / 2) \sigma_{g,t}^2 + (p_{\sigma x} \nu_x + \alpha p_x^2 / 2 + \alpha p_{\sigma x}^2 \sigma_{xw}^2 / 2) \sigma_{x,t}^2.
\end{aligned}$$

Plug $\log \mu_t (u_{t+1} g_{t+1})$ into the Bellman equation (3) and match coefficients:

$$\begin{aligned}
\text{constant :} \quad \log u &= \beta (\log u g + p_{\sigma g} (1 - \nu_g) v_g + p_{\sigma x} (1 - \nu_x) v_x) \\
x_t : \quad p_x &= \beta (1 + p_x \gamma) \\
\sigma_{g,t}^2 : \quad p_{\sigma g} &= \beta (p_{\sigma g} \nu_g + \alpha k^2 / 2 + \alpha p_{\sigma g}^2 \sigma_{gw}^2 / 2) \\
\sigma_{x,t}^2 : \quad p_{\sigma x} &= \beta (p_{\sigma x} \nu_x + \alpha p_x^2 / 2 + \alpha p_{\sigma x}^2 \sigma_{xw}^2 / 2).
\end{aligned}$$

These equations imply that

$$\begin{aligned}\log u &= \beta(\log g + p_{\sigma g}(1 - \nu_g)v_g + p_{\sigma x}(1 - \nu_x)v_x)/(1 - \beta) \\ p_x &= \beta/(1 - \beta\gamma)\end{aligned}$$

and $p_{\sigma g}$ and $p_{\sigma x}$ are the smallest roots of the following quadratic equations:

$$\begin{aligned}\alpha\beta\sigma_{gw}^2p_{\sigma g}^2 + 2(\beta\nu_g - 1)p_{\sigma g} + \alpha\beta k^2 &= 0 \\ \alpha\beta\sigma_{xw}^2p_{\sigma x}^2 + 2(\beta\nu_x - 1)p_{\sigma x} + \alpha\beta p_x^2 &= 0.\end{aligned}$$

We select the smallest roots because they ensure that the corresponding risk premium is zero when variance is zero.

The foreign value function is computed following identical steps.

Now we can compute the exchange rate growth process:

$$\begin{aligned}s_{t+1} - s_t &= \log \tilde{m}_{t+1} - \log m_{t+1} \\ &= [\alpha^2(k^2 + \sigma_{gw}^2p_{\sigma g}^2) - \tilde{\alpha}^2(\tilde{k}^2 + \sigma_{gw}^2\tilde{p}_{\sigma g}^2)]\sigma_{g,t}^2/2 \\ &+ [\alpha^2(p_x^2 + p_{\sigma x}^2\sigma_{xw}^2) - \tilde{\alpha}^2(\tilde{p}_x^2 + \tilde{p}_{\sigma x}^2\sigma_{xw}^2)]\sigma_{x,t}^2/2 \\ &+ [(\tilde{\alpha} - 1)\tilde{k}\tilde{\eta}_{t+1} - (\alpha - 1)k\eta_{t+1}]\sigma_{g,t} + p_x(\tilde{\alpha} - \alpha)\sigma_{x,t}e_{t+1} \\ &+ (\tilde{\alpha}\tilde{p}_{\sigma g} - \alpha p_{\sigma g})\sigma_{gw}\sigma_{g,t}w_{g,t+1} + (\tilde{\alpha}\tilde{p}_{\sigma x} - \alpha p_{\sigma x})\sigma_{xw}\sigma_{x,t}w_{x,t+1}.\end{aligned}$$

Domestic and foreign interest rates are:

$$\begin{aligned}r_t &= -\log \beta + \log g + x_t + (2\alpha - 1)k^2\sigma_{g,t}^2/2, \\ \tilde{r}_t &= -\log \beta + \log g + x_t + (2\tilde{\alpha} - 1)\tilde{k}^2\sigma_{g,t}^2/2.\end{aligned}$$

Interest rate differential is

$$(4) \quad r_t - \tilde{r}_t = [(2\alpha - 1)k^2 - (2\tilde{\alpha} - 1)\tilde{k}^2]\sigma_{g,t}^2/2.$$

The conditional variance of the exchange rate growth is

$$\begin{aligned}(5) \quad var_t(s_{t+1} - s_t) &= [(\tilde{\alpha} - 1)^2\tilde{k}^2 + (\alpha - 1)^2k^2 + (\tilde{\alpha}\tilde{p}_{\sigma g} - \alpha p_{\sigma g})^2\sigma_{gw}^2]\sigma_{g,t}^2 \\ &+ [p_x^2(\tilde{\alpha} - \alpha)^2 + (\tilde{\alpha}\tilde{p}_{\sigma x} - \alpha p_{\sigma x})^2\sigma_{xw}^2]\sigma_{x,t}^2.\end{aligned}$$

The expected excess log currency return is

$$\begin{aligned}(6) \quad E_t(s_{t+1} - s_t - (r_t - \tilde{r}_t)) &= (var_t(\log m_{t+1}) - var_t(\log \tilde{m}_{t+1}))/2 \\ &= [(\alpha - 1)^2k^2 - (\tilde{\alpha} - 1)^2\tilde{k}^2 + \alpha^2p_{\sigma g}^2\sigma_{gw}^2 - \tilde{\alpha}^2\tilde{p}_{\sigma g}^2\sigma_{gw}^2]\sigma_{g,t}^2/2 \\ &+ [p_x^2(\alpha^2 - \tilde{\alpha}^2) + \alpha^2p_{\sigma x}^2\sigma_{xw}^2 - \tilde{\alpha}^2\tilde{p}_{\sigma x}^2\sigma_{xw}^2]\sigma_{x,t}^2/2.\end{aligned}$$

Solve the system of equations (4)-(5) for the stochastic variances:

$$(7) \quad \sigma_{g,t}^2 = \frac{B_v(r_t - \tilde{r}_t) - B_r \text{var}_t(s_{t+1} - s_t)}{A_r B_v},$$

$$(8) \quad \sigma_{x,t}^2 = \frac{-A_v(r_t - \tilde{r}_t) + A_r \text{var}_t(s_{t+1} - s_t)}{A_r B_v},$$

where

$$\begin{aligned} A_r &= [(2\alpha - 1)k^2 - (2\tilde{\alpha} - 1)\tilde{k}^2]/2, \\ A_v &= (\tilde{\alpha} - 1)^2\tilde{k}^2 + (\alpha - 1)^2k^2 + (\tilde{\alpha}\tilde{p}_{\sigma g} - \alpha p_{\sigma g})^2\sigma_{gw}^2, \\ B_v &= p_x^2(\tilde{\alpha} - \alpha)^2 + (\tilde{\alpha}\tilde{p}_{\sigma x} - \alpha p_{\sigma x})^2\sigma_{xw}^2. \end{aligned}$$

Expressions (6)-(8) imply that the log expected excess currency return is a linear function of the interest rate differential and the variance of exchange rate growth:

$$E_t y_{t+1} = E_t(s_{t+1} - s_t - (r_t - \tilde{r}_t)) = \delta_r(r_t - \tilde{r}_t) + \delta_v \text{var}_t(s_{t+1} - s_t),$$

where

$$\begin{aligned} \delta_r &= (B_v s_g - A_v s_x)/(A_r B_v), \\ \delta_v &= s_x/B_v, \\ s_g &= [(\alpha - 1)^2 k^2 - (\tilde{\alpha} - 1)^2 \tilde{k}^2 + \alpha^2 p_{\sigma g}^2 \sigma_{gw}^2 - \tilde{\alpha}^2 \tilde{p}_{\sigma g}^2 \sigma_{gw}^2]/2, \\ s_x &= [p_x^2(\alpha^2 - \tilde{\alpha}^2) + \alpha^2 p_{\sigma x}^2 \sigma_{xw}^2 - \tilde{\alpha}^2 \tilde{p}_{\sigma x}^2 \sigma_{xw}^2]/2. \end{aligned}$$

III.B Model 2: Disasters

Guess the domestic value function:

$$\log u_t = \log u + p_x x_t + p_{hg} h_{g,t} + p_{hx} h_{x,t}.$$

Compute

$$\begin{aligned} \log u_{t+1} g_{t+1} &= [\log u g + p_{hg}(1 - \nu_{hg})v_{hg} + p_{hx}(1 - \nu_{hx})v_{hx}] + (p_x \gamma + 1)x_t + p_{hg}\nu_{hg}h_{g,t} \\ &+ p_{hx}\nu_{hx}h_{x,t} + \sigma_g \eta_{t+1} + p_x \sigma_x \epsilon_{t+1} + p_{hg}\sigma_{hg}h_{g,t}^{1/2} \varepsilon_{hg,t+1} + p_{hx}\sigma_{hx}h_{x,t}^{1/2} \varepsilon_{hx,t+1}, \\ &+ p_x z_{x,t+1} + z_{g,t+1}, \\ \log \mu_t(u_{t+1} g_{t+1}) &= [\log u g + p_{hg}(1 - \nu_{hg})v_{hg} + p_{hx}(1 - \nu_{hx})v_{hx}] + (p_x \gamma + 1)x_t + p_{hg}\nu_{hg}h_{g,t} \\ &+ p_{hx}\nu_{hx}h_{x,t} + \alpha \sigma_g^2/2 + \alpha p_x^2 \sigma_x^2/2 + \alpha p_{hg}^2 \sigma_{hg}^2 h_{g,t}/2 + \alpha p_{hx}^2 \sigma_{hx}^2 h_{x,t}/2 \\ &+ (e^{\alpha p_x \mu_x + (\alpha p_x \sigma_x)^2/2} - 1)h_{x,t}/\alpha + (e^{\alpha \mu_g + (\alpha \sigma_g)^2/2} - 1)h_{g,t}/\alpha. \end{aligned}$$

Plug $\log \mu_t(u_{t+1} g_{t+1})$ into the Bellman equation (3) and match coefficients:

$$\begin{aligned} \text{constant :} \quad \log u &= \beta(\log u g + p_{hg}(1 - \nu_{hg})v_{hg} + p_{hx}(1 - \nu_{hx})v_{hx} + \alpha \sigma_g^2/2 + \alpha p_x^2 \sigma_x^2/2) \\ x_t : \quad p_x &= \beta(1 + p_x \gamma) \\ h_{g,t} : \quad p_{hg} &= \beta(p_{hg}\nu_{hg} + \alpha p_{hg}^2 \sigma_{hg}^2/2 + (e^{\alpha \mu_g + (\alpha \sigma_g)^2/2} - 1)/\alpha) \\ h_{x,t} : \quad p_{hx} &= \beta(p_{hx}\nu_{hx} + \alpha p_{hx}^2 \sigma_{hx}^2/2 + (e^{\alpha p_x \mu_x + (\alpha p_x \sigma_x)^2/2} - 1)/\alpha). \end{aligned}$$

These equations imply that

$$\begin{aligned}\log u &= \beta(\log g + p_{hg}(1 - \nu_{hg})v_{hg} + p_{hx}(1 - \nu_{hx})v_{hx} + \alpha\sigma_g^2/2 + \alpha p_x^2\sigma_x^2/2)/(1 - \beta) \\ p_x &= \beta/(1 - \beta\gamma)\end{aligned}$$

and p_{hg} and p_{hx} are the smallest roots of the following quadratic equations:

$$\begin{aligned}\alpha^2\sigma_{hg}^2\beta p_{hg}^2 + 2\alpha(\beta\nu_{hg} - 1)p_{hg} + 2\beta(e^{\alpha\mu_g + (\alpha\sigma_g)^2/2} - 1) &= 0, \\ \alpha^2\sigma_{hx}^2\beta p_{hx}^2 + 2\alpha(\beta\nu_{hx} - 1)p_{hx} + 2\beta(e^{\alpha p_x\mu_x + (\alpha p_x\sigma_x)^2/2} - 1) &= 0.\end{aligned}$$

We select the smallest roots because they ensure that the corresponding risk premium is zero when variance is zero.

The foreign value function is computed following identical steps.

Now we can compute the exchange rate growth process:

$$\begin{aligned}s_{t+1} - s_t &= (\alpha^2 - \tilde{\alpha}^2)\sigma_g^2/2 + p_x^2(\alpha^2 - \tilde{\alpha}^2)\sigma_x^2/2 + (\alpha^2 p_{hg}^2 - \tilde{\alpha}^2 \tilde{p}_{hg}^2)\sigma_{hg}^2 h_{g,t}/2 \\ &+ (\alpha^2 p_{hx}^2 - \tilde{\alpha}^2 \tilde{p}_{hx}^2)\sigma_{hx}^2 h_{x,t}/2 + (e^{\alpha\mu_g + (\alpha\sigma_g)^2/2} - e^{\tilde{\alpha}\mu_g + (\tilde{\alpha}\sigma_g)^2/2})h_{g,t} \\ &+ (e^{\alpha p_x\mu_x + (\alpha p_x\sigma_x)^2/2} - e^{\tilde{\alpha} p_x\mu_x + (\tilde{\alpha} p_x\sigma_x)^2/2})h_{x,t} + (\tilde{\alpha} - 1)\sigma_g\tilde{\eta}_{t+1} - (\alpha - 1)\sigma_g\eta_{t+1} \\ &+ p_x(\tilde{\alpha} - \alpha)\sigma_x e_{t+1} + (\tilde{\alpha}\tilde{p}_{hg} - \alpha p_{hg})\sigma_{hg}h_{g,t}^{1/2}\varepsilon_{hg,t+1} \\ &+ (\tilde{\alpha}\tilde{p}_{hx} - \alpha p_{hx})\sigma_{hx}h_{x,t}^{1/2}\varepsilon_{hx,t+1} + (\tilde{\alpha} - \alpha)z_{g,t+1} + p_x(\tilde{\alpha} - \alpha)z_{x,t+1}.\end{aligned}$$

Compute risk-free rates at home and abroad:

$$\begin{aligned}r_t &= -\log E_t m_{t+1} = [-\log \beta + \log g + \alpha^2\sigma_g^2/2 - (\alpha - 1)^2\sigma_g^2/2] + x_t \\ &+ (e^{\alpha\mu_g + (\alpha\sigma_g)^2/2} - e^{(\alpha-1)\mu_g + ((\alpha-1)\sigma_g)^2/2})h_{g,t}, \\ \tilde{r}_t &= -\log E_t \tilde{m}_{t+1} = [-\log \beta + \log g + \tilde{\alpha}^2\sigma_g^2/2 - (\tilde{\alpha} - 1)^2\sigma_g^2/2] + x_t \\ &+ (e^{\tilde{\alpha}\mu_g + (\tilde{\alpha}\sigma_g)^2/2} - e^{(\tilde{\alpha}-1)\mu_g + ((\tilde{\alpha}-1)\sigma_g)^2/2})h_{g,t}.\end{aligned}$$

Interest rate differential is

$$\begin{aligned}r_t - \tilde{r}_t &= r_0 + [e^{\alpha\mu_g + (\alpha\sigma_g)^2/2} - e^{\tilde{\alpha}\mu_g + (\tilde{\alpha}\sigma_g)^2/2}]h_{g,t} \\ (9) \quad &+ (e^{(\tilde{\alpha}-1)\mu_g + ((\tilde{\alpha}-1)\sigma_g)^2/2} - e^{(\alpha-1)\mu_g + ((\alpha-1)\sigma_g)^2/2})h_{g,t},\end{aligned}$$

where

$$r_0 = (\alpha - \tilde{\alpha})\sigma_g^2.$$

The conditional variance of the exchange rate growth is

$$\begin{aligned}var_t(s_{t+1} - s_t) &= v_0 + (\tilde{\alpha}\tilde{p}_{hg} - \alpha p_{hg})^2\sigma_{hg}^2 h_{g,t} + (\tilde{\alpha}\tilde{p}_{hx} - \alpha p_{hx})^2\sigma_{hx}^2 h_{x,t} \\ (10) \quad &+ ((\tilde{\alpha} - \alpha)^2\mu_g^2 + \sigma_g^2)h_{g,t} + ((\tilde{\alpha}\tilde{p}_x - \alpha p_x)^2\mu_x^2 + \sigma_x^2)h_{x,t},\end{aligned}$$

where

$$v_0 = (\tilde{\alpha} - 1)^2 \sigma_g^2 + (\alpha - 1)^2 \sigma_g^2 + p_x^2 (\tilde{\alpha} - \alpha)^2 \sigma_x^2.$$

The expected log excess currency return is

$$\begin{aligned} E_t(s_{t+1} - s_t - (r_t - \tilde{r}_t)) &= rx_0 + (\alpha^2 p_{hg}^2 - \tilde{\alpha}^2 \tilde{p}_{hg}^2) \sigma_{hg}^2 h_{g,t}/2 + (\alpha^2 p_{hx}^2 - \tilde{\alpha}^2 \tilde{p}_{hx}^2) \sigma_{hx}^2 h_{x,t}/2 \\ &+ \mu_g (\tilde{\alpha} - \alpha) h_{g,t} + \mu_x p_x (\tilde{\alpha} - \alpha) h_{x,t} \\ &+ (e^{(\alpha-1)\mu_g + ((\alpha-1)\sigma_g)^2/2} - e^{(\tilde{\alpha}-1)\mu_g + ((\tilde{\alpha}-1)\sigma_g)^2/2}) h_{g,t} \\ (11) \quad &+ (e^{\alpha p_x \mu_x + (\alpha p_x \sigma_x)^2/2} - e^{\tilde{\alpha} p_x \mu_x + (\tilde{\alpha} p_x \sigma_x)^2/2}) h_{x,t}, \end{aligned}$$

where

$$rx_0 = ((\alpha - 1)^2 - (\tilde{\alpha} - 1)^2) \sigma_g^2/2 + p_x^2 (\alpha^2 - \tilde{\alpha}^2) \sigma_x^2/2.$$

Solve the system of equations (9)-(10) for the jump intensities:

$$(12) \quad h_{g,t} = \frac{B_v(r_t - \tilde{r}_t) - B_r var_t(s_{t+1} - s_t) + B_r v_0 - B_v r_0}{A_r B_v},$$

$$(13) \quad h_{x,t} = \frac{-A_v(r_t - \tilde{r}_t) + A_r var_t(s_{t+1} - s_t) + A_v r_0 - A_r v_0}{A_r B_v},$$

where

$$\begin{aligned} A_r &= e^{\alpha \mu_g + (\alpha \sigma_g)^2/2} - e^{\tilde{\alpha} \mu_g + (\tilde{\alpha} \sigma_g)^2/2} + e^{(\tilde{\alpha}-1)\mu_g + ((\tilde{\alpha}-1)\sigma_g)^2/2} - e^{(\alpha-1)\mu_g + ((\alpha-1)\sigma_g)^2/2}, \\ A_v &= (\tilde{\alpha} \tilde{p}_{hg} - \alpha p_{hg})^2 \sigma_{hg}^2 + (\tilde{\alpha} - \alpha)^2 \mu_g^2 + \sigma_g^2, \\ B_v &= (\tilde{\alpha} \tilde{p}_{hx} - \alpha p_{hx})^2 \sigma_{hx}^2 + p_x^2 (\tilde{\alpha} - \alpha)^2 \mu_x^2 + \sigma_x^2. \end{aligned}$$

Expressions (11)-(13) imply that the log expected excess currency return is a linear function of the interest rate differential and the variance of exchange rate growth:

$$E_t y_{t+1} = E_t(s_{t+1} - s_t - (r_t - \tilde{r}_t)) = \delta_0 + \delta_r(r_t - \tilde{r}_t) + \delta_v var_t(s_{t+1} - s_t),$$

where

$$\begin{aligned} \delta_0 &= rx_0 - s_g r_0 / A_r - s_x (A_r v_0 - A_v r_0) / (A_r B_v), \\ \delta_r &= (-A_v s_x + B_v s_g) / (A_r B_v), \\ \delta_v &= s_x / B_v, \\ s_g &= (\alpha^2 p_{hg}^2 - \tilde{\alpha}^2 \tilde{p}_{hg}^2) \sigma_{hg}^2/2 + (e^{\mu_g(\alpha-1) + ((\alpha-1)\sigma_g)^2/2} - e^{(\tilde{\alpha}-1)\mu_g + ((\tilde{\alpha}-1)\sigma_g)^2/2}) + \mu_g (\tilde{\alpha} - \alpha), \\ s_x &= (\alpha^2 p_{hx}^2 - \tilde{\alpha}^2 \tilde{p}_{hx}^2) \sigma_{hx}^2/2 + e^{\alpha p_x \mu_x + (\alpha p_x \sigma_x)^2/2} - e^{\tilde{\alpha} p_x \mu_x + (\tilde{\alpha} p_x \sigma_x)^2/2} + \mu_x p_x (\tilde{\alpha} - \alpha). \end{aligned}$$

IV Model implications for UIP regressions

The model implies that expected log excess return is equal to

$$E_t[y_{t+1}] = \mu_t + \underbrace{h_t^u \theta_u}_{E_t[z_{t+1}^u]} - \underbrace{h_t^d \theta_d}_{E_t[z_{t+1}^d]}.$$

We assume that

$$\mu_t = \mu_0 + \mu_r r_t + \tilde{\mu}_r \tilde{r}_t + \mu_v v_t.$$

The resulting expected excess return is

$$(14) \quad E_t[y_{t+1}] = \mu_0^* + \mu_r^* r_t + \tilde{\mu}_r^* \tilde{r}_t + \mu_v^* v_t$$

where

$$\begin{aligned} \mu_0^* &= \mu_0 + h_0^u \theta_u - h_0^d \theta_d, \\ \mu_r^* &= \mu_r + h_r^u \theta_u - h_r^d \theta_d, \\ \tilde{\mu}_r^* &= \tilde{\mu}_r + \tilde{h}_r^u \theta_u - \tilde{h}_r^d \theta_d, \\ \mu_v^* &= \mu_v + h_v^u \theta_u - h_v^d \theta_d. \end{aligned}$$

Thus, our risk premium encompasses the UIP regressions which set

$$(16) \quad \tilde{\mu}_r^* = -\mu_r^*,$$

$$(17) \quad \mu_v^* = 0.$$

The expected excess return in (14) can be simplified for the preferred model to

$$E_t(y_{t+1}) = \mu_0 + (\mu_r + h_r \theta) r_t + (\tilde{\mu}_r - h_r \theta) \tilde{r}_t + \mu_v v_t.$$

Thus, by testing if $\mu_r = -\tilde{\mu}_r$ and $\mu_v = 0$, we test the UIP regression specification (16) - (17) of currency excess returns across all three models. For all currency pairs, we cannot reject that $\mu_r = -\tilde{\mu}_r$ at the conventional significance levels. Moreover, $\mu_r \approx -3$ for all currencies, which is consistent with our earlier discussion of UIP regression results. In addition, the loading on the variance μ_v is significantly negative in all currencies except for JPY which has a significantly positive estimate. The tiny serial correlation of the residuals w^s suggests that this model is adequate in capturing the conditional mean of excess returns and, therefore, potentially omitted variables cannot materially affect our conclusions about the structure of currency risks.

