Crash Risk in Currency Markets*

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Abstract

How much of carry trade excess returns can be explained by the presence of disaster risk? To answer this question, we propose a simple structural model which includes both Gaussian and disaster risk premia and can be estimated even in samples that do not contain disasters. The model points to a novel estimation procedure based on currency options with potentially different strikes. We implement this procedure on a large set of countries over the 1996-2008 period, forming portfolios of hedged and unhedged carry trade excess returns by sorting currencies on their forward discounts. We find that disaster risk premia account for about 25% of carry trade excess returns in advanced countries.

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1 Introduction

Currency carry trades offer large, expected excess returns, challenging the benchmark models in international macroeconomics. In this paper, we explore whether a class of disaster-based models that postulate the existence of rare but large, adverse aggregate shocks to stochastic discount factors can explain these excess returns. This class of models, pioneered by Rietz (1988) and Barro (2006), has received a lot of attention recently in the macroeconomics and finance literature. However, this class of models is difficult to estimate due to the small number of disasters in sample. To address this difficulty, we provide a new method to estimate disaster risk premia even in samples that do not contain any disasters. We find that disaster risk premia are statistically significant and account for about one-fourth of carry trade excess returns.

Currency carry trades refer to investment strategies where one borrows in low-interest rate currencies and invests in high-interest rate currencies. The value of the exchange rate at the end of the investment period is the unique source of risk. If investment currencies depreciate or funding currencies appreciate, investors' returns decrease because they lose on their investment or have to reimburse larger amounts. With risk neutral and rational investors, high-interest currencies should depreciate on average against low-interest rate currencies and carry trade excess returns should be zero. Yet, in the data, these excess returns are large and positive on average. A natural explanation is that investors are risk-averse and demand to be compensated for taking on such risk.

Carry trade investors, however, have access to currency options to hedge this currency risk. For example, a domestic investor who is long in the foreign currency may buy a put contract that offers a large payoff in case of depreciation of the foreign currency. The investor thereby protects himself against adverse movements in the exchange rate. Likewise, a domestic investor who is short in the foreign currency may buy a call contract, protecting himself against an appreciation of the foreign currency. Using different currency option contracts, investors can tailor their exposure to exchange rate risk, buying protection against adverse exchange rate movements beyond any chosen cutoff. Intuitively, different hedged investment strategies should offer returns commensurate with their amounts of risk. For example, the difference in returns between a strategy that is immune to large adverse changes in exchange rates and a strategy that is not reflects the compensation for bearing the risk of a large currency depreciation. Yet, a simple comparison across unhedged and hedged returns does not allow a precise estimation of disaster risk premia. The reason is simple: hedged strategies protect investors both against large changes in exchange rates due to jump-like disasters, but also against large changes that might occasionally happen in a world of Gaussian shocks, without any jump.

In this paper, we propose a parsimonious exchange rate model to disentangle disaster from Gaussian risk premia. Following Backus, Foresi and Telmer (2001), we start off with the law of motion of the stochastic discount factor (SDF) in each country. These SDFs incorporate both a traditional log-normal component, as in Lustig, Roussanov and Verdelhan (2008), and a disaster component, as in Farhi and Gabaix (2008). We assume that financial markets are complete and thus define the change in exchange rate as the log difference between the domestic and foreign SDFs. In our model, expected currency excess returns are simply the sum of Gaussian and disaster risk premia. The former arise from random shocks observed every period, while the latter is due to rare disasters. We assume that these disasters do not occur in sample. As a consequence, changes in exchange rates follow a normal distribution in sample. Our model delivers closed form solutions for short dated put and call currency options, hedged currency excess returns, and risk reversals (traded option pairs that replicate a long out-of-the-money put position and a short out of-the-money call position).[1] We use these expressions to establish a simple empirical procedure to measure the compensation for disaster risk. The decomposition of risk premia presented in this paper is a methodological contribution that could be useful in other asset markets.