V Alternative modeling approaches

V.A Modeling exchange rates using pricing kernels

In this section we illustrate that our model can equivalently be viewed as the difference between an affine SDF denominated in different units.

In our model, log excess currency returns are an affine function of a set of normal and non-normal shocks, which we will denote jointly as x_{t+1} , so that

$$(18) \quad y_{t+1} \equiv (s_{t+1} - s_t) - (r_t - \tilde{r}_t) = \mu_t + \beta_t \cdot x_{t+1}.$$

For example, consider a simplified version of our model of exchange rate dynamics

$$y_{t+1} \equiv (s_{t+1} - s_t) - (r_t - \tilde{r}_t) = \mu + v^{1/2} w_{t+1}^s + z_{t+1}^u - z_{t+1}^d.$$

Here $x_{t+1} = (w_{t+1}^s, z_{t+1}^u, z_{t+1}^d)'$ and $\beta_t = (v^{1/2}, 1, -1)'$.

It is popular to model log currency returns as the difference between the log of a pricing kernel, \tilde{m}_{t+1} , for returns denominated in foreign currency and the log of a pricing kernel, m_{t+1} , for the same returns denominated in domestic currency, so that

$$y_{t+1} = \log \tilde{m}_{t+1} - \log m_{t+1} - (r_t - \tilde{r}_t).$$

For tractability in affine models, it is common to assume that m_{t+1} and \tilde{m}_{t+1} are both exponentially affine in the shocks, so that

$$\log m_{t+1} = -r_t - \lambda_t \cdot x_{t+1} - \alpha_t \quad \text{and} \quad \log \tilde{m}_{t+1} = -\tilde{r}_t - \tilde{\lambda}_t \cdot x_{t+1} - \tilde{\alpha}_t.$$

Here α_t and $\tilde{\alpha}_t$ are “convexity adjustments” ensuring that $E_t(m_{t+1}e^{r_t}) = 1$ and $E_t(\tilde{m}_{t+1}e^{\tilde{r}_t}) = 1$, respectively. Returning to our simplified example, an affine m_{t+1} is of the form

$$(19) \quad \begin{aligned} \log m_{t+1} &= -r_t - \underbrace{(\lambda_t^w w_{t+1}^s + \lambda_t^u z_{t+1}^u + \lambda_t^d z_{t+1}^d)}_{\lambda_t \cdot x_{t+1}} \\ &\quad - \underbrace{\log E_t \left[e^{-\lambda_t^w w_{t+1}^s - \lambda_t^u z_{t+1}^u - \lambda_t^d z_{t+1}^d} \right]}_{\alpha_t}, \end{aligned}$$

where λ_t^w , λ_t^u , and λ_t^d are frequently referred to as market prices of the risks w_{t+1}^s , z_{t+1}^u , and z_{t+1}^d , respectively. In the context of jumps, the notation $\lambda_t^k z_{t+1}^k$ means a process arriving at the same rate as jumps in exchange rates and λ_t^k is used to derive the distribution of the jump size in m_t from the distribution of the jump size in y_t .

Thus, our model in equation (18) can equivalently be viewed as the difference between an affine m_{t+1} and \tilde{m}_{t+1} , since

$$(20) \quad y_{t+1} = \log \tilde{m}_{t+1} - \log m_{t+1} - (r_t - \tilde{r}_t) = \underbrace{(\alpha_t - \tilde{\alpha}_t)}_{\mu_t} + \underbrace{(\lambda_t - \tilde{\lambda}_t)}_{\beta_t} \cdot x_{t+1}.$$

Therefore, in a setup in which $\log m_{t+1}$, $\log \tilde{m}_{t+1}$, and log excess currency returns, y_{t+1} , are all affine functions of a set of shocks, it's equivalent to model m_{t+1} and \tilde{m}_{t+1} , or y_{t+1} and m_{t+1} .

Although our model can be viewed as the difference between an affine m_{t+1} and \tilde{m}_{t+1} , log excess currency returns alone are not enough to identify either m_{t+1} or \tilde{m}_{t+1} in our model because exchange rates are driven by more than one shock. To illustrate, the pricing kernel in equation (19) prices the dollar-denominated return on the domestic bank account by construction because

$$E_t(m_{t+1}e^{r_t}) = E_t[e^{-r_t - \lambda_t \cdot x_{t+1} - \alpha_t} e^{r_t}] = 1.$$

It must also price the dollar-denominated return on the foreign bank account, that is,

$$1 = E_t(m_{t+1}e^{r_t + y_{t+1}}) = E_t[e^{-\lambda_t \cdot x_{t+1} - \alpha_t} e^{\mu_t + \beta_t \cdot x_{t+1}}].$$

If there are N sources of risk, this is a single equation in N unknown market prices of risk λ ($N = 3$ in our example). Therefore, it is impossible to separately identify these market prices of risk using only the dynamics of the exchange rate y (or, equivalently, using only one set of risk exposures β). Instead, one would also have to use the prices of options with different strikes and maturities (that is, securities that have different exposures to risks β s).

V.B Joint modeling of currencies in the presence of jumps

This section describes how one may approach joint modeling of currencies, as well as practical implications of such a model. We use a subscript i to denote our bilateral model for exchange rate i .

Joint modeling of risks. For simplicity in this section, we only consider three currencies (three exchange rates against USD), which, for concreteness, we'll assume are AUD, GBP, and JPY. For tractability, suppose that we begin by shutting down the stochastic volatility component and any jumps for these exchange rates, so that

$$(21) \quad y_{it+1} \equiv (s_{it+1} - s_{it}) - (r_t - \tilde{r}_{it}) = \mu_i + v_i^{1/2} w_{it+1}^s, \quad \text{for } i = 1, 2, 3,$$

where the three exchange rates against the USD in order are USD/AUD, USD/GBP, and USD/JPY.

A bilateral model of USD/GBP and USD/JPY is silent/agnostic about the distribution of GBP/JPY. For example, in this simple setup, the dynamics of the excess return on the yen against pound is

$$(22) \quad y_{3t+1} - y_{2t+1} = \mu_3 - \mu_2 + v_3^{1/2} w_{3t+1}^s - v_2^{1/2} w_{2t+1}^s.$$

In order to compute the volatility of GBP/JPY, we need to know the correlation between w_{2t+1}^s and w_{3t+1}^s , which is not specified in the bilateral models. Therefore, to take the simple bilateral models in equation (21) and extend them to a joint model, we have to specify the correlations between the normal shocks, i.e., $\text{corr}(w_{it+1}^s, w_{jt+1}^s) = \rho_{ij}$. In that case, the variance of GBP/JPY is $v_2 + v_3 - 2\rho_{23}\sqrt{v_2 v_3}$.

A joint model of these three exchange rates has a richer set of implications, but it also has more free parameters to capture all aspects of the joint distribution. Importantly, a joint model of these three exchange rates does not provide any additional restrictions for the bilateral exchange rates that the bilateral models ignore: the means and variances in a joint model of the excess currency returns against the USD are the same as those obtained in the bilateral models. Although our model is obviously much more complicated than this simple example, the same principle still applies. In short, the models of bilateral exchange rates that we develop and estimate will not be discarded in a joint model, but rather they are valuable inputs to such a model.

To provide a sense of the complexities involved with joint modeling of jumps, suppose that we add a single jump to equation (21), so that

$$(23) \quad y_{it+1} \equiv (s_{it+1} - s_{it}) - (r_t - \tilde{r}_{it}) = \mu_i + v_i^{1/2} w_{it+1}^s + z_{it+1}, \quad \text{for } i = 1, 2, 3,$$

where z_{it+1} is a jump in the i th exchange rate against the USD. A joint model of these three exchange rate dynamics requires that we specify how the jumps are distributed across different combinations of currencies. The jump dependencies are more complicated than those of normal shocks because they are primarily driven by common arrival processes. For example, consider a jump in currency i , that is, z_{it+1} . This jump could affect only currency i , it could affect currency i and only one of the other two currencies, or it could affect all three currencies. For clarity, we will assume that the size of any jump that hits currency i is distributed normally with mean 0 and variance θ_i , regardless of whether that jump also hits other exchange rates. Jumps that affect multiple exchange rates could have correlated sizes, but we ignore this possibility in this example.

Notationally, this decomposition of jumps across different exchange rates can be quite complex. For example, in a joint model of these three exchange rates against USD, let z_{1it+1} be a jump that only affects exchange rate i (against USD), let z_{2ijt+1} be a jump that only affects exchange rates i and j (against USD), and let z_{3it+1} be a jump that affects all three exchange rates (against USD). Denote the corresponding jump intensities as

$$\begin{aligned} h_{1it} &= h_{1i0} + h_{1i}r_t + \tilde{h}_{1i}\tilde{r}_{it}, \\ h_{2ijt} &= h_{2ij0} + h_{2ij}r_t + \tilde{h}_{2ij}^{(i)}\tilde{r}_{it} + \tilde{h}_{2ij}^{(j)}\tilde{r}_{jt}, \\ h_{3t} &= h_{30} + h_3r_t + \tilde{h}_{31}\tilde{r}_{1t} + \tilde{h}_{32}\tilde{r}_{2t} + \tilde{h}_{33}\tilde{r}_{3t}. \end{aligned}$$

In a bilateral model, we're only interested in the sum of all of these different combinations of jumps that affect a given exchange rate, that is,

$$z_{it+1} = z_{1it+1} + \sum_{j \neq i} z_{2ijt+1} + z_{3it+1}.$$

Likewise, the intensity of jump z_{it+1} is the sum of the intensities of the individual components. In this simplified example with a single normally distributed jump, the intensities, in general, depend on the interest rates in all currencies. However, our preferred model of bilateral

exchange rates can be shown to be entirely consistent with a joint model (that is, not just in spirit, but down to the functional form).

As we highlighted above, a bilateral model is silent/agnostic about how currency i moves against any currency other than USD, but a joint model is not. For example, consider again the GBP/JPY exchange rate. In the simple model in equation (23), the dynamics of the excess log return on the yen against the pound is

$$(24) \quad y_{3t+1} - y_{2t+1} = \mu_3 - \mu_2 + v_3^{1/2} w_{3t+1}^s - v_2^{1/2} w_{2t+1}^s + z_{13t+1} - z_{12t+1} + z_{231t+1} - z_{221t+1} + (z_{232t+1} - z_{223t+1}) + (z_{33t+1} - z_{32t+1}) .$$

Thus, there are six jumps that can affect the GBP/JPY exchange rate: (i) a jump in USD/JPY, i.e., z_{13t+1} ; (ii) a jump in USD/GBP, i.e., z_{12t+1} ; (iii) a jump USD/AUD and USD/JPY but not USD/GBP, i.e., z_{231t+1} ; (iv) a jump in USD/AUD and USD/GBP but not USD/JPY, i.e., z_{221t+1} ; (v) a jump in USD/GBP and USD/JPY, but not USD/AUD, i.e., z_{232t+1} and z_{223t+1} ; and finally, (vi) a jump in USD/AUD, USD/GBP, and USD/JPY, i.e., z_{33t+1} and z_{32t+1} . Note that for cases (v) and (vi) with jumps that affect both USD/GBP and USD/JPY, the net effect on GBP/JPY depends on the direction and magnitudes of the jumps in USD/GPB and USD/JPY (i.e., $z_{232t+1} - z_{223t+1}$ and $z_{33t+1} - z_{32t+1}$, respectively).

As the number of currencies in a joint model grows, so too does the flexibility and complexity. For example, if we consider three bilateral models that follow equation (23) then there are three jumps. However, if we jointly model those three exchange rates then there are $3+3+1 = 7$ jumps. If we jointly model 4 exchange rates according to equation (23) then there are $4+6+4+1 = 15$. And so on.

Finally, it is instructive to consider what additional data might be most helpful for identifying the new parameters in a joint model. The cross-rates are all pinned down by the exchange rates against USD (i.e., if we know USD/GBP and USD/JPY, then we know GBP/JPY). Thus, the joint time series of the exchange rates against USD can provide some of the additional necessary information (e.g., correlations). However, as Bakshi, Carr, and Wu (2008) point out, prices of options on the cross rates (e.g., options on GBP/JPY) also provide valuable information. As equations (22) and (24) illustrate, those option prices depend crucially on parameters in a joint model that do not show up in options on the exchange rate against the USD.

Joint modeling of risk premiums. The primary focus of our paper is on the higher order moments of excess currency returns rather than the drift. Nevertheless, in a joint model of excess currency returns one might wish to appeal to economic theory and impose some restrictions on the drift of exchange rates. For example, it might seem reasonable to impose the restriction that only shocks that affect all exchange rates are priced (i.e., command an excess return).

However, there are few important (and perhaps obvious) caveats to be aware of when imposing assumptions about priced risks in models of exchange rates. First, the expected excess return on any currency depends on the base currency against which it is measured.

For example, suppose that the expected log excess return on the JPY against the USD is positive, but it is smaller than that of the GBP against the USD. Then, as equation (22) illustrates, the expected log excess return on the JPY against the GBP will switch signs and be negative. Therefore, the notion of whether a currency carries a positive risk premium, a negative risk premium, or no risk premium is completely dependent on the base currency against which the expected excess return is measured.

The second item to note from equation (22) is that the notion of whether a shock affects all currencies (and, therefore, economic theory suggests that it should be priced) also depends on the particular choice of base currency against which exchange rates are measured. For example, as equation (22) illustrates, if we measure exchange rates relative to GBP as the base currency, then the normal shock, w_{2t+1}^s , affects all of the exchange rates. Conversely, if we measure exchange rates relative to JPY as the base currency, then the normal shock, w_{3t+1}^s , affects all of the exchange rates. Given the fact that there are a number of major currencies in the world, the choice of one particular currency to always serve as the base currency against which to measure excess returns and characterize global shocks seems somewhat arbitrary.

Finally, even if we're comfortable choosing a single currency, such as USD, against which to measure excess returns (and hence risk premiums), it's certainly not obvious which shocks one should assume are priced. For example, suppose that a shock affects USD/AUD and USD/GBP, but not USD/JPY. Such a shock does not affect all exchange rates (against the USD), but it affects more than one exchange rate. Therefore, it's not clear whether this shock should be considered to be systematic or global (in which case, economic theory would suggest that it may be priced and carry a risk premium against the base currency), or whether it should be considered to be unsystematic or local (in which case, economic theory would suggest that it should not carry a risk premium).

As we noted in Appendix V.A, we can equivalently express our model of bilateral log excess currency returns as the difference between log affine m and \tilde{m} . The same holds true in a joint model of log excess currency returns. At first glance, it may appear that formulating the model as a difference between pricing kernels leads to important restrictions on the drift of exchange rates in a joint model. These restrictions could have been overlooked in the discussion above that is based on direct exchange rate modeling. So, one may argue that even if there are no additional restrictions on parameters controlling the distribution of risks, there are advantages in joint modeling of risk premiums.

To illustrate, we expand on the model described in equation (21),

$$(25) \quad y_{i,t+1} = s_{i,t+1} - s_{i,t} - r_t + \tilde{r}_{i,t} = \mu_i + \sigma_{i,g} w_{t+1}^g + \sigma_{i,\ell} w_{i,t+1}^\ell,$$

where w_{t+1}^g is a standard normal shock that affects all exchange rates against the dollar, and $w_{i,t+1}^\ell$ and $w_{j,t+1}^\ell$ are standard normal shocks that are uncorrelated for $i \neq j$. Many researchers like to think of these shocks as global and local, respectively. In the notation of equation (21), this model corresponds to

$$\text{corr}(w_{it+1}^s, w_{jt+1}^s) = \rho_{ij} = \sigma_{i,g} \sigma_{j,g} [(\sigma_{i,g}^2 + \sigma_{i,\ell}^2)(\sigma_{j,g}^2 + \sigma_{j,\ell}^2)]^{-1/2}.$$

Suppose that one wanted to write the model in equation (25) as the difference between log pricing kernels denominated in different currencies. Let m denote an exponential affine pricing kernel denominated in dollars and let \tilde{m}_i denote that pricing kernel denominated in foreign currency i . One model of m and \tilde{m}_i 's that captures the same covariance structure of exchange rates in equation (25) is

$$(26a) \quad \log m_{t+1} = -r_t - \underbrace{\lambda_g w_{t+1}^g}_{\lambda \cdot x_{t+1}} - \underbrace{\frac{1}{2} \lambda_g^2}_{\alpha}$$

and

$$(26b) \quad \log \tilde{m}_{i,t+1} = -\tilde{r}_{i,t} - \underbrace{\left(\tilde{\lambda}_{i,g} w_{t+1}^g + \tilde{\lambda}_{i,\ell} w_{i,t+1}^\ell \right)}_{\tilde{\lambda}_i \cdot x_{t+1}} - \underbrace{\frac{1}{2} \left(\tilde{\lambda}_{i,g}^2 + \tilde{\lambda}_{i,\ell}^2 \right)}_{\tilde{\alpha}_i},$$

because in that case,

$$(27) \quad \begin{aligned} y_{i,t+1} &= \log \tilde{m}_{i,t+1} - \log m_{t+1} - (r_t - \tilde{r}_{i,t}), \\ &= \frac{1}{2} \left(\lambda_g^2 - \tilde{\lambda}_{i,g}^2 - \tilde{\lambda}_{i,\ell}^2 \right) + \left(\lambda_g - \tilde{\lambda}_{i,g} \right) w_{t+1}^g - \tilde{\lambda}_{i,\ell} w_{i,t+1}^\ell. \end{aligned}$$

If we compare equations (25) and (27), both formulations capture the same covariance structure of exchange rates, with the mapping $\sigma_{i,g} = \lambda_g - \tilde{\lambda}_{i,g}$ and $\sigma_{i,\ell} = \tilde{\lambda}_{i,\ell}$. However, the two formulations have a different number of parameters. With n foreign exchange rates against the dollar (and therefore $n+1$ currencies including the dollar), in general, the formulation in equation (25) has n free drift parameters (i.e., μ_i for each of the n exchange rates), and $2n$ covariance parameters ($\sigma_{i,g}$, and $\sigma_{i,\ell}$ for $i = 1, \dots, n$), for a total of $3n$ parameters. By contrast, the formulation in equation (27) only has $2n+1$ free parameters (λ_g , plus $\tilde{\lambda}_{i,g}$ and $\tilde{\lambda}_{i,\ell}$ for $i = 1, \dots, n$). Because both of the formulations capture the same covariance structure of exchange rates dynamics, which requires $2n$ parameters, the formulation in equation (27) leaves only one free parameter (as opposed to n free parameters) for the drift of the n exchange rates. These observations might lead one to conclude that formulating the model as a difference between pricing kernels leads to tight restrictions on risk premiums.

In fact, there is an infinite number of models that imply the same covariance structure of exchange rates, but different expected excess returns. This is because formulating the model as a difference between pricing kernels does not in fact impose any restrictions on its conditional mean. For example, consider another model of m and \tilde{m}_i 's

$$(28a) \quad \log m_{t+1} = -r_t - \underbrace{\left(\lambda_{1,\ell} w_{1,t+1}^\ell + \dots + \lambda_{n,\ell} w_{n,t+1}^\ell \right)}_{\lambda \cdot x_{t+1}} - \underbrace{\frac{1}{2} \left(\lambda_{1,\ell}^2 + \dots + \lambda_{n,\ell}^2 \right)}_{\alpha}$$

and

$$(28b) \quad \log \tilde{m}_{i,t+1} = -\tilde{r}_{i,t} - \underbrace{\left(\tilde{\lambda}_{i,g} w_{t+1}^g + \tilde{\lambda}_{i,\ell} w_{i,t+1}^\ell \right)}_{\tilde{\lambda}_i \cdot x_{t+1}} - \underbrace{\frac{1}{2} \left(\tilde{\lambda}_{i,g}^2 + \tilde{\lambda}_{i,\ell}^2 \right)}_{\tilde{\alpha}_i}.$$

This formulation also captures the covariance structure of exchange rates in equation (25), with the mapping $\sigma_{i,g} = -\tilde{\lambda}_{i,g}$ and $\sigma_{i,\ell} = -\lambda_{i,\ell} - \tilde{\lambda}_{i,\ell}$. Yet, it has $3n$ parameters ($\tilde{\lambda}_{i,g}$, $\tilde{\lambda}_{i,\ell}$, and $\lambda_{i,\ell}$ for $i = 1, \dots, n$), and therefore it does not impose any restrictions on the drift of the exchange rates (i.e., there is a one-to-one mapping between the model formulations in equations (25) and (28)).

Thus, it is necessary to consider the first moment of currency returns along with their higher-order moments to identify a pricing kernel. Our model is more rich than the simple example, and therefore the first moment of currency returns is not sufficient to identify a pricing kernel. Instead, in our richer framework, one must also consider the returns on currency options with different strikes/maturities, as pointed out in Appendix V.A.

VI Expected future variance

We do not consider the most general model to streamline the presentation. We focus on the empirically relevant case where intensity of jumps in variance depends on variance only, and jumps up (down) in FX depend on domestic (foreign) interest rate only. We start by computing expectation of the variance process in

$$v_{t+1} = (1 - \nu)v + \nu v_t + \sigma_v v_t^{1/2} \omega_{t+1}^v + z_{t+1}^v.$$

Conditional expectation $E_t(v_{t+\tau}) \equiv v_{t,\tau}$ can be computed via a recursion. Note that $v_{t,0} = v_t$. Suppose we know $v_{t,\tau-1}$. Then

$$\begin{aligned} v_{t,\tau} &= (1 - \nu)v + \nu v_{t,\tau-1} + \sigma_v E_t(E_{t+\tau-1}(v_{t+\tau-1}^{1/2} w_{t+\tau}^v)) + E_t(E_{t+\tau-1} z_{t+\tau}^v) \\ &= (1 - \nu)v + \nu v_{t,\tau-1} + \theta_v h_0^v + \theta_v h_v^v v_{t,\tau-1} = (1 - \nu)v + \theta_v h_0^v + (\nu + \theta_v h_v^v) v_{t,\tau-1}. \end{aligned}$$

We can solve this recursion analytically:

$$\begin{aligned} v_{t,\tau} &= [(1 - \nu)v + \theta_v h_0^v](1 + (\nu + \theta_v h_v^v)) + (\nu + \theta_v h_v^v)^2 v_{t,\tau-2} \\ &= [(1 - \nu)v + \theta_v h_0^v](1 - (\nu + \theta_v h_v^v)^\tau)/(1 - (\nu + \theta_v h_v^v)) + (\nu + \theta_v h_v^v)^\tau v_t. \end{aligned}$$

Next, we can compute expectation of average future v :

$$\begin{aligned} E_t \left(\sum_{\tau=1}^n v_{t+\tau} \right) / n &= 1/n \sum_{\tau=1}^n E_t v_{t+\tau} = 1/n \sum_{\tau=1}^n v_{t,\tau} \\ &= 1/n \sum_{\tau=1}^n [(1 - \nu)v + \theta_v h_0^v](1 - (\nu + \theta_v h_v^v)^\tau)/(1 - (\nu + \theta_v h_v^v)) + 1/n \sum_{\tau=1}^n (\nu + \theta_v h_v^v)^\tau v_t \\ &= \frac{(1 - \nu)v + \theta_v h_0^v}{1 - (\nu + \theta_v h_v^v)} \left[1 - \frac{\nu + \theta_v h_v^v}{n} \frac{1 - (\nu + \theta_v h_v^v)^n}{1 - (\nu + \theta_v h_v^v)} \right] + \frac{\nu + \theta_v h_v^v}{n} \frac{1 - (\nu + \theta_v h_v^v)^n}{1 - (\nu + \theta_v h_v^v)} v_t \\ &\equiv \underbrace{\frac{(1 - \nu)v + \theta_v h_0^v}{1 - (\nu + \theta_v h_v^v)}}_{\alpha_n} [1 - \beta_n] + \beta_n v_t. \end{aligned}$$

Similarly, we can obtain conditional expectations of future interest rates:

$$r_{t,\tau} \equiv E_t(r_{t+\tau}) = a_r(1 - b_r^\tau) + b_r^\tau r_t,$$

and the expectations of average future interest rates:

$$\begin{aligned} E_t \left(\sum_{\tau=1}^n r_{t+\tau} \right) / n &= \frac{1}{n} \sum_{\tau=1}^n E_t r_{t+\tau} = \frac{1}{n} \sum_{\tau=1}^n r_{t,\tau} \\ &= a_r \left[1 - \frac{b_r}{n} \frac{1 - b_r^n}{1 - b_r} \right] + \frac{b_r}{n} \frac{1 - b_r^n}{1 - b_r} r_t \end{aligned}$$

and the similar expression holds for expectations associated with \tilde{r}_t .