We turn to currency data to implement our procedure and test the model's implications. To do so, we rely on currency spot, forward and option contracts collected by JP Morgan for 32 countries. The data start in January 1996 and end in December 2008. Based on exchange rate normality tests, we restrict our sample in two dimensions: we focus on advanced countries, and we exclude the fall of 2008. We take the view that the fall of 2008 corresponds to a unique disaster in our sample period and we devote a final section to it. As a robustness check, we report in a separate Appendix the results obtained with both and emerging countries. Our data set comprises the prices of one month options on bilateral exchange rates with different degrees of moneyness: far out-of-the-money puts (denoted 10-delta puts), out-of-the money puts (denoted 25-delta puts), at-the-money puts and calls, out-of-the-money calls (denoted 25-delta calls) and far out-of-the-money calls (denoted 10-delta calls).[2]

Following Lustig and Verdelhan (2007), we form portfolios of currency excess returns by sorting currencies on their interest rates. We consider zero-investment strategies that go long in the highest interest rate currencies and short in the lowest interest rate currencies. We apply this methodology to both hedged and unhedged excess returns. Unhedged carry trades yield an average annual excess return of 6.5% in our sample. Carry trades hedged at 10-delta and 25-delta yield

[1] An option is said to be at-the-money if its strike price is equal to the forward exchange rate. A put (call) option is said to be out-of-the-money if its strike price is below the forward (above the forward), that is, if it takes a large depreciation (appreciation) to make the option worthwhile exercising. Figure 1 presents the payoffs of three option based strategies considered throughout this paper: (i) being long an out-of-the-money put option, (ii) being long an out-of-the-money call option and (iii) being long a risk-reversal, i.e. being long an out-the-money put option and short an out-of-the-money call option with symmetric strikes.

[2] The delta of an option represents its sensitivity to changes in the spot exchange rate. The delta of a put varies between 0 for extremely out of the money options to -1 for extremely in the money options. A 10-delta (25-delta) put is an option with a delta of 10% (25%). Figure 2 presents the deltas of put options as a function of their prices.

4.8% and 3.7% per annum, respectively, while carry trades hedged at the money yield 1.7% per annum. Hedged (except at the money) and unhedged returns and their differences are statistically all significant. Using Hansen (1982)'s Generalized Method of Moments (GMM) with at the money, 25-delta and 10-delta options, we obtain a disaster risk premium of 1% per annum. This estimate is significantly different from zero, even after taking into account the small sample size. It represents approximately one-fifth of unhedged carry excess returns. We investigate the robustness of this result to the presence of transaction costs and counterparty risk. Bid ask spreads are easily available on currency forward rates, but not on options. We thus assume that bid-ask spreads are equal to 5 percent of implied volatilities for advanced countries and 10 percent for the other countries.[3] As a result, our simulated bid-ask spreads increase in bad times. Their values are lower than the ones observed during the recent subprime mortgage crisis but correspond to market estimates. Taking into account bid-ask spreads, we obtain a significant estimate of the disaster risk premium, which in this case is equal to 1.3% and represents one-fourth of carry excess returns. This is our benchmark estimate. It is a lower bound because it does not take into account counterparty risk. We derive the sensitivity of this estimate to default probabilities on currency options markets.

The model also implies strong links between interest rates, contemporaneous and future changes in exchange rates, and the price of risk reversals, that is the difference between the price of an out-of-the-money put option and the price of an out-of-the-money call option with symmetric strikes. Risk reversals captures the presence of asymmetric downside or upside risk. If the foreign currency is expected to depreciate, out-of-the money puts should be more expensive than symmetric out-of-the money calls. On the other hand, if exchange rates were normally distributed, symmetric puts and calls should have the same prices. The model predicts that:(i) risk reversals increase with interest rates; (ii) an increase in risk reversals is associated with a contemporaneous exchange rate depreciation reflecting the higher riskiness of the currency; and (iii) high risk reversals predict high average future currency returns since high exposures to disaster risk have to be compensated by high returns. We check these predictions on individual countries, panel data and currency portfolios. Empirically, risk reversals increase with interest rates, as in the model. Protection against crash risk is more expensive for high interest rate currencies than for low interest rate ones. We find, as in the model, that increases in risk reversals and foreign currency depreciations tend to occur simultaneously. However, evidence is mixed as to whether risk reversals predict future exchange rates. Overall, risk reversals appear to contain useful information on potential disasters. Building portfolios on the basis of risk reversals delivers a monotonic cross-section of currency excess returns. The implied disaster risk premia is in line with our previous estimates.