Now, we can characterize the variance of excess returns:

$$v_t^y \equiv \text{var}_t(y_{t+1}) = v_t + 2h_t^u \theta_u^2 + 2h_t^d \theta_d^2.$$

Therefore, the conditional expectation of this variance can be computed on the basis of our results for the variance of the normal component v_t and the expectations of interest rates:

$$v_{t,\tau}^y \equiv E_t(v_{t+\tau}^y) = v_{t,\tau} + 2\theta_u^2 h_0^u + 2\theta_u^2 h_r^u E_t(r_{t+\tau}) + 2\theta_d^2 h_0^d + 2\theta_d^2 \tilde{h}_r^d E_t(\tilde{r}_{t+\tau}).$$

This expression implies that the unconditional expectation, or long-run mean, of the variance is:

$$\begin{aligned} v_J = \lim_{i \rightarrow \infty} v_{t,\tau}^y &= [(1 - \nu)v + \theta_v h_0^v] / (1 - (\nu + \theta_v h_v^v)) \\ &+ 2\theta_u^2 h_0^u + 2\theta_u^2 h_r^u a_r + 2\theta_d^2 h_0^d + 2\theta_d^2 \tilde{h}_r^d \tilde{a}_r. \end{aligned}$$

When there are no jumps, that is, $\theta_v = 0$, $\theta_u = 0$, and $\theta_d = 0$, then $v_J = v$.

Next, we compute $E_t(\sum_{\tau=1}^n v_{t+\tau}^y) / n$

$$\begin{aligned} E_t \left(\sum_{\tau=1}^n v_{t+\tau}^y \right) / n &= \frac{1}{n} \sum_{\tau=1}^n E_t v_{t+\tau}^y = \frac{1}{n} \sum_{\tau=1}^n v_{t,\tau}^y \\ &= \alpha_n + 2\theta_u^2 h_0^u + 2\theta_u^2 h_r^u a_r \left[1 - \frac{b_r}{n} \frac{1 - b_r^n}{1 - b_r} \right] + 2\theta_d^2 h_0^d + 2\theta_d^2 \tilde{h}_r^d \tilde{a}_r \left[1 - \frac{\tilde{b}_r}{n} \frac{1 - \tilde{b}_r^n}{1 - \tilde{b}_r} \right] \\ &+ \beta_n v_t + 2\theta_u^2 h_r^u \frac{b_r}{n} \frac{1 - b_r^n}{1 - b_r} r_t + 2\theta_d^2 \tilde{h}_r^d \frac{\tilde{b}_r}{n} \frac{1 - \tilde{b}_r^n}{1 - \tilde{b}_r} \tilde{r}_t. \end{aligned}$$

VII Computing entropy

Entropy of currency changes over a horizon of n days is equal to:

$$L_t(S_{t+n}/S_t) = \log E_t(e^{x_{t,n}}) - E_t(x_{t,n}) = k_t(1; x_{t,n}) - \kappa_{1t}(x_{t,n}),$$

where $x_{t,n} = \log(S_{t+n}/S_t) = \sum_{\tau=t}^{t+n} (s_{\tau+1} - s_\tau)$, $k_t(s; x_{t,n})$ is a cumulant-generating function of $x_{t,n}$, and $\kappa_{1t}(x_{t,n})$ is the first cumulant of $x_{t,n}$. Thus, we need to compute the cumulant-generating function of $x_{t,n}$:

$$k_t(s; x_{t,n}) = \log E_t e^{s x_{t,n}}.$$

The first cumulant can be recovered as $\partial k_t(s; x_{t,n})/\partial s$ at $s = 0$. Denote the drift of log currency changes by $\bar{\mu}_t = \mu_t + (r_t - \tilde{r}_t)$.

Guess

$$k_t(s; x_{t,n}) = A(n) + B_v(n)v_t + B_r(n)r_t + \tilde{B}_r(n)\tilde{r}_t.$$

Then

$$\begin{aligned} & A(n) + B_v(n)v_t + B_r(n)r_t + \tilde{B}_r(n)\tilde{r}_t \\ = & k(s; x_{t,n}) = \log E_t [e^{s x_{t,1}} E_{t+1} e^{s x_{t+1,n-1}}] \\ = & \log E_t [e^{s x_{t,1}} e^{A(n-1) + B_v(n-1)v_{t+1} + B_r(n-1)r_{t+1} + \tilde{B}_r(n-1)\tilde{r}_{t+1}}] \\ = & A(n-1) + \log E_t e^{s x_{t,1} + B_v(n-1)v_{t+1}} + \log E_t e^{B_r(n-1)r_{t+1} + \tilde{B}_r(n-1)\tilde{r}_{t+1}} \\ = & A(n-1) + s\bar{\mu}_t + B_v(n-1)((1-\nu)v + \nu v_t) \\ & + B_r(n-1)((1-b_r)a_r + b_r r_t) + \tilde{B}_r(n-1)((1-\tilde{b}_r)\tilde{a}_r + \tilde{b}_r \tilde{r}_t) \\ & + \log E_t e^{s(1-\rho^2)^{1/2} v_t^{1/2} w_{t+1}^s + s\rho v_t^{1/2} w_{t+1}^v + s z_{t+1}^u + s z_{t+1}^d + B_v(n-1)\sigma_v v_t^{1/2} w_{t+1}^v + B_v(n-1)z_{t+1}^v} \\ & + \log E_t e^{B_r(n-1)r_t^{1/2} \sigma_r w_{t+1}^r + \tilde{B}_r(n-1)\tilde{r}_t^{1/2} \tilde{\sigma}_r \tilde{w}_{t+1}^r} \\ = & A(n-1) + s\bar{\mu}_t + B_v(n-1)((1-\nu)v + \nu v_t) \\ & + B_r(n-1)((1-b_r)a_r + b_r r_t) + \tilde{B}_r(n-1)((1-\tilde{b}_r)\tilde{a}_r + \tilde{b}_r \tilde{r}_t) \\ & + s^2 v_t/2 + v_t s \rho \sigma_v B_v(n-1) + B_v^2(n-1)\sigma_v^2 v_t/2 + h_t^u((1-s\theta_u)^{-1} - 1) \\ & + h_t^d((1+s\theta_d)^{-1} - 1) + h_t^v((1-B_v(n-1)\theta_v)^{-1} - 1) + B_r^2(n-1)\sigma_r^2 r_t/2 \\ & + \tilde{B}_r^2(n-1)\tilde{\sigma}_r^2 \tilde{r}_t/2 \\ = & A(n-1) + s(\mu + (\mu_r + 1)(r_t - \tilde{r}_t) + \mu_v v_t) + B_v(n-1)((1-\nu)v + \nu v_t) \\ & + B_r(n-1)((1-b_r)a_r + b_r r_t) + \tilde{B}_r(n-1)((1-\tilde{b}_r)\tilde{a}_r + \tilde{b}_r \tilde{r}_t) \\ & + s^2 v_t/2 + v_t s \rho \sigma_v B_v(n-1) + B_v^2(n-1)\sigma_v^2 v_t/2 + s\theta_u(h_0^u + h_r^u r_t)/(1-s\theta_u) \\ & - s\theta_d(h_0^d + \tilde{h}_r^d \tilde{r}_t)/(1+s\theta_d) + (h_0^v + h_v^v v_t)B_v(n-1)\theta_v/(1-B_v(n-1)\theta_v) \\ & + B_r^2(n-1)\sigma_r^2 r_t/2 + \tilde{B}_r^2(n-1)\tilde{\sigma}_r^2 \tilde{r}_t/2. \end{aligned}$$

Collect terms, match them with the corresponding terms in the first line, solve for the coefficients:

$$\begin{aligned} A(n) &= A(n-1) + s\mu + B_v(n-1)(1-\nu)v + s\theta_u h_0^u/(1-s\theta_u) - s\theta_d h_0^d/(1+s\theta_d) \\ &\quad + h_0^v B_v(n-1)\theta_v/(1-\theta_v B_v(n-1)) + B_r(n-1)(1-b_r)a_r + \tilde{B}_r(n-1)(1-\tilde{b}_r)\tilde{a}_r \\ B_v(n) &= s\mu_v + B_v(n-1)\nu + s^2/2 + s\rho\sigma_v B_v(n-1) + B_v^2(n-1)\sigma_v^2/2 \\ &\quad + h_v^v B_v(n-1)\theta_v/(1-B_v(n-1)\theta_v), \\ B_r(n) &= s(\mu_r + 1) + B_r(n-1)b_r + s\theta_u h_r^u/(1-s\theta_u) + B_r^2(n-1)\sigma_r^2/2, \\ \tilde{B}_r(n) &= -s(\mu_r + 1) + \tilde{B}_r(n-1)\tilde{b}_r - s\theta_d \tilde{h}_r^d/(1+s\theta_d) + \tilde{B}_r^2(n-1)\tilde{\sigma}_r^2/2. \end{aligned}$$

To compute initial conditions for the above recursion, write down the cumulant generating function of a one-period return:

$$k_t(s; x_{t,1}) = s\bar{\mu}_t + s^2 v_t/2 + (h_0^u + h_r^u r_t) \frac{s\theta_u}{1 - s\theta_u} - (h_0^d + \tilde{h}_r^d \tilde{r}_t) \frac{s\theta_d}{1 + s\theta_d}.$$

Therefore,

$$\begin{aligned} A(1) &= s\mu + h_0^u \frac{s\theta_u}{1 - s\theta_u} - h_0^d \frac{s\theta_d}{1 + s\theta_d}, \\ B_v(1) &= s\mu_v + s^2/2, \\ B_r(1) &= s(\mu_r + 1) + s\theta_u h_r^u / (1 - s\theta_u), \\ \tilde{B}_r(1) &= -s(\mu_r + 1) - s\theta_d \tilde{h}_r^d / (1 + s\theta_d). \end{aligned}$$

VIII The estimation algorithm

In this section we outline the estimation algorithm for the Preferred model. We estimate the discrete time model on the basis of daily data. We assume that there is no more than one jump per day. We re-write our model using notation that is more convenient for estimation purposes:

$$\begin{aligned} y_{t+1} &= \mu_0 + \mu_r(r_t - \tilde{r}_t) + \mu_v v_t + v_t^{1/2} w_{t+1}^s + \bar{z}_{t+1}^u \bar{j}_{t+1}^u - \bar{z}_{t+1}^d \bar{j}_{t+1}^d, \\ v_{t+1} &= (1 - \nu)v + \nu v_t + \sigma_v v_t^{1/2} w_{t+1}^v + \bar{z}_{t+1}^v \bar{j}_{t+1}^v, \\ (29) \quad IV_t &= \alpha_{iv} + \beta_{iv} v_t + \sigma_{iv} v_t \sqrt{\lambda_t} \varepsilon_t. \end{aligned}$$

Indicator \bar{j}_t^k , $k = \{u, d, v\}$, is equal to one if there is a jump at t , and zero otherwise. Correspondingly, \bar{z}_t^k is a jump size:

$$\begin{aligned} \bar{z}_t^u &\sim \mathcal{Exp}(\theta), \\ \bar{z}_t^d &\sim \mathcal{Exp}(\theta), \\ \bar{z}_t^v &\sim \mathcal{Exp}(\theta_v). \end{aligned}$$

Introduce new notations: $\psi = \rho\sigma_v$, $\eta = \sigma_v^2(1 - \rho^2)$, $\alpha = (1 - \nu)v$, $\beta = \nu$, and Θ is the collection of all parameters. Denote the full history of excess returns, variance, implied variance, domestic and foreign interest rates, jump times and sizes by Y , V , IV , R , \tilde{R} , \bar{J}^k , \bar{Z}^k ($k = \{u, d, v\}$), respectively. All the data are available on the interval $t \in [1, T]$, except for the implied variance which is available on the interval $t \in [T_2 + 1, T]$, $T_2 > 0$.

Posterior distributions for the parameters

- Assume a normal prior for μ_0 : $\mu_0 \sim N(a, A)$.

Posterior distribution is

$$p(\mu_0|Y, V, \bar{Z}^u, \bar{Z}^d, \bar{Z}^v, \bar{J}^u, \bar{J}^d, \bar{J}^v, R, \tilde{R}, \Theta_{\{-\mu_0\}}) \propto N(\hat{a}, \hat{A}),$$

where

$$\begin{aligned}\hat{A} &= \left(\frac{1}{A} + \left(\frac{\psi^2}{\eta} + 1 \right) \sum_{t=0}^{T-1} \frac{1}{v_t} \right)^{-1}, \\ \hat{a} &= \hat{A} \left(\frac{a}{A} + \left(\frac{\psi^2}{\eta} + 1 \right) \sum_{t=0}^{T-1} \frac{y_{t+1} - \mu_r(r_t - \tilde{r}_t) - \mu_v v_t - \bar{z}_{t+1}^u \bar{j}_{t+1}^u + \bar{z}_{t+1}^d \bar{j}_{t+1}^d}{v_t} \right) - \\ &\quad - \hat{A} \left(\frac{\psi}{\eta} \sum_{t=0}^{T-1} \frac{(v_{t+1} - \alpha - \beta v_t - \bar{z}_{t+1}^v \bar{j}_{t+1}^v)}{v_t} \right).\end{aligned}$$

- Assume a normal prior for μ_v : $\mu_v \sim N(a, A)$.

Posterior distribution is

$$p(\mu_v|Y, V, \bar{Z}^u, \bar{Z}^d, \bar{Z}^v, \bar{J}^u, \bar{J}^d, \bar{J}^v, R, \tilde{R}, \Theta_{\{-\mu_v\}}) \propto N(\hat{a}, \hat{A}),$$

where

$$\begin{aligned}\hat{A} &= \left(\frac{1}{A} + \left(\frac{\psi^2}{\eta} + 1 \right) \sum_{t=0}^{T-1} v_t \right)^{-1}, \\ \hat{a} &= \hat{A} \left(\frac{a}{A} + \left(\frac{\psi^2}{\eta} + 1 \right) \sum_{t=0}^{T-1} (y_{t+1} - \mu_0 - \mu_r(r_t - \tilde{r}_t) - \bar{z}_{t+1}^u \bar{j}_{t+1}^u + \bar{z}_{t+1}^d \bar{j}_{t+1}^d) \right) - \\ &\quad - \hat{A} \left(\frac{\psi}{\eta} \sum_{t=0}^{T-1} (v_{t+1} - \alpha - \beta v_t - \bar{z}_{t+1}^v \bar{j}_{t+1}^v) \right).\end{aligned}$$

- Assume a normal prior for μ_r : $\mu_r \sim N(a, A)$.

Posterior distribution is

$$p(\mu_r|Y, V, \bar{Z}^u, \bar{Z}^d, \bar{Z}^v, \bar{J}^u, \bar{J}^d, \bar{J}^v, R, \tilde{R}, \Theta_{\{-\mu_r\}}) \propto N(\hat{a}, \hat{A})$$

where

$$\begin{aligned}\hat{A} &= \left(\frac{1}{A} + \left(\frac{\psi^2}{\eta} + 1 \right) \sum_{t=0}^{T-1} \frac{(r_t - \tilde{r}_t)^2}{v_t} \right)^{-1}, \\ \hat{a} &= \hat{A} \left(\frac{a}{A} + \left(\frac{\psi^2}{\eta} + 1 \right) \sum_{t=0}^{T-1} \frac{(y_{t+1} - \mu_0 - \mu_v v_t - \bar{z}_{t+1}^u \bar{j}_{t+1}^u + \bar{z}_{t+1}^d \bar{j}_{t+1}^d)(r_t - \tilde{r}_t)}{v_t} \right) - \\ &\quad - \hat{A} \left(\frac{\psi}{\eta} \sum_{t=0}^{T-1} \frac{(r_t - \tilde{r}_t)(v_{t+1} - \alpha - \beta v_t - \bar{z}_{t+1}^v \bar{j}_{t+1}^v)}{v_t} \right).\end{aligned}$$

- Assume a normal prior for α : $\alpha \sim N(a, A)$.

Posterior distribution is

$$p(\alpha|Y, V, \bar{Z}^u, \bar{Z}^d, \bar{Z}^v, \bar{J}^u, \bar{J}^d, \bar{J}^v, \Theta_{\{-\alpha\}}) \propto N(\hat{a}, \hat{A}),$$

where

$$\begin{aligned} \hat{A} &= \left(\frac{1}{A} + \frac{1}{\eta} \sum_{t=0}^{T-1} \frac{1}{v_t} \right)^{-1}, \\ \hat{a} &= \hat{A} \left(\frac{a}{A} + \frac{1}{\eta} \sum_{t=0}^{T-1} \frac{v_{t+1} - \beta v_t - \bar{j}_{t+1}^v \bar{z}_{t+1}^v}{v_t} \right) - \\ &\quad - \hat{A} \left(\frac{\psi}{\eta} \sum_{t=0}^{T-1} \frac{(y_{t+1} - \mu_0 - \mu_r(r_t - \tilde{r}_t) - \mu_v v_t - \bar{j}_{t+1}^u \bar{z}_{t+1}^u + \bar{j}_{t+1}^d \bar{z}_{t+1}^d)}{v_t} \right). \end{aligned}$$

- Assume a normal prior for β : $\beta \sim N(a, A)$.

Posterior distribution is

$$p(\beta|Y, V, \bar{Z}^u, \bar{Z}^d, \bar{Z}^v, \bar{J}^u, \bar{J}^d, \bar{J}^v, \Theta_{\{-\beta\}}) \propto N(\hat{a}, \hat{A}),$$

where

$$\begin{aligned} \hat{A} &= \left(\frac{1}{A} + \frac{1}{\eta} \sum_{t=0}^{T-1} v_t \right)^{-1}, \\ \hat{a} &= \hat{A} \left(\frac{a}{A} + \sum_{t=0}^{T-1} \frac{v_{t+1} - \alpha - \bar{j}_{t+1}^v \bar{z}_{t+1}^v}{\eta} \right) - \\ &\quad - \hat{A} \left(\frac{\psi}{\eta} \sum_{t=0}^{T-1} (y_{t+1} - \mu_0 - \mu_r(r_t - \tilde{r}_t) - \mu_v v_t - \bar{j}_{t+1}^u \bar{z}_{t+1}^u + \bar{j}_{t+1}^d \bar{z}_{t+1}^d) \right). \end{aligned}$$

- Assume dependent normal-inverse gamma priors for ψ and η :

$$\begin{aligned} \psi|\eta &\sim N(a, A\eta), \\ \eta &\sim IG(b, B). \end{aligned}$$

Posterior distributions are

$$\begin{aligned} p(\psi|Y, V, \bar{Z}^u, \bar{Z}^d, \bar{Z}^v, \bar{J}^u, \bar{J}^d, \bar{J}^v, R, \tilde{R}, \Theta_{\{-\psi\}}) &\propto N(\hat{a}, \hat{A}\eta), \\ p(\eta|Y, V, \bar{Z}^v, \bar{J}^v, R, \tilde{R}, \Theta_{\{-\eta\}}) &\propto IG(\hat{b}, \hat{B}), \end{aligned}$$

where

$$\begin{aligned}\hat{A} &= \left(\sum_{t=0}^{T-1} (w_{t+1}^s)^2 + \frac{1}{A} \right)^{-1}, \\ \hat{a} &= \hat{A} \left(\frac{a}{A} + \sum_{t=0}^{T-1} \xi_{t+1} w_{t+1}^s \right), \\ \hat{b} &= b + \frac{T}{2}, \\ \hat{B} &= B + \frac{1}{2} \sum_{t=0}^{T-1} \xi_{t+1}^2 + \frac{a^2}{2A} - \frac{\hat{a}^2}{2\hat{A}}, \\ \xi_{t+1} &= \frac{v_{t+1} - \alpha - \beta v_t - \bar{j}_{t+1}^v \bar{z}_{t+1}^v}{\sqrt{v_t}}.\end{aligned}$$

- Assume a normal prior for α_{iv} : $\alpha_{iv} \sim N(a, A)$.

Posterior distribution is

$$p(\alpha_{iv} | \beta_{iv}, \sigma_{iv}, IV, \{\lambda_t\}_{t=T_2+1}^T, \{v_t\}_{t=T_2+1}^T) \propto N(\hat{a}, \hat{A}),$$

where

$$\begin{aligned}\hat{A} &= \left(\frac{1}{A} + \sum_{t=T_2+1}^T \frac{1}{\sigma_{iv}^2 v_t^2 \lambda_t} \right)^{-1}, \\ \hat{a} &= \hat{A} \left(\frac{1}{\sigma_{iv}^2} \sum_{t=T_2+1}^T \frac{IV_t - \beta_{iv} v_t}{v_t^2 \lambda_t} + \frac{a}{A} \right).\end{aligned}$$

- Assume a normal prior for β_{iv} : $\beta_{iv} \sim N(a, A)$.

Posterior distribution is

$$p(\beta_{iv} | \alpha_{iv}, \sigma_{iv}, IV, \{\lambda_t\}_{t=T_2+1}^T, \{v_t\}_{t=T_2+1}^T) \propto N(\hat{a}, \hat{A}),$$

where

$$\begin{aligned}\hat{A} &= \left(\frac{1}{A} + \sum_{t=T_2+1}^T \frac{1}{\sigma_{iv}^2 \lambda_t} \right)^{-1}, \\ \hat{a} &= \hat{A} \left(\frac{1}{\sigma_{iv}^2} \sum_{t=T_2+1}^T \frac{IV_t - \alpha_{iv}}{v_t \lambda_t} + \frac{a}{A} \right).\end{aligned}$$

- Assume an inverse-gamma prior for σ_{iv}^2 : $\sigma_{iv}^2 \sim IG(b, B)$.

Posterior distribution is

$$p(\sigma_{iv}^2 | \alpha_{iv}, \beta_{iv}, \{v_t\}_{t=T_2+1}^T, IV, \{\lambda_t\}_{t=T_2+1}^T) \propto IG(\hat{b}, \hat{B}),$$

where

$$\hat{b} = b + \frac{T - T_2}{2},$$

$$\hat{B} = B + \sum_{t=T_2+1}^T \frac{(IV_t - \alpha_{iv} - \beta_{iv}v_t)^2}{2\lambda_t v_t^2}.$$

- Assume an inverse-gamma prior for θ_v : $\theta_v \sim IG(b, B)$.

Posterior distribution is

$$p(\theta_v | \bar{Z}^v) \propto p(\bar{Z}^v | \theta_v) p(\theta_v) \propto IG(\hat{b}, \hat{B}),$$

where

$$\hat{b} = b + T,$$

$$\hat{B} = B + \sum_{t=1}^T \bar{z}_t^v.$$

- Assume an inverse-gamma prior for θ : $\theta \sim IG(b, B)$.

Posterior distribution is

$$p(\theta | \bar{Z}^u, \bar{Z}^d) \propto p(\bar{Z}^u, \bar{Z}^d | \theta) p(\theta) \propto IG(\hat{b}, \hat{B}),$$

where

$$\hat{b} = b + 2T,$$

$$\hat{B} = B + \sum_{t=1}^T (\bar{z}_t^u - \bar{z}_t^d).$$

- We use the Metropolis-Hastings Random Walk algorithm to estimate the parameters of the jump intensities. In particular, we draw parameters in pairs – h_0^v and h_v ; h_0 and h_r . Also, we draw these parameters in logs to guarantee that jump intensities stay strictly positive.

Posterior distributions for the latent variables

We have eight unobservable objects in the model: variance, three paths of the jump times, three paths of the jump sizes, and λ_t .

For each $t \in [T_2 + 1, T]$:

- Prior distribution for λ_t is $IG(\frac{\nu}{2}, \frac{\nu}{2})$.

The posterior distribution is

$$p(\lambda_t | IV_t, v_t, \alpha_{iv}, \beta_{iv}, \sigma_{iv}, \nu) \propto IG\left(\frac{\nu}{2} + \frac{1}{2}, \frac{\nu}{2} + \frac{(IV_t - \alpha_{iv} - \beta_{iv}v_t)^2}{2\sigma_{iv}^2 v_t^2}\right).$$

For each $t \in [1, T]$:

- Jumps in variance arrive with a time-varying intensity $h_t^v = h_0^v + h_v v_t$, i.e., $p(\bar{j}_{t+1}^v = 1) = h_t^v$. The posterior distribution for the jump in variance is the Bernoulli distribution with the success probability equal to $b^v = \frac{p}{p+q}$, where

$$\begin{aligned} p &= h_t^v \exp\left(-\frac{X'_{t+1} \Sigma^{-1} X_{t+1}}{2}\right), \\ q &= (1 - h_t^v) \exp\left(-\frac{Y'_{t+1} \Sigma^{-1} Y_{t+1}}{2}\right), \\ X_{1,t+1} &= Y_{1,t+1} = \frac{y_{t+1} - \mu_0 - \mu_r(r_t - \tilde{r}_t) - \mu_v v_t - \bar{j}_{t+1}^u \bar{z}_{t+1}^u + \bar{j}_{t+1}^d \bar{z}_{t+1}^d}{\sqrt{v_t}}, \\ X_{2,t+1} &= \frac{v_{t+1} - \alpha - \beta v_t - \bar{z}_{t+1}^v}{\sqrt{v_t}}, \\ Y_{2,t+1} &= \frac{v_{t+1} - \alpha - \beta v_t}{\sqrt{v_t}}. \end{aligned}$$

and Σ denotes the variance-covariance matrix of $X_{t+1} = (X_{1,t+1} \ X_{2,t+1})'$ and $Y_{t+1} = (Y_{1,t+1} \ Y_{2,t+1})'$.

- The prior distribution for the size of the jump in variance \bar{z}_{t+1}^v is the exponential distribution with mean θ_v . Note that:

$$\begin{aligned} &p(\bar{z}_{t+1}^v | y_{t+1}, v_{t+1}, v_t, \bar{z}_{t+1}^u, \bar{z}_{t+1}^d, \bar{j}_{t+1}^u, \bar{j}_{t+1}^d, \bar{j}_{t+1}^v = 1, r_t, \tilde{r}_t, \Theta) \\ &\propto p(y_{t+1}, v_{t+1} | v_t, \bar{z}_{t+1}^u, \bar{z}_{t+1}^d, \bar{z}_{t+1}^v, \bar{j}_{t+1}^u, \bar{j}_{t+1}^d, \bar{j}_{t+1}^v = 1, r_t, \tilde{r}_t, \Theta) p(\bar{z}_{t+1}^v) \\ &\propto \exp\left(-\frac{X'_{t+1} \Sigma^{-1} X_{t+1}}{2}\right) \frac{1}{\theta_v} \exp\left(-\frac{\bar{z}_{t+1}^v}{\theta_v}\right) I_{(\bar{z}_{t+1}^v > 0)} \\ &\propto \exp\left(\frac{\psi}{\eta} X_{1,t+1} X_{2,t+1} - \frac{1}{2\eta} X_{2,t+1}^2\right) \exp\left(-\frac{\bar{z}_{t+1}^v}{\theta_v}\right) I_{(\bar{z}_{t+1}^v > 0)} \\ &\propto \exp\left(-\frac{(\bar{z}_{t+1}^v - m_{t+1})^2}{2M_{t+1}}\right) I_{(\bar{z}_{t+1}^v > 0)}, \end{aligned}$$

where

$$\begin{aligned} X_{1,t+1} &= \frac{y_{t+1} - \mu_0 - \mu_r(r_t - \tilde{r}_t) - \mu_v v_t - \bar{j}_{t+1}^u \bar{z}_{t+1}^u + \bar{j}_{t+1}^d \bar{z}_{t+1}^d}{\sqrt{v_t}}, \\ X_{2,t+1} &= \frac{v_{t+1} - \alpha - \beta v_t - \bar{z}_{t+1}^v}{\sqrt{v_t}}. \end{aligned}$$

Thus, the posterior distribution for \bar{z}_{t+1}^v is the truncated normal distribution with the parameters m_{t+1} (mean) and M_{t+1} (variance):

$$\begin{aligned} M_{t+1} &= \eta v_t, \\ m_{t+1} &= -\psi(y_{t+1} - \mu_0 - \mu_r(r_t - \tilde{r}_t) - \mu_v v_t - \bar{j}_{t+1}^u \bar{z}_{t+1}^u + \bar{j}_{t+1}^d \bar{z}_{t+1}^d) \\ &\quad + v_{t+1} - \alpha - \beta v_t - \frac{M_{t+1}}{\mu_z}. \end{aligned}$$

Correspondingly, $p(\bar{z}_{t+1}^v | \bar{j}_{t+1}^v = 0, \theta_v) \sim \mathcal{Exp}(\theta_v)$.

- Upward jumps in excess returns arrive with a time-varying intensity $h_t^u = h_0 + h_r r_t$, i.e., $p(\bar{j}_{t+1}^u = 1) = h_t^u$. The posterior distribution for the upward jump in excess returns is the Bernoulli distribution with the success probability $b^u = \frac{p}{p+q}$, where

$$\begin{aligned} p &= h_t^u \exp\left(-\frac{X'_{t+1} \Sigma^{-1} X_{t+1}}{2}\right), \\ q &= (1 - h_t^u) \exp\left(-\frac{Y'_{t+1} \Sigma^{-1} Y_{t+1}}{2}\right), \\ X_{1,t+1} &= \frac{y_{t+1} - \mu_0 - \mu_r(r_t - \tilde{r}_t) - \mu_v v_t - \bar{z}_{t+1}^u + \bar{j}_{t+1}^d \bar{z}_{t+1}^d}{\sqrt{v_t}}, \\ Y_{1,t+1} &= \frac{y_{t+1} - \mu_0 - \mu_r(r_t - \tilde{r}_t) - \mu_v v_t + \bar{j}_{t+1}^d \bar{z}_{t+1}^d}{\sqrt{v_t}}, \\ X_{2,t+1} &= Y_{2,t+1} = \frac{v_{t+1} - \alpha - \beta v_t - \bar{j}_{t+1}^v \bar{z}_{t+1}^v}{\sqrt{v_t}}, \end{aligned}$$

and Σ denotes the variance-covariance matrix of $X_{t+1} = (X_{1,t+1} \ X_{2,t+1})'$ and $Y_{t+1} = (Y_{1,t+1} \ Y_{2,t+1})'$.

- The prior distribution for the size of the upward jump in excess returns \bar{z}_{t+1}^u is the exponential distribution with the mean θ . Note that:

$$\begin{aligned} &p(\bar{z}_{t+1}^u | y_{t+1}, v_{t+1}, v_t, \bar{z}_{t+1}^d, \bar{z}_{t+1}^v, \bar{j}_{t+1}^u = 1, \bar{j}_{t+1}^d, \bar{j}_{t+1}^v, r_t, \tilde{r}_t, \Theta) \\ &\propto p(y_{t+1}, v_{t+1} | \bar{z}_{t+1}^u, \bar{z}_{t+1}^d, \bar{z}_{t+1}^v, \bar{j}_{t+1}^u = 1, \bar{j}_{t+1}^d, \bar{j}_{t+1}^v, v_t, r_t, \tilde{r}_t, \Theta) p(\bar{z}_{t+1}^u) \\ &\propto \exp\left(-\frac{X'_{t+1} \Sigma^{-1} X_{t+1}}{2}\right) \frac{1}{\theta} \exp\left(-\frac{\bar{z}_{t+1}^u}{\theta}\right) I_{(\bar{z}_{t+1}^u > 0)} \\ &\propto \exp\left(-\frac{1}{2} \left(1 + \frac{\psi^2}{\eta}\right) X_{1,t+1}^2 + \frac{\psi}{\eta} X_{1,t+1} X_{2,t+1}\right) \exp\left(-\frac{\bar{z}_{t+1}^u}{\theta}\right) I_{(\bar{z}_{t+1}^u > 0)} \\ &\propto \exp\left(-\frac{(\bar{z}_{t+1}^u - m_{t+1})^2}{2M_{t+1}}\right) I_{(\bar{z}_{t+1}^u > 0)}, \end{aligned}$$

where

$$X_{1,t+1} = \frac{y_{t+1} - \mu_0 - \mu_r(r_t - \tilde{r}_t) - \mu_v v_t - \bar{z}_{t+1}^u + \bar{j}_{t+1}^d \bar{z}_{t+1}^d}{\sqrt{v_t}},$$

$$X_{2,t+1} = \frac{v_{t+1} - \alpha - \beta v_t - \bar{j}_{t+1}^v \bar{z}_{t+1}^v}{\sqrt{v_t}}.$$

Thus, the posterior distribution for \bar{z}_{t+1}^u is the truncated normal distribution with the parameters m_{t+1} (mean) and M_{t+1} (variance):

$$M_{t+1} = \frac{v_t}{\left(1 + \frac{\psi^2}{\eta}\right)},$$

$$m_{t+1} = (y_{t+1} - \mu_0 - \mu_r(r_t - \tilde{r}_t) - \mu_v v_t + \bar{j}_{t+1}^d \bar{z}_{t+1}^d) - \frac{\psi}{(\eta + \psi^2)}(v_{t+1} - \alpha - \beta v_t - \bar{j}_{t+1}^v \bar{z}_{t+1}^v) - \frac{M_{t+1}}{\theta}.$$

Correspondingly, $p(\bar{z}_{t+1}^u | \bar{j}_{t+1}^u = 0, \theta) \sim \mathcal{Exp}(\theta)$.

- Downward jumps in excess returns arrive with a time-varying intensity $h_t^d = h_0 + h_r \tilde{r}_t$, i.e., $p(\bar{j}_{t+1}^d = 1) = h_t^d$. The posterior distribution for the downward jump in excess returns is the Bernoulli distribution with the success probability $b^d = \frac{p}{p+q}$, where

$$p = h_t^d \exp\left(-\frac{X'_{t+1} \Sigma^{-1} X_{t+1}}{2}\right),$$

$$q = (1 - h_t^d) \exp\left(-\frac{Y'_{t+1} \Sigma^{-1} Y_{t+1}}{2}\right),$$

$$X_{1,t+1} = \frac{y_{t+1} - \mu_0 - \mu_r(r_t - \tilde{r}_t) - \mu_v v_t + \bar{z}_{t+1}^d - \bar{j}_{t+1}^u \bar{z}_{t+1}^u}{\sqrt{v_t}},$$

$$Y_{1,t+1} = \frac{y_{t+1} - \mu_0 - \mu_r(r_t - \tilde{r}_t) - \mu_v v_t - \bar{j}_{t+1}^u \bar{z}_{t+1}^u}{\sqrt{v_t}},$$

$$X_{2,t+1} = Y_{2,t+1} = \frac{v_{t+1} - \alpha - \beta v_t - \bar{j}_{t+1}^v \bar{z}_{t+1}^v}{\sqrt{v_t}},$$

and Σ denotes the variance-covariance matrix of $X_{t+1} = (X_{1,t+1} \ X_{2,t+1})'$ and $Y_{t+1} = (Y_{1,t+1} \ Y_{2,t+1})'$.

- The prior distribution for the size of the downward jump in excess returns is the

exponential distribution with mean θ . Note that

$$\begin{aligned}
& p(\bar{z}_{t+1}^d | y_{t+1}, v_{t+1}, v_t, \bar{z}_{t+1}^u, \bar{z}_{t+1}^v, \bar{j}_{t+1}^u, \bar{j}_{t+1}^d = 1, \bar{j}_{t+1}^v, r_t, \tilde{r}_t, \Theta) \\
& \propto p(y_{t+1}, v_{t+1} | \bar{z}_{t+1}^u, \bar{z}_{t+1}^d, \bar{z}_{t+1}^v, \bar{j}_{t+1}^u, \bar{j}_{t+1}^d = 1, \bar{j}_{t+1}^v, v_t, r_t, \tilde{r}_t, \Theta) p(\bar{z}_{t+1}^d) \\
& \propto \exp\left(-\frac{X'_{t+1} \Sigma^{-1} X_{t+1}}{2}\right) \frac{1}{\theta} \exp\left(-\frac{\bar{z}_{t+1}^d}{\theta}\right) I_{(\bar{z}_{t+1}^d > 0)} \\
& \propto \exp\left(-\frac{1}{2} \left(1 + \frac{\psi^2}{\eta}\right) X_{1,t+1}^2 + \frac{\psi}{\eta} X_{1,t+1} X_{2,t+1}\right) \exp\left(-\frac{\bar{z}_{t+1}^d}{\theta}\right) I_{(\bar{z}_{t+1}^d > 0)} \\
& \propto \exp\left(-\frac{(\bar{z}_{t+1}^d - m_{t+1})^2}{2M_{t+1}}\right) I_{(\bar{z}_{t+1}^d > 0)},
\end{aligned}$$

where

$$\begin{aligned}
X_{1,t+1} &= \frac{y_{t+1} - \mu_0 - \mu_r(r_t - \tilde{r}_t) - \mu_v v_t + \bar{z}_{t+1}^d - \bar{j}_{t+1}^u \bar{z}_{t+1}^u}{\sqrt{v_t}}, \\
X_{2,t+1} &= \frac{v_{t+1} - \alpha - \beta v_t - \bar{j}_{t+1}^v \bar{z}_{t+1}^v}{\sqrt{v_t}}.
\end{aligned}$$

Thus, the posterior distribution for \bar{z}_{t+1}^d is the truncated normal distribution with the parameters m_{t+1} (mean) and M_{t+1} (variance):

$$\begin{aligned}
M_{t+1} &= \frac{v_t}{\left(1 + \frac{\psi^2}{\eta}\right)}, \\
m_{t+1} &= -(y_{t+1} - \mu_0 - \mu_r(r_t - \tilde{r}_t) - \mu_v v_t - \bar{j}_{t+1}^u \bar{z}_{t+1}^u) \\
&\quad + \frac{\psi}{(\eta + \psi^2)} (v_{t+1} - \alpha - \beta v_t - \bar{j}_{t+1}^v \bar{z}_{t+1}^v) - \frac{M_{t+1}}{\theta}.
\end{aligned}$$

Correspondingly, $p(\bar{z}_{t+1}^d | \bar{j}_{t+1}^d = 0, \theta) \sim \mathcal{Exp}(\theta)$.

- To guarantee that the estimated variance is strictly positive, we draw it in logs: $l_{vt} = \log v_t$. The posterior distribution for the variance differs depending on whether *IV* data are available ($t > T_2$) or not ($t \leq T_2$).

If *IV* is not available, the posterior distribution for the spot variance is

$$\begin{aligned}
& p(l_{vt} | v_{t-1}, v_{t+1}, \bar{j}_t^u, \bar{j}_{t+1}^u, \bar{j}_t^d, \bar{j}_{t+1}^d, \bar{j}_t^v, \bar{j}_{t+1}^v, \bar{z}_t^u, \bar{z}_{t+1}^u, \bar{z}_t^d, \bar{z}_{t+1}^d, \bar{z}_t^v, \bar{z}_{t+1}^v, r_{t-1}, r_t, \tilde{r}_{t-1}, \tilde{r}_t, \Theta) \\
& \propto \exp\left(-\frac{1}{2} \left(\frac{\psi^2}{\eta} + 1\right) \left(\frac{(y_{t+1} - \mu_0 - \mu_r(r_t - \tilde{r}_t) - \bar{j}_{t+1}^u \bar{z}_{t+1}^u + \bar{j}_{t+1}^d \bar{z}_{t+1}^d)^2}{\exp(l_{vt})} + \mu_v^2 \exp(l_{vt})\right)\right) \\
& \times \exp\left(\frac{\psi}{\eta} \mu_v \beta \exp(l_{vt})\right) \\
& \times \exp\left(\frac{\psi}{\eta} \left(\frac{(y_{t+1} - \mu_0 - \mu_r(r_t - \tilde{r}_t) - \bar{j}_{t+1}^u \bar{z}_{t+1}^u + \bar{j}_{t+1}^d \bar{z}_{t+1}^d)(v_{t+1} - \alpha - \bar{j}_{t+1}^v \bar{z}_{t+1}^v)}{\exp(l_{vt})}\right)\right) \\
& \times \exp\left(\frac{\psi}{\eta} \frac{(y_t - \mu_0 - \mu_r(r_{t-1} - \tilde{r}_{t-1}) - \mu_v v_{t-1} - \bar{j}_t^u \bar{z}_t^u + \bar{j}_t^d \bar{z}_t^d) \exp(l_{vt})}{v_{t-1}}\right) \\
& \times \exp\left(-\frac{1}{2\eta} \left(\frac{(v_{t+1} - \alpha - \bar{j}_{t+1}^v \bar{z}_{t+1}^v)^2}{\exp(l_{vt})} + \beta^2 \exp(l_{vt}) + \frac{v_t^2 - 2v_t(\alpha + \beta v_{t-1} + \bar{j}_t^v \bar{z}_t^v)}{v_{t-1}}\right)\right).
\end{aligned}$$

If IV is available, the posterior distribution for the spot variance is

$$\begin{aligned}
& p(l_{vt}|IV_t, v_{t-1}, v_{t+1}, \bar{j}_t^u, \bar{j}_{t+1}^u, \bar{j}_t^d, \bar{j}_{t+1}^d, \bar{j}_t^v, \bar{j}_{t+1}^v, \bar{z}_t^u, \bar{z}_{t+1}^u, \bar{z}_t^d, \bar{z}_{t+1}^d, \bar{z}_t^v, \bar{z}_{t+1}^v, r_{t-1}, r_t, \tilde{r}_{t-1}, \tilde{r}_t, \Theta) \\
& \propto \exp\left(-\frac{1}{2}\left(\frac{\psi^2}{\eta} + 1\right)\left(\frac{(y_{t+1} - \mu_0 - \mu_r(r_t - \tilde{r}_t) - \bar{j}_{t+1}^u \bar{z}_{t+1}^u + \bar{j}_{t+1}^d \bar{z}_{t+1}^d)^2}{\exp(l_{vt})} + \mu_v^2 \exp(l_{vt})\right)\right) \\
& \times \exp\left(\frac{\psi}{\eta} \mu_v \beta \exp(l_{vt})\right) \\
& \times \exp\left(\frac{\psi}{\eta} \left(\frac{(y_{t+1} - \mu_0 - \mu_r(r_t - \tilde{r}_t) - \bar{j}_{t+1}^u \bar{z}_{t+1}^u + \bar{j}_{t+1}^d \bar{z}_{t+1}^d)(v_{t+1} - \alpha - \bar{j}_{t+1}^v \bar{z}_{t+1}^v)}{\exp(l_{vt})}\right)\right) \\
& \times \exp\left(\frac{\psi}{\eta} \frac{(y_t - \mu_0 - \mu_r(r_{t-1} - \tilde{r}_{t-1}) - \mu_v v_{t-1} - \bar{j}_t^u \bar{z}_t^u + \bar{j}_t^d \bar{z}_t^d) \exp(l_{vt})}{v_{t-1}}\right) \\
& \times \exp\left(-\frac{1}{2\eta} \left(\frac{(v_{t+1} - \alpha - \bar{j}_{t+1}^v \bar{z}_{t+1}^v)^2}{\exp(l_{vt})} + \beta^2 \exp(l_{vt})\right)\right) \\
& \times \exp\left(-\frac{1}{2\eta} \left(\frac{\exp(2l_{vt}) - 2\exp(l_{vt})(\alpha + \beta v_{t-1} + \bar{j}_t^v \bar{z}_t^v)}{v_{t-1}}\right)\right) \\
& \times \frac{1}{v_t} \exp\left(-\frac{(IV_t - \alpha_{iv} - \beta_{iv} \exp(l_{vt}))^2}{2\sigma_{iv}^2 \lambda_t \exp(2l_{vt})}\right).
\end{aligned}$$

Thus, if implied variance is observed, the posterior distribution for the spot variance has one additional component (the last multiplier).

IX Model diagnostics

The Bayesian MCMC approach provides output that is useful for the model diagnostics purposes. In particular, we estimate a system

$$(30) \quad y_{t+1} = \mu_0 + \mu_r(r_t - \tilde{r}_t) + \mu_v v_t + v_t^{1/2} w_{t+1}^s + \bar{z}_{t+1}^u \bar{j}_{t+1}^u - \bar{z}_{t+1}^d \bar{j}_{t+1}^d,$$

$$v_{t+1} = (1 - \nu)v + \nu v_t + \sigma_v v_t^{1/2} w_{t+1}^v + \bar{z}_{t+1}^v \bar{j}_{t+1}^v,$$

$$(31) \quad IV_t = \alpha_{iv} + \beta_{iv} v_t + \sigma_{iv} v_t \sqrt{\lambda_t} \varepsilon_t,$$

and construct distributions for the residuals $\{w_t^{s,g}\}$ and $\{\varepsilon_t^g\}$ (the superscript g stands for a simulation path). Our model implies that the residuals from equations (30) and (31), w_t^s and ε_t , are iid standard normal, i.e., skewness=0, kurtosis=3, and no serial correlation.

For each g , we construct fitted residuals,

$$\begin{aligned}
\hat{w}_{t+1}^{s,g} &= \frac{y_{t+1} - \hat{\mu}_0^g - \hat{\mu}_r^g(r_t - \tilde{r}_t) - \hat{\mu}_v^g \hat{v}_t^g - \hat{z}_{t+1}^{u,g} \hat{j}_{t+1}^{u,g} + \hat{z}_{t+1}^{d,g} \hat{j}_{t+1}^{d,g}}{\sqrt{\hat{v}_t^g}}, \\
\hat{\varepsilon}_{t+1}^g &= \frac{IV_t - \hat{\alpha}_{iv}^g - \hat{\beta}_{iv}^g \hat{v}_t^g}{\hat{\sigma}_{iv}^g \hat{v}_t^g \sqrt{\hat{\lambda}_t^g}},
\end{aligned}$$

and we compute their third and fourth moments, and autocorrelations: $\text{skew}(\hat{w}^{s,g})$, $\text{skew}(\hat{\varepsilon}^g)$, $\text{kurt}(\hat{w}^{s,g})$, $\text{kurt}(\hat{\varepsilon}^g)$, $\text{autocorr}(\hat{w}^{s,g})$, and $\text{autocorr}(\hat{\varepsilon}^g)$. Therefore, as a natural by-product of our estimation, we have distributions of skewness, kurtosis, and autocorrelation for $\{w^s\}$ and $\{\varepsilon\}$:

$$M = \{\text{skew}(w^{s,g}), \text{kurt}(w^{s,g}), \text{autocorr}(w^{s,g}), \text{skew}(\varepsilon^g), \text{kurt}(\varepsilon^g), \text{autocorr}(\varepsilon^g)\}_{g=1}^G,$$

where G is the number of executed simulations. Hence, we can easily construct confidence intervals for these six components of M and check whether they contain skewness of zero, kurtosis of 3, and serial correlation of zero.

One has to exhibit caution when interpreting the evidence on normality of ε . The variance of the error term in the implied variance equation (29), $\sigma_{iv}^2 v_t^2 \lambda_t$, is very flexible. If a model is misspecified, λ_t will adjust so that the ε is close to a normal variable. Therefore, diagnostics of ε are not enough. We should be tracking the size of the variance of the error term. A better specified model should have smaller variance. We keep track of the time-series average of this variance – which we refer to as $IVvar$ – and report its posterior distribution. Similar to other diagnostics, we store the whole distribution of $\{\sigma_{iv}^{2,g} v_t^{2,g} \lambda_t^g\}_{g=1}^G$ and report its mean and 95% confidence bound in the main text of the paper.

Tables 6 – 10 report the results. The diagnostics of residuals w^s indicate that the major improvement in moving from stochastic variance with jumps to the preferred model comes from a statistically significant drop in kurtosis from roughly 4 to 3.5 across all currencies. The absolute value of skewness of w experiences a significant drop for all currencies except for GBP, where it was insignificantly different from zero in the model with stochastic variance with jumps already. Serial correlation is slightly negative for all currencies except for GBP (where it is zero in the model with stochastic variance with jumps already), and the change from one model to another is insignificant. $IVvar$ does not change appreciably because we did not change our model for variance. Bayes odds ratios strongly favor the preferred model. In summary, the preferred model is clearly superior, but there are some residual non-normalities left in the fitted shocks to exchange rates. We leave improvements to future research.

X Bayes odds ratios

In Bayesian statistics, a common formal approach to model selection is a comparison of the posterior model probabilities. If the prior model probabilities are uniformly distributed, the posterior model probabilities collapse to the Bayes factor (for a detailed discussion, see Gamerman and Lopes, 2006). The Bayes factor simplifies in the case of nested models with similar priors for common parameters. It equals to the ratio of the posterior and the prior under the encompassing model. This ratio is known as the Savage-Dickey density ratio (Verdinelli and Wasserman, 1995).

SV versus SVJ

In this section, we are evaluating two models: stochastic volatility model (SV)

$$\begin{aligned} y_{t+1} &= \mu_0 + \mu_r(r_t - \tilde{r}_t) + \mu_v v_t + v_t^{1/2} w_{t+1}^s, \\ v_{t+1} &= (1 - \nu)v + \nu v_t + \sigma_v v_t^{1/2} w_{t+1}^v, \\ IV_t &= \alpha_{iv} + \beta_{iv} v_t + \sigma_{iv} v_t \sqrt{\lambda_t} \varepsilon_t \end{aligned}$$

and stochastic volatility model with jumps in variance (SVJ)

$$\begin{aligned} (32) \quad y_{t+1} &= \mu_0 + \mu_r(r_t - \tilde{r}_t) + \mu_v v_t + v_t^{1/2} w_{t+1}^s, \\ (33) \quad v_{t+1} &= (1 - \nu)v + \nu v_t + \sigma_v v_t^{1/2} w_{t+1}^v + \tilde{z}_{t+1}^v \tilde{j}_{t+1}^v, \\ (34) \quad IV_t &= \alpha_{iv} + \beta_{iv} v_t + \sigma_{iv} v_t \sqrt{\lambda_t} \varepsilon_t. \end{aligned}$$

Let Ω denote the collection of the latent variables and parameters of the models, i.e., $\Omega = \{\Theta, \bar{J}^v, \bar{Z}^v, \Lambda\}$ ($\Lambda = \{\lambda_t\}_{t=T_2+1}^T$). We treat variance as observable in this case (this subsection only). First, variance in the model with jumps in variance has an unknown unconditional distribution. Second, in our model the intensity of the jumps in variance is governed by the variance itself. These two observations mean that evaluation of the Bayes factor would involve the use of an intractable distribution if variance is latent. We view this simplification as reasonable because in order to estimate variance we use information embedded in ATM options, i.e., implied variance tells us very accurately what the spot variance is.

We compare two nested models; if $\tilde{j}_t^v = 0$ for any $t \in [1, T]$ then the SVJ model is equivalent to the SV model. Therefore, we have the following identity for predictive densities:

$$p(Y, IV | \Omega, R, \tilde{R}, V, \text{SV}) = p(Y, IV | \Omega, R, \tilde{R}, \bar{J}^v = 0, V, \text{SVJ}).$$

We make an additional assumption that models share the same prior distributions for the common parameters, i.e., $p(\Omega | \text{SV}) = p(\Omega | \bar{J}^v = 0, \text{SVJ})$. Thereby, we work with the Bayes factor in the form of the Savage-Dickey density ratio. We follow Eraker, Johannes, and Polson (2003) to show this.

Start with the predictive density for the SV model and use two facts: (1) the SV model is nested in the SVJ model, and (2) models have identical priors for the common parameters:

$$\begin{aligned} p(Y, IV | R, \tilde{R}, V, \text{SV}) &= \int p(Y, IV | \Omega, R, \tilde{R}, V, \text{SV}) p(\Omega | \text{SV}) d\Omega \\ &= \int p(Y, IV | \Omega, R, \tilde{R}, V, \bar{J}^v = 0, \text{SVJ}) p(\Omega | \text{SV}) d\Omega \\ &= \int p(Y, IV | \Omega, R, \tilde{R}, V, \bar{J}^v = 0, \text{SVJ}) p(\Omega | \bar{J}^v = 0, \text{SVJ}) d\Omega \\ &= p(Y, IV | \bar{J}^v = 0, R, \tilde{R}, V, \text{SVJ}). \end{aligned}$$

The posterior odds ratio of the model SV to the model SVJ is

$$\begin{aligned} Odds(\text{SV}, \text{SVJ}) &= \frac{Pr(\text{SV}|Y, IV, V, R, \tilde{R})}{Pr(\text{SVJ}|Y, IV, V, R, \tilde{R})} = \frac{p(Y, IV|R, \tilde{R}, V, \text{SV})}{p(Y, IV|R, \tilde{R}, V, \text{SVJ})} \\ &= \frac{p(Y, IV|\bar{J}^v = 0, R, \tilde{R}, V, \text{SVJ})}{p(Y, IV|R, \tilde{R}, V, \text{SVJ})} = \frac{Pr(\bar{J}^v = 0|Y, IV, R, \tilde{R}, V, \text{SVJ})}{Pr(\bar{J}^v = 0|R, \tilde{R}, V, \text{SVJ})}. \end{aligned}$$

Consider the denominator. Let $x = \{h_0^v, h_v\}$ and X to be the domain of x .

$$\begin{aligned} Pr(\bar{J}^v = 0|R, \tilde{R}, V, \text{SVJ}) &= \int_{x \in X} Pr(\bar{J}^v = 0|h_0^v, h_v, V, \text{SVJ})p(h_0^v, h_v|\text{SVJ})dx \\ &= \int_{x \in X} \prod_{t=1}^T (1 - h_0^v - h_v v_{t-1})p(h_0^v, h_v|\text{SVJ})dx = \int_{x \in X} \prod_{t=1}^T (1 - h_0^v - h_v v_{t-1})p(h_0^v)p(h_v)dx \\ (35) \quad &= \frac{1}{K} \sum_{k=1}^K \left(\prod_{t=1}^T (1 - h_0^{v,k} - h_v^k v_{t-1}) \right). \end{aligned}$$

Thereby, we evaluate a prior ordinate numerically by fixing a large number K , drawing independently $\{h_0^{v,k}\}_{k=1}^K$ and $\{h_v^k\}_{k=1}^K$ from the uniform distributions with domains $[\underline{h}_0^v, \bar{h}_0^v]$ and $[\underline{h}_v, \bar{h}_v]$, respectively, and approximating the integral by a sum.

Consider the numerator

$$\begin{aligned} &Pr(\bar{J}^v = 0|Y, IV, R, \tilde{R}, V, \text{SVJ}) \\ (36) \quad &= \int_{x \in X} Pr(\bar{J}^v = 0|h_0^v, h_v, V, Y, IV, \text{SVJ})p(h_0^v, h_v|Y, IV, V, \text{SVJ})dx. \end{aligned}$$

Work with the second component in (36):

$$\begin{aligned} &p(h_0^v, h_v|Y, IV, V, \text{SVJ}) = \int_{\bar{J}^v} p(h_0^v, h_v|\bar{J}^v, V, \text{SVJ})p(\bar{J}^v|Y, IV)d\bar{J}^v \\ (37) \quad &= \int_{\bar{J}^v} \left(\prod_{t=1}^T (h_0^v + h_v v_{t-1})^{\bar{J}_t^v} (1 - h_0^v - h_v v_{t-1})^{1-\bar{J}_t^v} / C^m \right) p(\bar{J}^v|Y, IV)d\bar{J}^v. \end{aligned}$$

C^m is a normalization constant which guarantees that the first multiplier under the integral in (35) is a density function:

$$\begin{aligned} C^m &= \int_{x \in X} \prod_{t=1}^T (h_0^v + h_v v_{t-1})^{\bar{J}_t^v} (1 - h_0^v - h_v v_{t-1})^{1-\bar{J}_t^v} dx \\ &\approx \frac{1}{K} \sum_{k=1}^K \prod_{t=1}^T (h_0^{v,k} + h_v^k v_{t-1})^{\bar{J}_t^v} (1 - h_0^{v,k} - h_v^k v_{t-1})^{1-\bar{J}_t^v}. \end{aligned}$$

Component (37) becomes

$$p(h_0^v, h_v|Y, IV, V, \text{SVJ}) = \frac{1}{M} \sum_{m=1}^M \prod_{t=1}^T (h_0^v + h_v v_{t-1})^{\bar{j}_t^{v,m}} (1 - h_0^v - h_v v_{t-1})^{1-\bar{j}_t^{v,m}} / C^m.$$

Finally, we compute the posterior ordinate (36).

$$\begin{aligned} & Pr(\bar{J}^v = 0|Y, IV, R, \tilde{R}, V, \text{SVJ}) \\ \approx & \frac{1}{KM} \sum_{k=1}^K \left(\prod_{t=1}^T (1 - h_0^{v,k} - h_v^k v_{t-1}) \right) \sum_{m=1}^M \prod_{t=1}^T (h_0^{v,k} + h_v^k v_{t-1})^{\bar{j}_t^{v,m}} (1 - h_0^{v,k} - h_v^k v_{t-1})^{1-\bar{j}_t^{v,m}} / C^m. \end{aligned}$$

SVJ versus Preferred

In this section, we are working with the SVJ model (32)-(34) and our preferred model given by

$$\begin{aligned} y_{t+1} &= \mu_0 + \mu_r(r_t - \tilde{r}_t) + \mu_v v_t + v_t^{1/2} w_{t+1}^s + \bar{z}_{t+1}^u \bar{j}_{t+1}^u - \bar{z}_{t+1}^d \bar{j}_{t+1}^d, \\ v_{t+1} &= (1 - \nu)v + \nu v_t + \sigma_v v_t^{1/2} w_{t+1}^v + \bar{z}_{t+1}^v \bar{j}_{t+1}^v, \\ IV_t &= \alpha_{iv} + \beta_{iv} v_t + \sigma_{iv} v_t \sqrt{\lambda_t} \varepsilon_t. \end{aligned}$$

Similar arguments tell us that the Bayes factor takes the form of the Savage-Dickey density ratio if we assume identical priors for common parameters, i.e., $p(\Omega|\text{SVJ}) = p(\Omega|\bar{J}^u = 0, \bar{J}^d = 0, \text{Preferred})$. Note that Ω includes latent variables corresponding to jump times and jump sizes in currency returns. Here we do not have to assume that variance is observable because it cancels out in the final expression (see below). The posterior odds ratio of the model SVJ to the model Preferred is

$$\begin{aligned} \text{Odds}(\text{SVJ}, \text{Preferred}) &= \frac{Pr(\text{SVJ}|Y, IV, V, R, \tilde{R})}{Pr(\text{Preferred}|Y, IV, V, R, \tilde{R})} \\ (38) \quad &= \frac{Pr(\bar{J}^u = 0, \bar{J}^d = 0|Y, IV, R, \tilde{R}, V, \text{Preferred})}{Pr(\bar{J}^u = 0, \bar{J}^d = 0|R, \tilde{R}, V, \text{Preferred})}. \end{aligned}$$

We start with the denominator:

$$\begin{aligned} & Pr(\bar{J}^u = 0, \bar{J}^d = 0|R, \tilde{R}, V, \text{Preferred}) \\ &= \int_{x \in X} Pr(\bar{J}^u = 0, \bar{J}^d = 0|h_0, h_r, R, \tilde{R}, \text{Preferred}) p(h_0, h_r) dx \\ (39) \quad &\approx \frac{1}{K} \sum_{k=1}^K \prod_{t=1}^T (1 - h_0^k - h_r^k r_{t-1})(1 - h_0^k - h_r^k \tilde{r}_{t-1}). \end{aligned}$$

We denote $x = (h_0, h_r)$ and X is the domain of x .

For the numerator, we have

$$\begin{aligned}
(40) \quad & Pr(\bar{J}^u = 0, \bar{J}^d = 0 | Y, IV, R, \tilde{R}, V, \text{Preferred}) \\
&= \int_{x \in X} Pr(\bar{J}^u = 0, \bar{J}^d = 0 | h_0, h_r, R, \tilde{R}) p(h_0, h_r | Y, IV, R, \tilde{R}, V, \text{Preferred}) dx.
\end{aligned}$$

Work with the second component of (40):

$$\begin{aligned}
& p(h_0, h_r | Y, IV, R, \tilde{R}, V, \text{Preferred}) \\
&= \int_{\bar{J}^u, \bar{J}^d} p(h_0, h_r | \bar{J}^u, \bar{J}^d, R, \tilde{R}, \text{Preferred}) p(\bar{J}^u, \bar{J}^d | Y, IV, \text{Preferred}) d\bar{J}^u d\bar{J}^d \\
&= \int_{\bar{J}^u, \bar{J}^d} p(h_0, h_r | \bar{J}^u, \bar{J}^d, R, \tilde{R}, \text{Preferred}) p(\bar{J}^u | Y) p(\bar{J}^d | Y) d\bar{J}^u d\bar{J}^d.
\end{aligned}$$

We approximate $p(\bar{J}^u | Y)$ and $p(\bar{J}^d | Y)$ by using the MCMC draws for the jump times. Therefore, to complete our derivation all we need is to evaluate the conditional joint density function of the parameters of the jumps' intensities:

$$\begin{aligned}
& p(h_0, h_r | \bar{J}^u, \bar{J}^d, R, \tilde{R}, \text{Preferred}) \\
&= \prod_{t=1}^T (h_0 + h_r r_{t-1})^{\bar{J}_t^u} (h_0 + h_r \tilde{r}_{t-1})^{\bar{J}_t^d} (1 - h_0 - h_r r_{t-1})^{1-\bar{J}_t^u} (1 - h_0 - h_r \tilde{r}_{t-1})^{1-\bar{J}_t^d} / C^m,
\end{aligned}$$

where

$$\begin{aligned}
C^m &= \int_{x \in X} \prod_{t=1}^T (h_0 + h_r r_{t-1})^{\bar{J}_t^u} (h_0 + h_r \tilde{r}_{t-1})^{\bar{J}_t^d} (1 - h_0 - h_r r_{t-1})^{1-\bar{J}_t^u} (1 - h_0 - h_r \tilde{r}_{t-1})^{1-\bar{J}_t^d} dx \\
&= \frac{1}{K} \sum_{k=1}^K \prod_{t=1}^T (h_0^k + h_r^k r_{t-1})^{\bar{J}_t^u} (h_0^k + h_r^k \tilde{r}_{t-1})^{\bar{J}_t^d} (1 - h_0^k - h_r^k r_{t-1})^{1-\bar{J}_t^u} (1 - h_0^k - h_r^k \tilde{r}_{t-1})^{1-\bar{J}_t^d}.
\end{aligned}$$

Thereby,

$$\begin{aligned}
& p(h_0, h_r | Y, IV, R, \tilde{R}, V, \text{Preferred}) \\
&\approx \frac{1}{M} \sum_{m=1}^M \prod_{t=1}^T (h_0 + h_r r_{t-1})^{\bar{J}_t^{u,m}} (h_0 + h_r \tilde{r}_{t-1})^{\bar{J}_t^{d,m}} (1 - h_0 - h_r r_{t-1})^{1-\bar{J}_t^{u,m}} (1 - h_0 - h_r \tilde{r}_{t-1})^{1-\bar{J}_t^{d,m}} / C^m.
\end{aligned}$$

The numerator in (38) is as follows

$$\begin{aligned}
& Pr(\bar{J}^u = 0, \bar{J}^d = 0 | R, \tilde{R}, Y, IV, V, \text{Preferred}) \\
&\approx \frac{1}{KM} \sum_{k=1}^K \prod_{t=1}^T (1 - h_0^k - h_r^k r_{t-1}) (1 - h_0^k - h_r^k \tilde{r}_{t-1}) \\
&= \sum_{m=1}^M \prod_{t=1}^T (h_0^k + h_r^k r_{t-1})^{\bar{J}_t^{u,m}} (h_0^k + h_r^k \tilde{r}_{t-1})^{\bar{J}_t^{d,m}} (1 - h_0^k - h_r^k r_{t-1})^{1-\bar{J}_t^{u,m}} (1 - h_0^k - h_r^k \tilde{r}_{t-1})^{1-\bar{J}_t^{d,m}} / C^m.
\end{aligned}$$

This completes our derivation.

References

- Akgiray, Vedat, and G. Geoffrey Booth, 1988, Mixed diffusion-jump process modeling of exchange rate movements, *Review of Economics and Statistics* 70, 631–637.
- Backus, David K., Federico Gavazzoni, Christopher Telmer, and Stanley E. Zin, 2010, Monetary policy and the uncovered interest rate parity puzzle, Working paper, NBER.
- Bakshi, Gurdip, Peter Carr, and Liuren Wu, 2008, Stochastic risk premiums, stochastic skewness in currency options, and stochastic discount factors in international economies, *Journal of Financial Economics* 87, 132–156.
- Bansal, Ravi, and Ivan Shaliastovich, 2013, A long-run risks explanation of predictability puzzles in bond and currency markets, *Review of Financial Studies* 26, 1–33.
- Bansal, Ravi, and Amir Yaron, 2004, Risks for the long run: A potential resolution of asset pricing puzzles, *Journal of Finance* 59, 1481–1509.
- Bates, David S., 1996, Jumps and stochastic volatility: Exchange rate processes implicit in Deutsche mark options, *Review of Financial Studies* 9, 69–107.
- Bekaert, Geert, 1996, The time variation of risk and return in foreign exchange markets: a general equilibrium perspective, *Review of Financial Studies* 9, 427–470.
- Benzoni, Luca, Pierre Collin-Dufresne, and Robert S. Goldstein, 2011, Explaining asset pricing puzzles associated with the 1987 market crash, *Journal of Financial Economics* 101, 552–573.
- Boothe, Paul, and Debra Glassman, 1987, The statistical distribution of exchange rates: empirical evidence and economic implications, *Journal of International Economics* 22, 297–319.
- Brandt, Michael W., and Pedro Santa-Clara, 2002, Simulated likelihood estimation of diffusions with an application to exchange rate dynamics in incomplete markets, *Journal of Financial Economics* 63, 161–210.
- Brunnermeier, Markus K., Stefan Nagel, and Lasse H. Pedersen, 2008, Carry trades and currency crashes, in Daron Acemoglu, Kenneth Rogoff, and Michael Woodford, ed.: *NBER Macroeconomics Annual*, 23(1), 313–347 (University of Chicago Press).
- Burnside, Craig, Martin Eichenbaum, Isaac Kleshchelski, and Sergio Rebelo, 2011, Do peso problems explain the returns to the carry trade?, *Review of Financial Studies* 24, 853–891.
- Carr, Peter, and Liuren Wu, 2007, Stochastic skew in currency options, *Journal of Financial Economics* 86, 213–247.
- Chatrath, Arjun, Hong Miao, Sanjay Ramchander, and Sriram Villupuram, 2014, Currency jumps, cojumps and the role of macro news, *Journal of International Money and Finance* 40, 42–62.

- Colacito, Riccardo, 2009, Six anomalies looking for a model. A consumption based explanation of international finance puzzles, Working Paper, University of North Carolina at Chapel Hill.
- , and Mariano M. Croce, 2013, International asset pricing with recursive preferences, *Journal of Finance* 68, 2651–2686.
- Drechsler, Itamar, and Amir Yaron, 2011, What’s vol got to do with it, *Review of Financial Studies* 24, 1–45.
- Eraker, Bjørn, Michael Johannes, and Nicholas Polson, 2003, The impact of jumps in volatility and returns, *Journal of Finance* 58, 1269–1300.
- Farhi, Emmanuel, Samuel P. Fraiberger, Xavier Gabaix, Romain Ranciere, and Adrien Verdelhan, 2009, Crash risk in currency markets, Working Paper, NBER.
- Farhi, Emmanuel, and Xavier Gabaix, 2015, Rare disasters and exchange rates, forthcoming, *Quarterly Journal of Economics*.
- Gamerman, Dani, and Hedibert F. Lopes, 2006, *Markov Chain Monte Carlo: Stochastic Simulation for Bayesian Inference* (Chapman & Hall/CRC: Boca Raton London New York Washington, D.C.) second edn.
- Gourio, François, Michael Siemer, and Adrien Verdelhan, 2013, International risk cycles, *Journal of International Economics* 89, 471–484.
- Graveline, Jeremy J., 2006, Exchange rate volatility and the forward premium anomaly, Working Paper, University of Minnesota.
- Guo, Kai, 2007, Exchange rates and asset prices in an open economy with rare disasters, Working Paper, Harvard University.
- Hansen, Lars Peter, John C. Heaton, and Nan Li, 2008, Consumption strikes back? Measuring long-run risk, *Journal of Political Economy* 116, 260–302.
- Johnson, Gordon, and Thomas Schneeweis, 1994, Jump-diffusion processes in the foreign exchange markets and the release of macroeconomic news, *Computational Economics* 7, 309–329.
- Jordà, Òscar, and Alan M. Taylor, 2012, The carry trade and fundamentals: Nothing to fear but fear itself, *Journal of International Economics* 88, 74–90.
- Jorion, Philippe, 1988, On jump processes in the foreign exchange and stock markets, *Review of Financial Studies* 1, 427–445.
- Jurek, Jakub W., 2014, Crash-neutral currency carry trades, *Journal of Financial Economics* 113, 325–347.
- , and Zhikai Xu, 2013, Option-implied currency risk premia, Working Paper, Princeton University.

- Neely, Christopher J., 2011, A survey of announcement effects on foreign exchange volatility and jumps, *Federal Reserve Bank of St. Louis Review* 93, 361–385.
- Nieuwland, Frederick G. M. C., Willem F. C. Verschoor, and Christian C. P. Wolff, 1994, Stochastic trends and jumps in EMS exchange rates, *Journal of International Money and Finance* 13, 699–727.
- Plantin, Guillaume, and Hyun Song Shin, 2011, Carry trades, monetary policy and speculative dynamics, Working Paper, CEPR.
- Ready, Robert, Nikolai Roussanov, and Colin Ward, 2013, Commodity trade and the carry trade: a tale of two countries, Working paper, NBER.
- Tucker, Alan L., and Lallan Pond, 1988, The probability distribution of foreign exchange price changes: tests of candidate processes, *Review of Economics and Statistics* 70, 638–647.
- Verdinelli, Isabella, and Larry Wasserman, 1995, Computing Bayes factors using a generalization of the Savage-Dickey density ratio, *Journal of American Statistical Association* 90, 614–618.
- Vlaar, Peter J. G., and Franz C. Palm, 1993, The message in weekly exchange rates in the European Monetary System: mean reversion, conditional heteroscedasticity, and jumps, *Journal of Business and Economic Statistics* 11, 351–359.
- Wachter, Jessica, 2013, Can time-varying risk of rare disasters explain aggregate stock market volatility?, *Journal of Finance* 68, 987–1035.

Table 1
AUD events

Date	Excess return	Jump in FX	Jump in Vol	Events/Sources of uncertainty	Impact on FX
Dec 24, 1986	-1.41	-0.90 (0.59)		No significant news. Thin pre-Christmas trading day	<i>JPY^u</i>
Jan 14, 1987	-2.68	-2.67 (1.00)		Listing of the Australian dollar futures for the first time on the Chicago futures exchange. The Reagan administration was reported to support decline of the US dollar in order to maintain the trade deficit	
Jan 20, 1987	2.62	2.36 (1.00)		Encouraging narrowing of the AU monthly deficit along with worst-ever current account figures	
Oct 29, 1987	-2.46	-1.56 (0.74)		Upheaval in world financial markets	<i>GBP^d</i>
Feb 16, 1989	-4.06	-3.72 (1.00)		Positive US trade news. Poor balance of payment figures in AU	
Feb 27, 1989	-3.24	-2.67 (0.93)		Australian Treasurer Paul Keating says that figures for the trade balance would continue bad. No increase of interest rates	
Apr 5, 1989	-3.82	-3.50 (0.98)		Intervention by the Reserve Bank of Australia (RBA) to temper the rise of AUD	
Jan 23, 1990	-2.42	-2.21 (0.97)		Reserve Bank of Australia relaxes restrictive monetary policy. Interest rate cut	
Apr 26, 1990	-1.66	-1.02 (0.62)		Intervention by the Reserve Bank of Australia. Sell AUD for USD	
Aug 30, 1990	-2.32	-1.26 (0.63)		Third RBA intervention in four trading days. Sell AUD for USD	
Oct 15, 1990	-3.38	-3.19 (1.00)		The Reserve Bank of Australia cuts its official money market rate	
May 22, 1991	-1.72	-1.58 (0.93)		Intervention by the Reserve Bank of Australia. Announcement of the RBA's governor about intention to devalue AUD	
June 5, 1991	-1.91	-1.89 (0.99)		Jittery market in anticipation of the release of AU unemployment figures and subsequent comments by government	
May 18, 1995	-2.19	-1.74 (0.86)		Goldman Sachs report shows negative prospects for AUD	<i>CHF^v</i>
Nov 21, 1996	1.09	0.84 (0.58)		Australian and New Zealand banking group release – strong annual result	
Dec 3, 1996	-1.41	-0.96 (0.67)		Speculation of an interest rate cut following the meeting of the Reserve Bank of Australia	
May 21, 1997	1.63	0.94 (0.59)		The US Federal Reserve decides not to raise interest rates. Strong positive wage growth in AU	
Oct 22, 1997	-1.38		0.14 (0.79)	Release of the AU CPI data – annual inflation reaches 35-year low. Anticipation of a regular cut in AU interest rates. Uncertainty about the effect of the Asian crisis on the AU economy	
Oct 24, 1997	-2.48	-0.98 (0.53)		Hong Kong suffered the biggest equity market slump in its history on Oct 23, 1997	
Oct 27, 1997	-0.42		0.16 (0.95)	Impact of the South East Asian currency crisis. Price of gold sliding – Swiss government considers selling about a half of its gold reserves	
Oct 28, 1997	3.42	2.30 (0.85)		Huge losses in the US stock market – largest drop since Black Monday	
Jan 6, 1998	-0.90		0.11 (0.87)	Sharp drop in the price of gold which recorded an 18-year low. Soaring US dollar. Concerns over the Asian currency crisis	

Table 1
AUD events continued

Date	Excess return	Jump in FX	Jump in Vol	Events/Sources of uncertainty	Impact on FX
June 18, 1998	-1.06		0.14 (0.66)	Speculation that the US may try to help stop the slide of the Japanese yen. Intervention by the Bank of Japan and the Fed to buy the yen for USD (major factor in AUDUSD movements is the direction of JPYUSD)	
Oct 7, 1998	4.68	3.34 (0.89)		Greenspan: negative prospects for the US economy, credit crunch. Possible further cut of the US interest rates. Threat of Clinton impeachment. Strong AU employment report	JPY^u , $Index^u$
Oct 8, 1998	-0.78		0.20 (1.00)	Large moves in the US dollar/yen rate. Hedge funds unwind their positions	CHF^v , JPY^v
Jan 28, 2000	-2.97	-2.75 (1.00)	0.11 (1.00)	AU Release of the December quarter CPI – lower than expected	
Dec 22, 2000	3.22	1.75 (0.68)		Downward revision to US Q3 growth data. Concerns over a sharp economic US slowdown loom. Thin trading exaggerates FX moves	
Apr 18, 2001	-0.02		0.12 (0.59)	Westpac/Melbourne Institute releases an index showing that AU economy is in a weak state	
Sep 17, 2001	-2.41		0.12 (0.94)	Intervention by the Bank of Japan to support the US dollar. Markets are turbulent ahead of Wall Street's open after September 11	CHF^v , JPY^v , $Index^v$
Jan 6, 2003	1.47		0.19 (0.51)	Robust AU economic data	
Feb 20, 2004	-2.61	-1.35 (0.64)		Japan is on terror alert. Japan dispatches troops on a humanitarian mission to Iraq	JPY^d
July 27, 2007	-2.24	-1.80 (0.89)	0.11 (0.98)	Flight to safety – sharp fall on Wall Street	
Aug 10, 2007	-0.61		0.11 (0.99)	Bad signs of credit crisis. BNP Paribas warns of credit problems	
Aug 16, 2007	-3.57	-3.14 (0.98)	0.25 (1.00)	The Fed unexpectedly cuts the discount rate on its lending to banks. Bad US employment figures	JPY^v , $Index^v$
Oct 16, 2007	-1.19		0.12 (0.80)	Flight to safety away from high-yielding currencies. Talk that G7 would act to stop the US dollar falling any further	
Nov 12, 2007	-4.00	-1.59 (0.61)		Credit crunch continues to batter high-yielding currencies	
Jan 16, 2008	-0.12		0.11 (1.00)	Positive AU economic data but flight to quality effect dominates market sentiment	
Sep 5, 2008	-0.82		0.14 (0.85)	Downbeat US employment figures, disappointing retail sales data, growing speculation about troubles at major hedge funds	JPY^v
Sep 15, 2008	-2.08		0.13 (0.99)	Lehman Brothers collapse	CHF^v , GBP^v , JPY^u , JPY^v , $Index^v$
Sep 16, 2008	-0.77		0.20 (0.85)	Sharp drop in commodity prices. Expectations of a big rate cut by the RBA	
Sep 29, 2008	-3.21		0.24 (0.97)	Unprecedented coordinated attempt to pour liquidity into the financial system through short-term loans by the Fed, the ECB, the Bank of Japan, the Reserve bank of Australia, and the Bank of England. The US House of Representatives rejects a proposed \$700 billion financial bailout package	CHF^v , GBP^v , JPY^v , $Index^v$
Sep 30, 2008	-1.51		0.14 (0.60)	Banking crisis deepens in Europe. Banking bailouts	GBP^v , $Index^v$

Table 1
AUD events continued

Date	Excess return	Jump in FX	Jump in Vol	Events/Sources of uncertainty	Impact on FX
Oct 6, 2008	-6.92	-5.64 (0.99)	0.46 (1.00)	Crash in the European and US equity markets. The Reserve Bank of Australia cuts its benchmark rate	$CHF^v, GBP^v, JPY^v, Index^v$
Oct 8, 2008	-6.06		0.45 (1.00)	Coordinated cut of interest rates by the FED, the ECB, the Bank of England, the Bank of Canada, the Swiss National Bank, and the Swedish Riksbank	$JPY^v, Index^v$
Oct 22, 2008	0.31		0.30 (0.95)	Fear of the great recession worsening	$CHF^v, GBP^v, JPY^v, Index^v$
Oct 24, 2008	-7.28		0.14 (0.61)	The White House announces that the widespread recession is inevitable. British Prime Minister acknowledges that the UK is likely entering recession. Global stocks plumb multi-year lows	$GBP^v, JPY^v, Index^v$
Nov 12, 2008	-2.56		0.17 (0.96)	Turmoil in equity markets, thin trading before the Veteran's day in the US	$GBP^v, JPY^v, Index^v$
Dec 17, 2008	1.39		0.14 (0.89)	Drop in the US trade deficit	$CHF^v, GBP^v, Index^v$
Jan 5, 2009	0.90		0.11 (0.58)	Hopes that fresh stimulus plans from the US and Germany would help the global economy recover. Rebounding stock market encourages investors to pick up higher-yielding currencies	GBP^v
Jan 13, 2009	-2.52		0.13 (0.95)	Deepening global slowdown. Decline in commodity prices	
Feb 10, 2009	-3.54		0.14 (0.88)	The measure of business confidence of the Reserve Bank's of Australia dives to the historical lowest. The US Treasury Secretary announces a plan to rescue the banking system which disappoints the market. The US Senate passes a massive economic stimulus package	$CHF^v, Index^v$
Mar 23, 2009	2.64		0.12 (0.65)	The US government fleshes out the plan to purge banks from toxic assets	
June 3, 2009	-2.47		0.11 (0.65)	Weaker than expected US economic data. Comments from Asian monetary officials that Asian central banks would keep buying US Treasuries even if the US credit rating were to be cut	
May 6, 2010	-2.34		0.21 (1.00)	Mounting fears over the Greek debt, Greek riots	$GBP^v, JPY^u, JPY^v, Index^v$
May 17, 2010	-0.95		0.12 (0.99)	Euro crisis consequences. High market risk aversion	
May 19, 2010	-2.00		0.23 (1.00)	German ban on naked short sales of euro-zone government bonds and CDSs increases risk aversion	$GBP^v, Index^v$
June 29, 2010	-2.71		0.13 (0.67)	Dismal reading of the US consumer confidence. Fear about the pace of global growth	

Notes: This table summarizes information about events and sources of uncertainty which are associated with substantial movements in FX market qualified as jumps in prices or volatility. The second column is daily excess log currency returns in percent per day. The third and fourth columns provide estimates of the size of jumps and probability of jumps (in parentheses); size of jumps is in percent. The last two columns describe the news and which cross rates are affected. If we cannot attribute FX dynamics to specific news or events we indicate what type of uncertainty causes market movements. Source of news: Factiva.

Table 2
CHF events

Date	Excess return	Jump in FX	Jump in Vol	Events/Sources of uncertainty	Impact on FX
June 2, 1987	2.25	1.29 (0.71)		Paul Volcker leaves the Fed	JPY^u
Aug 18, 1987	1.97	1.27 (0.75)		Disappointing US trade deficit report	JPY^u
Nov 5, 1987	3.08	1.30 (0.61)		Pessimism over the US budget deficit negotiations. Comments by the US Treasury Secretary, James Baker, – the US may be willing to let the dollar ease	
Jan 5, 1988	-3.08	-1.37 (0.64)		Coordinated intervention by the G7 on behalf of the Federal Reserve Board and the US Treasury	JPY^d , $Index^d$
Apr 14, 1988	2.21	1.91 (0.94)		Disappointing US trade deficit report	JPY^u
Sep 18, 1989	2.45	1.03 (0.58)		Intervention by the Bank of Japan to support the yen	JPY^u
Jan 2, 1990	-2.29	-1.12 (0.63)		Favorable US economic data: US index of economic activity	JPY^d
Jan 4, 1990	2.34	0.96 (0.56)		Intervention by the Bundesbank, the Bank of Japan, the Bank of England, and the Swiss National Bank. Sell US dollars	JPY^u , $Index^u$
May 9, 1990	2.05	0.93 (0.58)		Japan buys CHF to redeem franc debt	
June 4, 1993	-2.45	-0.90 (0.51)		Stronger than expected US May jobs report	
Dec 28, 1994	1.93	0.52 (0.80)		Speculation that Mexico may have drawn on its multi-billion dollar lines of credit expanded by the US and Canada one week earlier to halt the peso's decline	
Jan 9, 1995	2.11	1.08 (0.64)		Concerns of a protectionist American trade policy. US Ambassador warns Japan that the Clinton administration might use Super 301 trade sanctions against Japan. Fed's surprise intervention to support the Mexican peso	
Mar 1, 1995	-0.13	0.29 (0.41)		Richmond Federal Reserve Bank President: Fed did not target foreign exchange rates European currencies lose ground against the powerful Deutsche mark	JPY^v
May 11, 1995	-3.85	-2.35 (0.81)		Optimistic US producer price figures	$Index^d$
May 25, 1995	3.63	2.56 (0.88)		Weak US economic figures. Fear that trade war with Japan will depreciate the US dollar. Vague rumors that Mexico might be forced to default on \$20 billion US loan	$Index^u$
Aug 15, 1995	-3.30	-2.65 (0.94)		Unexpected intervention by the Fed, the Bundesbank, the Bank of Japan, and the Swiss National Bank. Buy US dollars	JPY^d , $Index^d$
Sep 20, 1995	2.62	1.68 (0.80)		Unexpected widening of the US trade deficit	
Sep 21, 1995	2.70	1.87 (0.84)		Disappointment over the lack of intervention to support the US dollar by the Fed, the Bundesbank, and the Bank of Japan. Record high US trade deficit	JPY^u , GBP^u , $Index^u$
July 16, 1996	2.49	2.31 (1.00)		US stock market plummets for the second consecutive day	$Index^u$
July 17, 1996	0.60	0.20 (1.00)		Markets anticipate Greenspan's speech on the economic outlook	GBP^v

Table 2
CHF events continued

Date	Excess return	Jump in FX	Jump in Vol	Events/Sources of uncertainty	Impact on FX
May 20, 1997	3.01	2.56 (0.97)		Fed's announcement: no interest rate increase	JPY^u, JPY^v
July 15, 1997	-0.04		0.11 (0.99)	The US dollar is lifted by continued weakness in the Deutsche Mark	
Oct 28, 1997	1.10		0.16 (1.00)	Huge losses in the US equity market – largest drop since Black Monday	AUD^u
Jan 6, 1998	-0.27		0.10 (0.58)	Soaring US dollar. Concerns over the Asian currency crisis	AUD^v
Jan 26, 1998	-1.04		0.11 (0.87)	Clinton negates that he had an affair with a White House intern	GBP^v
Aug 28, 1998	2.82	2.62 (1.00)		Yeltsin dismisses the rumors he would quit over Russian financial crisis. Investors see Russia as a big risk to Latin America, and that's a big risk for the US	$GBP^u, Index^u$
Aug 31, 1998	-0.15		0.19 (1.00)	Japan's Defence Agency reports that North Korea fires a ballistic missile into the Sea of Japan	GBP^v
Sep 11, 1998	-0.43		0.19 (1.00)	Markets are under influence of the political scandal around Clinton. Possibility of impeachment	GBP^v
Oct 2, 1998	0.23		0.10 (0.78)	Slow US jobs growth. Tumbling equity market in the US	
Oct 8, 1998	-0.57		0.09 (0.84)	Large moves in the US dollar/yen rate. Hedge funds unwind their positions	$AUD^v, JPY^v, Index^v$
Dec 11, 1998	0.58		0.11 (0.81)	Dollar is hurt by the Clinton impeachment proceedings	
Dec 29, 1998	0.01		0.09 (0.94)	Uncertainty about the January launch of the euro	JPY^v
Jan 14, 1999	0.28		0.10 (0.97)	Deepening of Brazil's financial crisis. Brazil's central bank president resigns. Official trading band for Brazil's real is widened	
Nov 24, 1999	-0.94		0.11 (0.57)	Weak euro-zone economic data	
Nov 29, 1999	-0.74		0.12 (0.55)	Intervention by the Bank of Japan to support the US dollar	
Jan 31, 2000	-0.42		0.11 (0.98)	Euro erodes further. Expectation of US strong economic data. Heightened expectation of the aggressive Fed credit tightening	
Feb 28, 2000	-0.35		0.21 (1.00)	Dramatic drop of the euro against the US dollar	GBP^v
Sep 7, 2000	0.02		0.13 (1.00)	The Euro keeps depreciating	
Oct 12, 2000	-0.06		0.11 (1.00)	Escalating conflict in the Middle East – Israel vs Palestine. Israel fires at targets near Yasser Arafat's headquarters, the US Navy destroyer is bombed in Yemen	
Oct 25, 2000	-1.30		0.09 (0.87)	US equities are recovering. Fading expectations of central bank intervention to support the Euro against the rampant US dollar	GBP^v
Sep 11, 2001	2.76	1.81 (0.82)		Terrorist attack on the US	$GBP^v, JPY^v, Index^v$

Table 2
CHF events continued

Date	Excess return	Jump in FX	Jump in Vol	Events/Sources of uncertainty	Impact on FX
Sep 12, 2001	-1.05		0.14 (0.97)	Aftermath of the terrorist attacks on the US. The ECB, the Swiss National Bank, and the Bank of Japan add liquidity to the financial system	
Sep 17, 2001	1.10		0.11 (0.54)	Intervention by the Bank of Japan to support the US dollar. Markets are turbulent ahead of Wall Street's open after September 11	$AUD^v, JPY^v, Index^v$
Dec 24, 2001	-2.50	-2.31 (0.99)		Argentina's massive debt constraints euro	
Dec 25, 2001	0.25		0.09 (0.98)	Argentina stops servicing most of its foreign debt	
Jan 2, 2002	1.12		0.14 (1.00)	Euro is boosted by launch of physical currency	$Index^v$
Jan 25, 2002	-1.83		0.09 (0.92)	Alan Greenspan's says that the US economy is coming out of its recession	
June 24, 2002	-0.01		0.10 (0.79)	Bush's speech on the Middle East boosts stock market. Intervention by the Bank of Japan to support the US dollar	$Index^v$
June 26, 2002	0.26		0.11 (0.52)	Accounting WorldCom scandal. US Securities and Exchange Commission launches investigation	$GBP^v, Index^v$
Nov 18, 2003	2.52	0.89 (0.51)		Geopolitical jitters: weekend bombings in Turkey and reports that al-Qaeda could target Japan. The US reduces import quotas on selected Chinese textiles. Fear that protectionism would hurt the US economic recovery	
Nov 7, 2007	0.96		0.11 (1.00)	Ben Bernanke emphasizes bleak picture of the US economy	$GBP^v, JPY^v, Index^v$
Mar 17, 2008	1.38		0.15 (0.97)	JPMorgan Chase offers to acquire Bear Sterns at a price of 2 US dollars. Dramatic sell-off in global equity market	$Index^v$
June 9, 2008	-0.88		0.09 (0.60)	Better than expected US pending home sales data	
Aug 8, 2008	-1.85		0.10 (0.99)	President of the ECB predicts that eurozone economy would weaken substantially in the coming months	$GBP^v, Index^d$
Sep 15, 2008	1.30		0.12 (0.99)	Lehman Brothers collapse	$AUD^v, GBP^v, JPY^u, JPY^v, Index^v$
Sep 29, 2008	0.03		0.13 (0.95)	Unprecedented coordinated attempt to pour liquidity into the financial system through short-term loans by the Fed, the ECB, the Bank of Japan, the Reserve bank of Australia, and the Bank of England. The US House of Representatives rejects a proposed \$700 billion financial bailout package	$AUD^v, GBP^v, JPY^v, Index^v$
Oct 6, 2008	-1.74		0.12 (0.98)	Crash in the European and US equity markets	$AUD^v, AUD^d, GBP^v, JPY^v, Index^v$

Table 2
CHF events continued

Date	Excess return	Jump in FX	Jump in Vol	Events/Sources of uncertainty	Impact on FX
Oct 22, 2008	-1.04		0.15 (0.72)	Fear of the great recession worsening	$AUD^v, GBP^v, JPY^v, Index^v$
Nov 21, 2008	-0.06		0.11 (0.93)	Surprise interest rate cut by the Swiss National Bank	
Dec 15, 2008	1.56		0.23 (0.99)	Widely expected interest rate cut by the Fed. Concerns over the health of the US economy and the impact of the US government's rescue plan	$GBP^v, Index^v$
Dec 17, 2008	4.69		0.23 (0.98)	Drop in the US trade deficit	$AUD^v, GBP^v, Index^v$
Dec 29, 2008	0.73		0.19 (0.99)	Israeli air strikes in the Gaza Strip boost dollar-denominated oil prices	$Index^v$
Feb 10, 2009	0.63		0.10 (0.92)	The US Treasury Secretary announces a plan to rescue the banking system which disappoints the market. The US Senate passes a massive economic stimulus package	$AUD^v, Index^v$
Mar 12, 2009	-2.74		0.09 (0.90)	The Swiss National Bank targets to decrease LIBOR	
May 22, 2009	0.74		0.09 (0.83)	Signs of higher inflation in the US. US Labor Department report: unemployment hits a record high	$GBP^v, Index^v$
Aug 3, 2009	0.85		0.09 (0.91)	Signs of recovery from data on manufacturing surveys across the globe	$Index^v$
Feb 4, 2010	-0.69		0.11 (0.51)	Strong economic US data	$Index^v$
May 5, 2010	-1.37		0.12 (0.69)	Turbulent European markets, debt problems	$Index^v$

Notes: This table summarizes information about events and sources of uncertainty which are associated with substantial movements in FX market qualified as jumps in prices or volatility. The second column is daily excess log currency returns in percent per day. The third and fourth columns provide estimates of the size of jumps and probability of jumps (in parentheses), size of jumps is in percent. The last two columns describe the news and which cross rates are affected. If we cannot attribute FX dynamics to specific news or events we indicate what type of uncertainty causes market movements. Source of news: Factiva.

Table 3
GBP events

Date	Excess return	Jump in FX	Jump in Vol	Events/Sources of uncertainty	Impact on FX
Jan 20, 1986	0.02		0.29 (0.54)	Financial representatives of the US, the UK, France, West Germany, and Japan reject a Japanese proposal of interest rate cut	
Mar 7, 1988	2.46	1.38 (0.73)		The Bank of England abandons its defense of the 3.00-mark level. Expected negative release of the US trade figures	
Sep 25, 1989	2.87	1.26(0.64)		G-7 meeting stresses that strong USD contributes to a world trade imbalance. Coordinated intervention by the Bank of Japan, the Fed, the Bank of Canada, the Swiss National Bank, the Bank of France, the Bank of Italy, and the central bank of Denmark. Sell USD	JPY^u , $Index^u$
Oct 26, 1989	-2.39	-1.23 (0.67)		Surprise news – Britain's finance minister Lawson has resigned. Alan Greenspan says that the Fed is concerned about inflation	
Jan 9, 1992	-3.38	-1.34 (0.62)		Speculation about devaluation or an ERM realignment	
July 20, 1992	-2.25	-0.87 (0.54)		Two rounds of concerted central bank intervention to support the US dollar by the Bundesbank, the Fed, and Western-European central banks	
Sep 4, 1992	1.09		0.25 (0.39)	Bad unemployment US data. UK Treasury announces that it would borrow money in foreign currency to buy pounds	$Index^v$
Sep 8, 1992	0.63		0.25 (0.47)	The Bank of England announces that it temporarily stops linking the Finnish markka to the Deutsche mark. Finland is expected to devalue. Investors buy the Deutsche mark; sterling is under pressure, US dollar suffers even more	
Dec 29, 1993	-2.03	-1.36 (0.79)		Positive US economic data	
Aug 26, 1994	-1.86	-0.98 (0.65)		Speculation about imminent further US interest rate hike. Positive US economic data	$Index^d$
Sep 21, 1995	2.54	2.35 (1.00)		Disappointment over the lack of intervention to support the US dollar by the Fed, the Bundesbank, and the Bank of Japan. Record high US trade deficit	CHF^u , JPY^u , $Index^u$
May 29, 1996	1.14	0.87 (0.81)		Richmond Federal Reserve Bank President says that the Fed may need to move toward greater monetary restraint. UK government bond auction highlights strong investor demand for British government debt	
May 30, 1996	0.17		0.09 (0.90)	Surprise positive UK economic data. Germany decides to keep interest rates steady contrary to expectations to cut the rates	
July 17, 1996	-0.76		0.10 (0.82)	Markets anticipate Greenspan's speech on the US economic outlook	CHF^v
Oct 31, 1996	-0.33		0.10 (0.80)	Bank of England raises key lending rate	
Nov 5, 1996	0.16		0.11 (0.62)	US presidential elections	
Dec 3, 1996	-2.23	-2.03 (1.00)		British Chancellor of the Exchequer says that strong pound worries UK businesses, UK is exempted from a proposed European stability act in the run-up to a single currency	AUD^d

Table 3
GBP events continued

Date	Excess return	Jump in FX	Jump in Vol	Events/Sources of uncertainty	Impact on FX
Dec 6, 1996	0.73		0.09 (0.89)	Surprisingly weak US payrolls report	
Jan 6, 1997	0.54		0.10 (0.52)	Additional political risks for GBP: UK election campaign	
Jan 23, 1997	-0.30		0.10 (0.93)	Remarks by Japanese and French officials hint that all G7 countries want dollar to continue to rise	
Aug 7, 1997	-1.02		0.09 (1.00)	Governor of the Bank of England: no need to increase interest rates further	
Oct 29, 1997	0.23		0.18 (1.00)	Jittering US and Asian equity markets	
Jan 26, 1998	-0.92		0.10 (0.52)	Clinton negates that he had an affair with a White House intern	CHF^v
Aug 28, 1998	1.88	1.74 (0.98)		Yeltsin dismisses the rumors he would quit over Russian financial crisis. Investors see Russia as a big risk to Latin America, and that's a big risk for the US	CHF^u , $Index^u$
Aug 31, 1998	-0.04		0.10 (1.00)	Japan's Defence Agency reports that North Korea fires a ballistic missile into the Sea of Japan	CHF^v
Sep 11, 1998	-1.00		0.09 (0.80)	The Bank of England's Monetary Policy Committee: British inflation could fall below government's target. Markets are under influence of the political scandal around Clinton. Possibility of impeachment	CHF^v
Oct 9, 1998	-0.17		0.16 (0.96)	Instability in Brazil. Expectations of interest rate cuts in the UK and the US. Massive purchase of yen by hedge funds and other speculators to cover earlier positions	
Dec 4, 1998	-0.11		0.11 (0.93)	Expectations of interest rate cuts in the UK	
Jan 4, 1999	-0.00		0.10 (0.61)	The first day of Euro trade	
Nov 30, 1999	-0.52		0.16 (1.00)	Speculation that the ECB will intervene to support the Euro	
Feb 28, 2000	0.03		0.10 (0.63)	Dramatic drop of the Euro against the US dollar	CHF^v
Apr 28, 2000	-1.33		0.09 (0.80)	Weak UK growth data dampens expectations of interest rate increase	
May 11, 2000	-0.55		0.08 (0.97)	Fear of rising interest rates in the US	
Sep 8, 2000	-1.61		0.08 (0.98)	Speculation that the UK interest rates would stay on hold for the months to come amid the benign inflation	
Oct 17, 2000	0.18		0.10 (0.66)	Progress at an emergency Middle East summit. Firmer stock markets, easing oil prices. Sterling is weighed down by relentless euro weakness	
Oct 25, 2000	-1.25		0.09 (0.66)	US equities are recovering. Fading expectations of central bank intervention to support the Euro against the rampant US dollar. Quarterly survey by the Confederation of the UK industry shows that the country's manufacturing sector suffers a profit squeeze	CHF^v

Table 3
GBP events continued

Date	Excess return	Jump in FX	Jump in Vol	Events/Sources of uncertainty	Impact on FX
Jan 6, 2001	-1.51		0.09 (1.00)	Fear of rising interest rates in the US	
Sep 11, 2001	1.34		0.13 (0.99)	Terrorist attacks on the US	$CHF^u, JPY^v, Index^v$
June 26, 2002	1.18		0.13 (1.00)	Accounting WorldCom scandal. US securities and Exchange Commission launches investigation. British Prime Minister Brown says that he supports any decision the Bank of England might make to increase interest rates in order to prevent house prices from rising too far and stop strong consumer demand from high inflation	$CHF^v, Index^v$
Nov 24, 2006	0.87		0.07 (0.99)	The deputy governor of the People's Bank of China: dollar's recent decline increased risk for Asian reserve assets; possibility of selling the US dollar.	
Nov 7, 2007	0.76		0.08 (1.00)	Ben Bernanke emphasizes bleak picture of the US economy	$CHF^v, JPY^v, Index^v$
Dec 17, 2007	0.16		0.10 (0.62)	Falling global stock prices. Investor speculation that Fed would cut interest rates further. Liquidation of bets against USD	
Mar 14, 2008	-0.64		0.09 (0.77)	The US government and JPMorgan Chase bail out Bear Sterns	JPY^v
Aug 8, 2008	-1.16		0.11 (1.00)	President of the ECB: eurozone economy would weaken substantially in the coming months	$CHF^v, Index^d$
Sep 15, 2008	0.37		0.11 (1.00)	Lehman Brothers collapse	
Sep 29, 2008	-1.96		0.13 (0.96)	Unprecedented coordinated attempt to pour liquidity into the financial system through short-term loans by the Fed, the ECB, the Bank of Japan, the Reserve bank of Australia, and the Bank of England. The US House of Representatives rejects a proposed \$700 billion bailout package	$AUD^v, CHF^v, JPY^u, JPY^v, Index^v$ $AUD^v, CHF^v, JPY^u, JPY^v, Index^v$
Sep 30, 2008	-1.56		0.08 (0.82)	Bank crisis deepens in Europe. Banking bailouts	$AUD^v, Index^v$
Oct 6, 2008	-1.55		0.13 (0.99)	Crash in the European and US equity markets	$AUD^d, AUD^v, CHF^v, JPY^v, Index^v$
Oct 21, 2008	-2.63		0.17 (0.97)	Bernanke's speech about fiscal stimulus supports the view that the US will recover from a global economic slowdown earlier than other countries. Fear that European banks may be forced to pay default protection at a Lehman Brothers Holding CDS settlement	
Oct 22, 2008	-2.65		0.18 (0.97)	Fear of the great recession worsening	$AUD^v, CHF^v, JPY^v, Index^v$
Oct 24, 2008	-2.06		0.31 (1.00)	The White House announces that the widespread recession is inevitable. British Prime Minister acknowledges that the UK is likely entering recession. Global stocks plumb multi-year lows	$AUD^v, JPY^v, Index^v$
Oct 30, 2008	0.49		0.31 (1.00)	The Fed cuts interest rates and stresses downside economic risks	
Nov 12, 2008	-2.76		0.20 (1.00)	Turmoil in equity markets, thin trading before the Veteran's day in the US. The Bank of England considers a further cut of the interest rates as disinflation is forecasted	$AUD^v, JPY^v, Index^v$
Dec 1, 2008	-3.25		0.09 (0.61)	Meltdown in the equity markets	$Index^v$

Table 3
GBP events continued

Date	Excess return	Jump in FX	Jump in Vol	Events/Sources of uncertainty	Impact on FX
Dec 15, 2008	2.40		0.08 (0.75)	Widely expected interest rate cut by the Fed. Concerns over the health of the US economy and the impact of the US government's rescue plan	CHF^v , $Index^v$
Dec 17, 2008	-0.28		0.13 (0.97)	Drop in the US trade deficit.	AUD^v , CHF^v , $Index^v$
Jan 5, 2009	1.05		0.07 (0.62)	Hopes that fresh stimulus plans from the US and Germany would help the global economy recover. Rebounding stock market encourages investors to pick up higher-yielding currencies. Pound takes advantage from the pressure on Euro	AUD^v
Jan 19, 2009	-2.14		0.09 (0.67)	The UK expands bailout package for the banking system. The UK government decides to take a larger stake in RBS	
Jan 20, 2009	-3.47		0.19 (0.97)	Crisis in UK banking sector and ratings downgrade for Spain	JPY^v , $Index^v$
Feb 11, 2009	-1.00		0.09 (0.87)	Governor of the Bank of England: perspectives of implementing quantitative easing	
May 22, 2009	0.57		0.09 (0.67)	Signs of higher inflation in the US. US Labor Department report – unemployment hits a record high	CHF^v , $Index^v$
Sep 28, 2009	-0.43		0.08 (0.75)	Traders interpret comments by governor of the Bank of England as suggesting that British authorities would be comfortable with a weaker pound	
Feb 5, 2010	-0.72		0.08 (0.88)	Fears of a sovereign debt crisis among Europe's nations	
Mar 1, 2010	-1.63		0.11 (1.00)	Worries about the outcome of forthcoming UK general election and ability of the UK government to remedy the high fiscal deficit	
Mar 22, 2010	0.58		0.08 (0.77)	Director of currency research at Global Forex Trading: final approval of the health care bill has contributed to the US dollar weakness	
May 6, 2010	-1.80		0.17 (1.00)	General election in the UK. Mounting fears over the Greek debt, Greek riots	AUD^v , JPY^u , JPY^v , $Index^v$
May 19, 2010	0.77		0.08 (0.73)	German ban on naked short sales of euro-zone government bonds and CDSs increases risk aversion	AUD^v , $Index^v$

Notes: This table summarizes information about events and sources of uncertainty which are associated with substantial movements in FX market qualified as jumps in prices or volatility. The second column is daily excess log currency returns in percent per day. The third and fourth columns provide estimates of the size of jumps and probability of jumps (in parentheses), size of jumps is in percent. The last two columns describe the news and which cross rates are affected. If we cannot attribute FX dynamics to specific news or events we indicate what type of uncertainty causes market movements. Source of news: Factiva.

Table 4
JPY events

Date	Excess return	Jump in FX	Jump in Vol	Events/Sources of uncertainty	Impact on FX
Oct 24, 1986	-2.02	-1.30 (0.77)		Positive US trade deficit report	
Jan 14, 1987	1.90	0.73 (0.50)		The Reagan administration was reported to support the decline of the US dollar in order to maintain the trade deficit	AUD ^d
June 2, 1987	2.21	1.36 (0.76)		Paul Volcker leaves the Fed	CHF ^u
Aug 18, 1987	2.59	2.16 (0.95)		Disappointing US trade deficit report	CHF ^u
Dec 10, 1987	2.28	1.04 (0.62)		Record US trade deficit report	
Dec 28, 1987	2.37	0.80 (0.50)		Persistent bearish sentiment: pessimism about the US budget and trade deficit	
Jan 5, 1988	-3.38	-2.47 (0.90)		Coordinated intervention by the G7 on behalf of the Federal Reserve Board and the US Treasury	CHF ^d , Index ^d
Jan 15, 1988	-2.94	-1.85 (0.82)		Positive US trade deficit report	
Apr 14, 1988	2.13	2.11 (1.00)		Disappointing US trade deficit report	CHF ^u
Oct 11, 1988	1.67	0.80 (0.58)		Weaker than expected US employment figures	
Oct 12, 1988	1.61	0.68 (0.51)		Expectations of very high US trade deficit figures to be released on Oct, 13	
Sep 18, 1989	1.96	0.95 (0.61)		Intervention by the Bank of Japan to support the yen	CHF ^u
Sep 25, 1989	2.00	1.09 (0.68)		G-7 meeting: strong US dollar contributes to a world trade imbalance. Coordinated intervention by the Bank of Japan, the Fed, the Bank of Canada, the Swiss National Bank, the Bank of France, the Bank of Italy, and the central bank of Denmark. Sell USD	GBP ^u , Index ^u
Jan 2, 1990	-1.70	-1.25 (0.83)		Rumors about a political scandal in Japan. Favorable US economic data: index of economic activity	CHF ^d
Jan 4, 1990	1.61	1.21 (0.83)		Intervention by the Bundesbank, the Bank of Japan, the Bank of England, and Swiss National Bank. Sell USD	CHF ^u , Index ^u
Apr 19, 1990	1.64	0.73 (0.53)		Intervention by the Bank of Japan	
May 11, 1990	2.75	2.46 (0.99)		Negative announcements of the US Labor Department and Department of Commerce.	
Jan 17, 1991	2.95	2.54 (0.97)		Gulf War: start of the Desert Storm	
Nov 27, 1991	-1.68	-0.73 (0.53)		False rumor of a second Soviet coup. Germany's top economist Moellemen says that dollar is undervalued relative to the Deutsche Mark	
Jan 20, 1992	2.77	2.40 (0.98)		Intervention by the Fed and the Bank of Japan. Buy the yen	
May 12, 1992	2.03	1.68 (0.93)		Treasury department official (Mulford): huge trade surplus of Japan, G7 should intervene. Speculation about the US interest rate cuts	
Sep 22, 1992	2.20	0.91 (0.57)		Speculation of an easier US monetary policy	
Feb 9, 1993	2.09	1.42 (0.82)		European parliament - yen is undervalued, raised speculation that the Clinton administration wants to see a stronger yen to reduce Japan's trade surplus	
June 11, 1993	-0.12		0.38 (0.59)	Expectations of the US producer price index release	

Table 4
JPY events continued

Date	Excess return	Jump in FX	Jump in Vol	Events/Sources of uncertainty	Impact on FX
Aug 19, 1993	-4.06	-3.41 (0.97)		Intervention by the Fed and the Bank of Japan to support the US dollar after news on widest US trade gap since Oct 1987	
Feb 14, 1994	4.87	4.41 (1.00)		US failure to reach a trade pact with Japan	
Mar 1, 1995	-0.09		0.61 (0.88)	Richmond Federal Reserve Bank President: Fed did not target foreign exchange rates	CHF^v
Aug 2, 1995	-3.47	-1.65 (0.68)		Intervention by the US Fed	
Aug 15, 1995	-3.80	-2.21 (0.78)		Unexpected intervention by the Fed, the Bundesbank, the Bank of Japan, and the Swiss National Bank. Buy US dollar	CHF^d , $Index^d$
Sep 21, 1995	3.45	2.35 (0.86)		New economic stimulus program of Japan. Disappointment over the lack of intervention to support the US dollar by the Fed, the Bundesbank, and the Bank of Japan. Record high US trade deficit	CHF^u , GBP^u , $Index^u$
Apr 30, 1996	-0.20		0.17 (0.86)	Thin trading before holidays	
Jan 29, 1997	-0.88		0.14 (0.98)	Expectation of the US interest rate increase due to sharply higher inflation	
May 9, 1997	2.94	2.51 (1.00)		Japan's Finance Minister: probable intervention to limit the US dollar rise	
May 15, 1997	1.06		0.14 (0.86)	Downward pressure on USD due to option and hedge-related selling. Larger than expected fall in the US producer prices	
May 20, 1997	2.66	0.91 (0.53)	0.17 (0.59)	Fed's announcement: no interest rate increase.	CHF^u
June 9, 1997	1.13		0.21 (1.00)	US Trade Representative: "the US won't tolerate a widening trade gap with Japan"	
Aug 8, 1997	3.18	2.82 (0.99)		Japan reports its widened trade surplus	
Jan 5, 1998	-0.85		0.12 (0.83)	Alan Greenspan's speech: global deflation	
June 12, 1998	0.17		0.20 (0.89)	Release of official Japanese figures: recession	
June 15, 1998	-1.36		0.16 (0.57)	No significant news. Yen is victim of the Asian crisis and weak state of the JP economy	
June 17, 1998	4.57	3.19 (0.93)		Coordinated intervention by the US and Japan. Buy the yen for the US dollar	
Sep 8, 1998	-0.18		0.12 (0.65)	Stock market gains in the US, Germany, France. Impact of Russia's economic turmoil	
Oct 7, 1998	6.93	5.33 (1.00)		Greenspan: negative prospects for the US economy, credit crunch. Possible further cut of the US interest rate. Threat of Clinton impeachment	AUD^u , $Index^u$
Oct 8, 1998	2.02		0.49 (1.00)	Large moves in the US dollar/yen rate. Japanese shares collapse. Hedge funds unwind their positions	AUD^v , CHF^v
Nov 11, 1998	0.31		0.15 (0.57)	Rumor of consumption tax cut in Japan. This trading day amid US Veterans Day holiday	
Dec 3, 1998	1.67		0.18 (0.99)	Negative news from the US equity market	
Dec 10, 1998	0.69		0.13 (0.58)	Japanese Finance Minister suggests that the US would like to have a weaker dollar	
Dec 29, 1998	0.38		0.13 (0.53)	Uncertainty about the January launch of the Euro. Sharp increase of the Japanese interest rates and stock prices	CHF^v
Feb 2, 1999	2.61		0.15 (0.98)	Soaring long-term interest rates	
Feb 16, 1999	-2.46		0.13 (0.86)	Top financial Japanese diplomat Eisuke Sakakibara: G7 and US can accept weak yen	

Table 4
JPY events continued

Date	Excess return	Jump in FX	Jump in Vol	Events/Sources of uncertainty	Impact on FX
July 20, 1999	-0.60		0.17 (0.51)	Expected intervention by the Bank of Japan to buy US dollar	
Aug 18, 1999	1.84		0.17 (1.00)	Disappointing US trade deficit report	
Sep 15, 1999	1.12		0.22 (0.95)	Growing optimism about the strength of the Japanese economy.	
Sep 21, 1999	1.17		0.13 (0.67)	US trade deficit ballooned to a record \$25.2 billion	
Nov 26, 1999	2.45	1.46 (0.76)	0.30 (1.00)	JP Trade Ministry: positive news about GDP	
Mar 31, 2000	2.65		0.18 (0.90)	Optimism about the Japanese economy: recovering from recession	
Jan 15, 2001	-0.40		0.13 (0.79)	Rumors that two large JP banks were facing financial difficulty in morning trading	
Mar 2, 2001	-1.38		0.16 (0.57)	Record figures for Japanese unemployment and fall in Tokyo area consumer prices	
May 23, 2001	2.24	0.89 (0.59)		Negative economic news in Europe. Pressure from Japanese and US bank sales	
Sep 11, 2001	1.33		0.16 (1.00)	Terrorist attack on the US	$CHF^u, GBP^v, Index^v$
Sep 17, 2001	-0.41		0.16 (0.61)	Intervention by the Bank of Japan to support the US dollar. Markets are turbulent ahead of Wall Street's opening after September 11	$AUD^v, CHF^v, Index^v$
Mar 7, 2002	2.40	0.98 (0.60)		US imposes tariffs on steel imports	
Dec 2, 2002	-1.55	-1.20 (0.75)		Japanese Finance minister calls for yen weakening to support Japanese companies	
Sep 19, 2003	1.09		0.13 (0.97)	Speculation about the intention of G7 to object Japan's weakening intervention policies	
Feb 20, 2004	-1.88	-2.00 (0.98)		Japan is on terror alert. Japan dispatches troops on a humanitarian mission to Iraq	AUD^d
July 21, 2005	2.35	1.87 (0.98)		China revalues its currency	
Dec 14, 2005	2.15	1.58 (0.92)		Negative US trade deficit report	
Feb 27, 2007	2.27	1.79 (0.99)		Steepest single-session US stock market decline in more than five years	
July 10, 2007	1.34	1.04 (0.82)		Announcement of Moody's investors service to review the credit rating of Japan's Asahi Bank for possible downgrade	
Aug 16, 2007	2.34		0.22 (0.91)	The Fed unexpectedly cuts the discount rate on its lending to banks. Bad US employment figures	$AUD^v, AUD^d, Index^v$
Nov 7, 2007	1.83		0.14 (0.89)	Ben Bernanke: bleak picture of the US economy	$CHF^v, GBP^v, Index^v$
Nov 9, 2007	1.70		0.17 (0.98)	Oil prices near record highs. Persistent fears of ongoing credit crisis	
Feb 29, 2008	1.55		0.15 (0.98)	Worsening US economic data. Fears of further aggressive US interest rate cut	
Mar 13, 2008	1.12		0.17 (0.65)	Fears of the recession in the US	
Mar 14, 2008	1.55		0.16 (0.57)	The US government and JPMorgan chase bail out Bear Sterns	GBP^v

Table 4
JPY events continued

Date	Excess return	Jump in FX	Jump in Vol	Events/Sources of uncertainty	Impact on FX
Sep 5, 2008	-0.61		0.14 (0.71)	Downbeat US employment figures, disappointing retail sales data, growing speculation about troubles at major hedge funds	AUD^v
Sep 15, 2008	3.08	1.68 (0.75)	0.28 (1.00)	Lehman Brothers collapse	$AUD^v, CHF^v, GBP^v, Index^v$
Sep 29, 2008	1.73		0.13 (0.55)	Unprecedented coordinated attempt to pour liquidity into the financial system through short-term loans by the Fed, the ECB, the Bank of Japan, the Reserve bank of Australia, and the Bank of England. The US House of Representatives rejects a proposed \$700 billion financial bailout package	$AUD^v, CHF^v, GBP^v, Index^v$
Oct 6, 2008	3.37		0.34 (1.00)	Crash in the European and US equity markets	$AUD^d, AUD^v, CHF^v, GBP^v, Index^v$
Oct 8, 2008	2.31		0.15 (0.63)	Coordinated interest rate cut: the Fed, the ECB, the Bank of England, the Bank of Canada, the Swiss National Bank, and the Swedish Riksbank	AUD^v, JPY^v
Oct 22, 2008	2.50		0.19 (0.50)	Fear of the great recession worsening	$AUD^v, CHF^v, GBP^v, Index^v$
Oct 23, 2008	0.35		0.17 (0.67)	US stocks decline on crumbling global economic outlook	
Oct 24, 2008	3.11		0.19 (0.62)	The White House announces that the widespread recession is inevitable. British Prime Minister acknowledges that the UK is likely entering recession	$AUD^v, GBP^v, Index^v$
Nov 12, 2008	2.74		0.20 (0.97)	Global stocks plumb multi-year lows	
Dec 12, 2008	0.26		0.17 (0.96)	Turmoil in equity markets, thin trading before the Veteran's day in the US	$AUD^v, GBP^v, Index^v$
Jan 20, 2009	0.98		0.15 (0.54)	Negative US trade deficit news. Failure of a proposed US government plan to bail out US auto makers	$Index^v$
Jan 21, 2009	0.30		0.21 (0.90)	Crisis in UK banking sector and ratings downgrade for Spain	$GBP^v, Index^v$
May 12, 2009	1.06		0.15 (0.54)	Strong concerns about European financial institutions	
July 8, 2009	2.14		0.14 (0.64)	Financial Times: does US deserve to keep triple A credit rating?	
Nov 27, 2009	0.07		0.15 (0.68)	Flight to safety and risk aversion	
Dec 4, 2009	-2.57	-1.07 (0.57)		Debt problems of Dubai World	
Mar 24, 2010	-2.08	-1.46 (0.75)		Positive report of the US Labor department	
May 6, 2010	3.50	3.05 (0.99)	0.19 (1.00)	Downgrading of Portugal's credit rating by Fitch Ratings boosts the US dollar	
May 20, 2010	2.24		0.19 (0.98)	Mounting fears over the Greek debt, Greek riots	$AUD^v, GBP^v, Index^v$
Sep 15, 2010	-3.21	-1.98 (0.83)		Concerns over policymakers' response to the euro zone debt crisis. Intervention by the Bank of Japan	

Notes: This table summarizes information about events and sources of uncertainty which are associated with substantial movements in FX market qualified as jumps in prices or volatility. The second column is daily excess log currency returns in percent per day. The third and fourth columns provide estimates of the size of jumps and probability of jumps (in parentheses), size of jumps is in percent. The last two columns describe the news and which cross rates are affected. If we cannot attribute FX dynamics to specific news or events we indicate what type of uncertainty causes market movements. Source of news: Factiva.

Table 5
Index events

Date	Excess return	Jump in FX	Jump in Vol	Events/Sources of uncertainty	Impact on FX
Jan 5, 1988	-1.71	-1.17 (0.72)		Coordinated intervention by the G7 on behalf of the Federal Reserve Board and the US Treasury	CHF^d, JPY^d
Jan 30, 1986	0.16		0.21 (0.60)	Report of the Commerce Department: record nations' trade deficit. Japan cuts its basic rate. Expectations of discount rate cut by the Fed.	
Sep 25, 1989	1.71	1.39 (0.87)		G-7 meeting: strong US dollar contributes to a world trade imbalance. Coordinated intervention by the Bank of Japan, the Fed, the Bank of Canada, the Swiss National Bank, the Bank of France, the Bank of Italy, and the central bank of Denmark. Sell USD	GBP^u, JPY^u
Nov 5, 1989	-0.37		0.34 (0.94)	Expectations of firm rates in US: positive employment news	
Jan 4, 1990	1.48	1.21 (0.86)		Intervention by the Bundesbank, the Bank of Japan, the Bank of England, and Swiss National Bank. Sell USD	CHF^u, JPY^u
Aug 24, 1992	1.61	1.00 (0.65)		The pound is under pressure: withdrawal from the ERM or devaluation. Expectations of the campaign to defend the pound	
Sep 8, 1992	-0.48		0.34 (0.73)	The Bank of England announces that it temporarily stops linking the Finnish markka to the Deutsche mark. Finland is expected to devalue. Investors buy the Deutsche mark: sterling is under pressure; US dollar suffers even more	GBP^v
July 11, 1994	1.64	0.94 (0.60)		Market nervousness due to the consensus of non-intervention of G7 in FX and bond markets	
Aug 26, 1994	-1.62	-1.29 (0.82)		Positive US economic data	GBP^d
Feb 27, 1995	-0.38		0.22 (0.56)	Spillovers from financial markets: collapse of merchant bank Baring plc. Political uncertainty in the UK	
May 11, 1995	-1.50	-1.50 (0.82)		Optimistic US producer price index	CHF^d
May 25, 1995	1.99	1.62 (0.89)		Weak US economic figures. Fear that trade war with Japan will depreciate the US dollar. Vague rumors that Mexico might be forced to default on \$20 billion US loan	CHF^u
Aug 15, 1995	-1.92	-1.81 (0.99)		Unexpected intervention by the Fed, the Bundesbank, the Bank of Japan and the Swiss National Bank. Buy US dollars	CHF^d, JPY^d
Sep 21, 1995	1.62	1.41 (0.92)		Disappointment over the lack of intervention to support the US dollar by the Fed, the Bundesbank, and the Bank of Japan. Record high US trade deficit	CHF^u, GBP^u, JPY^u
July 16, 1996	1.24	1.17 (0.96)		US stock market plunges for the second consecutive day	CHF^u
Aug 28, 1998	1.94	1.84 (0.99)		Yeltsin dismisses the rumors he would quit over Russian financial crisis. Investors see Russia as a big risk to Latin America, and that's a big risk for the US	CHF^v, GBP^u
Sep 10, 1998	1.51	1.09 (0.73)		Thatcher warns Tories to battle against Euro.	
Oct 7, 1998	1.68	1.35 (0.84)		Greenspan: negative prospects for the US economy, credit crunch. Possible further cut of the US interest rates. Threat of Clinton impeachment. Strong AU employment report	AUD^u, JPY^u
Jan 1, 2000	-0.26		0.57 (1.00)	Expectations of rising interest rates in Europe and US	
Nov 17, 2000	-0.36		0.60 (1.50)	Negative spillover from Canadian equity market	
Sep 11, 2001	1.38		0.06 (1.00)	Terrorist attack on the US	CHF^u, GBP^v, JPY^v

Table 5
Index events continued

Date	Excess return	Jump in FX	Jump in Vol	Events/Sources of uncertainty	Impact on FX
Sep 17, 2001	-0.03		0.07 (0.79)	Intervention by the Bank of Japan to support the US dollar. Markets are turbulent ahead of Wall Street's opening after September 11	AUD^v, CHF^v, JPY^v
Jan 2, 2002	1.09		0.04 (0.95)	Euro is boosted by launch of physical currency	CHF^v
June 24, 2002	-0.04		0.09 (0.63)	Bush's speech on the Middle East boosts stock market. Intervention by the Bank of Japan to support the US dollar	CHF^v
June 26, 2002	0.12		0.05 (0.99)	Accounting WorldCom scandal. US securities and Exchange Commission launches investigation	CHF^v, GBP^v
Aug 16, 2007	-0.31		0.07 (0.92)	The Fed unexpectedly cuts the discount rate on its lending to banks. Bad US unemployment data	AUD^d, AUD^v, JPY^v
Nov 7, 2007	0.42		0.04 (0.99)	Ben Bernanke emphasizes bleak picture of the US economy	CHF^v, GBP^v, JPY^v
Mar 17, 2008	0.10		0.09 (0.86)	JPMorgan Chase offers to acquire Bear Sterns at a price of 2 US dollars. Dramatic sell-off in global equity markets	CHF^v
Aug 8, 2008	-1.60	-1.20 (0.78)	0.04 (1.00)	President of the ECB predicts that eurozone economy would weaken substantially in the coming months	CHF^v, GBP^v
Sep 15, 2008	0.07		0.10 (1.00)	Lehman Brothers collapse	$AUD^v, CHF^v, GBP^v, JPY^u, JPY^v$
Sep 29, 2008	-1.10		0.11 (0.97)	Unprecedented coordinated attempt to pour liquidity into the financial system through short-term loans by the Fed, the ECB, the Bank of Japan, the Reserve bank of Australia, and the Bank of England. The US House of Representatives rejects a proposed \$700 billion financial bailout package	$AUD^v, CHF^v, GBP^v, JPY^v$
Sep 30, 2008	-1.74		0.12 (0.50)	Bank crisis deepens in Europe. Banking bailouts	AUD^v, GBP^v
Oct 6, 2008	-1.78		0.19 (1.00)	European and US stocks are crashed. The Reserve Bank of Australia cuts its benchmark rate	$AUD^v, CHF^v, GBP^v, JPY^v$
Oct 8, 2008	-0.16		0.17 (1.00)	Coordinated cut of interest rates by the FED, the ECB, the Bank of England, the Bank of Canada, the Swiss National Bank, and the Swedish Riksbank	AUD^v, JPY^v
Oct 22, 2008	-1.32		0.27 (1.00)	Fear of the great recession worsening	$AUD^v, CHF^v, GBP^v, JPY^v$
Oct 24, 2008	-2.15		0.37 (1.00)	The White House announces that the widespread recession is inevitable. British Prime Minister acknowledges that the UK is likely entering recession. Global stocks plumb multi-year lows	AUD^v, GBP^v, JPY^v
Nov 12, 2008	-0.48		0.20 (1.00)	Turmoil in equity markets, thin trading before the Veteran's day in the US	AUD^v, GBP^v, JPY^v
Dec 1, 2008	-0.83		0.14 (1.00)	Meltdown in equity markets	GBP^v
Dec 12, 2008	-0.18		0.08 (1.00)	Negative US trade deficit news. Failure of a proposed US government plan to bail out the US auto market	JPY^v
Dec 15, 2008	1.48		0.16 (1.00)	Widely expected interest rate cut by the Fed. Concerns over the health of the US economy and the impact of the US government's rescue plan	CHF^v, GBP^v
Dec 17, 2008	2.32		0.17 (1.00)	Drop in the US trade deficit	AUD^v, CHF^v, GBP^v

Table 5
Index events continued

Date	Excess return	Jump in FX	Jump in Vol	Events/Sources of uncertainty	Impact on FX
Dec 29, 2008	-0.24		0.12 (1.00)	Israeli air strikes in the Gaza Strip boost dollar-denominated oil prices	CHF^v
Jan 20, 2009	-1.22		0.11 (1.00)	Crisis in UK banking sector and ratings downgrade for Spain	GBP^v, JPY^v
Feb 10, 2009	-0.93		0.10 (1.00)	The US Treasury Secretary announces a plan to rescue the banking system which disappoints the market. The US senate passes a massive economic stimulus package. The measure of business confidence of the Reserve Bank of Australia dives to the historical lowest	AUD^v, CHF^v
Mar 19, 2009	1.25		0.12 (0.53)	Improved risk sentiment in currency markets	
May 22, 2009	0.68		0.07 (0.91)	Signs of higher inflation in the US. US Labor Department report: unemployment hits a record high	CHF^v, GBP^v
Aug 3, 2009	0.87		0.06 (0.87)	Signs of recovery from data on manufacturing surveys across the globe	CHF^v
Feb 4, 2010	-0.99		0.08 (0.73)	Strong US economic data	CHF^v
May 5, 2010	-0.87		0.10 (0.54)	Turbulent European markets, debt problems	CHF^v
May 6, 2010	-1.07		0.14 (1.00)	General election in the UK. Mounting fears over the Greek debt, Greek riots	$AUD^v, GBP^v, JPY^u, JPY^v$
May 19, 2010	0.59		0.10 (0.90)	German ban on naked short sales of euro-zone government bonds and CDSs increases risk aversion	AUD^v, GBP^v
Aug 11, 2010	-1.71		0.06 (0.81)	Fed has a gloomy outlook on the US economy	

Notes: This table summarizes information about events and sources of uncertainty which are associated with substantial movements in FX market qualified as jumps in prices or volatility. The second column is daily excess log currency returns in percent per day. The third and fourth columns provide estimates of the size of jumps and probability of jumps (in parentheses), size of jumps is in percent. The last two columns describe the news and which cross rates are affected. If we cannot attribute FX dynamics to specific news or events we indicate what type of uncertainty causes market movements.
Source of news: Factiva.

Table 6
Model diagnostics for AUD

	SV ($\theta = 0, \theta_v = 0$)	SVJ ($\theta = 0$)	Preferred
<i>skewness</i> ^C	-0.3080 (-0.3308, -0.2860)	-0.3074 (-0.3304, -0.2855)	-0.2004 (-0.2408, -0.1599)
<i>kurtosis</i> ^C	4.1472 (4.0677, 4.2366)	4.0822 (4.0006, 4.1810)	3.4892 (3.3802, 3.6055)
<i>autocorrelation</i> ^C	-0.0281 (-0.0311, -0.0252)	-0.0271 (-0.0303, -0.0241)	-0.0324 (-0.0406, -0.0242)
<i>skewness</i> ^{IV}	0.0402 (-0.0373, 0.1181)	0.0303 (-0.0466, 0.1070)	0.0310 (-0.0459, 0.1080)
<i>kurtosis</i> ^{IV}	3.0618 (2.9103, 3.2314)	3.0385 (2.8902, 3.2034)	3.0375 (2.8896, 3.2033)
<i>autocorrelation</i> ^{IV}	0.1043 (0.0749, 0.1336)	0.0634 (0.0331, 0.0937)	0.0637 (0.0334, 0.0940)
<i>IVvar</i>	0.0064 (0.0041, 0.0122)	0.0034 (0.0021, 0.0070)	0.0034 (0.0021, 0.0070)

Notes. Posterior means and 95% credible intervals (reported in parentheses) for the residuals from the currency return and from the IV equations. Superscript *C* stands for the residuals from the currency return equation, superscript *IV* stands for the residuals from the *IV* equation.

Table 7
Model diagnostics for CHF

	SV ($\theta = 0, \theta_v = 0$)	SVJ ($\theta = 0$)	Preferred
<i>skewness</i> ^C	0.1178 (0.0994, 0.1365)	0.1282 (0.1078, 0.1486)	0.0586 (0.0182, 0.0983)
<i>kurtosis</i> ^C	3.9497 (3.8825, 4.0198)	3.9438 (3.8919, 4.0011)	3.4333 (3.3373, 3.5405)
<i>autocorrelation</i> ^C	-0.0203 (-0.0227, -0.0179)	-0.0198 (-0.0226, -0.0170)	-0.0272 (-0.0352, -0.0192)
<i>skewness</i> ^{IV}	0.0224 (-0.0574, 0.1022)	0.0201 (-0.0585, 0.0985)	0.0210 (-0.0573, 0.0995)
<i>kurtosis</i> ^{IV}	3.0648 (2.9091, 3.2378)	3.0399 (2.8887, 3.2097)	3.0406 (2.8890, 3.2094)
<i>autocorrelation</i> ^{IV}	0.0777 (0.0459, 0.1094)	0.0565 (0.0247, 0.0883)	0.0564 (0.0246, 0.0881)
<i>IVvar</i>	0.0010 (0.0007, 0.0017)	0.0006 (0.0004, 0.0011)	0.0006 (0.0004, 0.0011)

Notes. Posterior means and 95% credible intervals (reported in parentheses) for the residuals from the currency return and from the IV equations. Superscript *C* stands for the residuals from the currency return equation, superscript *IV* stands for the residuals from the *IV* equation.

Table 8
Model diagnostics for GBP

	SV ($\theta = 0, \theta_v = 0$)	SVJ ($\theta = 0$)	Preferred
<i>skewness</i> ^C	-0.0407 (-0.0606, -0.0202)	-0.0211 (-0.0436, 0.0012)	-0.0232 (-0.0609, 0.0143)
<i>kurtosis</i> ^C	3.9181 (3.8427, 4.0061)	3.8540 (3.7784, 3.9423)	3.4947 (3.4006, 3.5969)
<i>autocorrelation</i> ^C	0.0009 (-0.0024, 0.0040)	0.0006 (-0.0038, 0.0047)	-0.0027 (-0.0094, 0.0037)
<i>skewness</i> ^{IV}	0.0352 (-0.0443, 0.1146)	0.0212 (-0.0565, 0.0995)	0.0215 (-0.0568, 0.0998)
<i>kurtosis</i> ^{IV}	3.0710 (2.9160, 3.2461)	3.0293 (2.8798, 3.1972)	3.0296 (2.8786, 3.1977)
<i>autocorrelation</i> ^{IV}	0.0791 (0.0483, 0.1096)	0.0510 (0.0204, 0.0814)	0.0510 (0.0204, 0.0815)
<i>IVvar</i>	0.0011 (0.0007, 0.0019)	0.0004 (0.0003, 0.0008)	0.0004 (0.0003, 0.0008)

Notes. Posterior means and 95% credible intervals (reported in parentheses) for the residuals from the currency return and from the IV equations. Superscript *C* stands for the residuals from the currency return equation, superscript *IV* stands for the residuals from the *IV* equation.

Table 9
Model diagnostics for JPY

	SV ($\theta = 0, \theta_v = 0$)	SVJ ($\theta = 0$)	Preferred
<i>skewness</i> ^C	0.3348 (0.3060, 0.3650)	0.3360 (0.3038, 0.3668)	0.1298 (0.0799, 0.1800)
<i>kurtosis</i> ^C	4.8254 (4.7109, 4.9645)	4.7148 (4.5982, 4.8361)	3.6054 (3.4829, 3.7445)
<i>autocorrelation</i> ^C	-0.0146 (-0.0176, -0.0116)	-0.0140 (-0.0174, -0.0108)	-0.0221 (-0.0312, -0.0131)
<i>skewness</i> ^{IV}	0.0568 (-0.0210, 0.1349)	0.0278 (-0.0495, 0.1054)	0.0311 (-0.0465, 0.1087)
<i>kurtosis</i> ^{IV}	3.0707 (2.9175, 3.2420)	3.0430 (2.8940, 3.2100)	3.0423 (2.8923, 3.2098)
<i>autocorrelation</i> ^{IV}	0.1042 (0.0733, 0.1349)	0.0758 (0.0443, 0.1070)	0.0768 (0.0453, 0.1083)
<i>IVvar</i>	0.0061 (0.0036, 0.0125)	0.0029 (0.0017, 0.0059)	0.0037 (0.0021, 0.0078)

Notes. Posterior means and 95% credible intervals (reported in parentheses) for the residuals from the currency return and from the IV equations. Superscript *C* stands for the residuals from the currency return equation, superscript *IV* stands for the residuals from the *IV* equation.

Table 10
Model diagnostics for Currency Index

	SV ($\theta = 0, \theta_v = 0$)	SVJ ($\theta = 0$)	Preferred
<i>skewness</i> ^C	0.0144 (-0.0053, 0.0342)	0.0222 (0.0032, 0.0456)	0.0049 (-0.0292, 0.0389)
<i>kurtosis</i> ^C	3.6921 (3.6292, 3.7611)	3.6386 (3.5790, 3.7057)	3.4022 (3.3053, 3.5100)
<i>autocorrelation</i> ^C	0.0020 (-0.0010, 0.0049)	0.0005 (-0.0027, 0.0041)	-0.0081 (-0.0155, -0.0012)
<i>skewness</i> ^{IV}	0.0220 (-0.0729, 0.1173)	0.0212 (-0.0743, 0.1169)	0.0153 (-0.0794, 0.1097)
<i>kurtosis</i> ^{IV}	3.0422 (2.8601, 3.2515)	3.0419 (2.8598, 3.2506)	3.0206 (2.8423, 3.2248)
<i>autocorrelation</i> ^{IV}	0.0604 (0.0240, 0.0966)	0.0508 (0.0141, 0.0873)	0.0499 (0.0138, 0.0859)
<i>IVvar</i>	0.0518 (0.0304, 0.1077)	0.0388 (0.0229, 0.0810)	0.0239 (0.0155, 0.0416)

Notes. Posterior means and 95% credible intervals (reported in parentheses) for the residuals from the currency return and from the IV equations. Superscript *C* stands for the residuals from the currency return equation, superscript *IV* stands for the residuals from the *IV* equation.