[3] The implied volatility is defined as the volatility necessary to match the observed option price using a standard Black-Scholes formula. Figure 3 presents the link between implied volatilities and exchange rate distributions.

We also examine the implications of our model for the implied volatility smile.[4] We present a simple calibration of the model that simultaneously matches our estimate of the disaster risk premium and provides a good fit for the smile observed in the data.

Overall, our model is not rejected by the data. We reach this conclusion by performing a J-test of the model's pricing errors. This validates our strategy of using a parsimonious and tractable model. In our view, resorting to a richer but more complex model would be justified only if we had access to a larger dataset.

As a case study of a disaster episode, we use the fall of 2008. This period certainly represented bad times - corresponding to a high SDF - as evidenced by the deterioration in a large set of conventional risk measures. For example, during the fall 2008, the US stock market index declined by 33 percent according to the MSCI index. Consistent with the disaster hypothesis, we document that the carry trade performed very poorly during that period. The cumulative loss amounts to 17.8 percent from September to December. This also represents an extreme drop from a statistical perspective, as the standard deviation of monthly carry trade returns over the whole sample is just 2 percent.

Our estimates of disaster risk premia and carry trade losses during fall 2008 are broadly consistent with the findings and calibration of Barro (2006) and Barro and Ursua (2008, 2009). In our model, the disaster risk premium depends on two main components: (i) the probability of disasters and the impact of disasters on SDFs, and (ii) the carry trade payoffs in times of disaster. We use fall 2008 episode to calibrate the latter and the values in Barro and Ursua (2008) to characterize the former. These parameters imply a disaster risk premium of 2.8% which is higher than, but comparable to, our estimate of 1.3%. This exercise should be viewed as a back of the envelope calculation rather than a rigorous estimate, since our inference relies on a single disaster.

Our paper is related to two different literatures: the forward premium puzzle and its potential explanations, and option pricing with jumps. Since the pioneering work of Hansen and Hodrick (1980) and Fama (1984), many papers have reported deviations from the uncovered interest rate parity (UIP) condition. These deviations are also known as the forward premium puzzle. In a recent contribution, Lustig et al. (2008) build a cross-section of currency excess returns and show that it can be explained by covariances between returns and return-based risk factors. In order to replicate this result, stochastic discount factors must have a common component across countries, but also heterogenous loadings on this common component. This paper builds on the disaster risk literature to satisfy this condition.[5] Our model derives from Farhi and Gabaix (2008), who augment

[4]The implied volatility of an option is a convenient normalization of the price of this option as a function of its strike. The smile refers to the relationship between the implied volatility and the strike. We provide formal definitions in section 3 of the paper.

[5]Other consumption-based models replicate the forward premium puzzle. Verdelhan (2009) uses habit preferences

the standard consumption-based model with disaster risk, following Rietz (1988) and Barro (2006). World disaster risk is a common component, but countries differ in their exposures to world disasters. As a result, this paper contributes to the large literature on Peso problems in international finance.[6]

Our paper also belongs to a recent literature using options to investigate the quantitative importance of disasters in currency markets. Bhansali (2007) was the first to document the empirical properties of hedged carry trade strategies. Brunnermeier, Nagel and Pedersen (2008) show that risk reversals increase with interest rates. In their view, the crash risk of the carry trade is due to a possible unwinding of hedge fund portfolios. This is consistent with one interpretation of disasters. Most closely related to this paper, Jurek (2008) provides a comprehensive empirical investigation of hedged carry trade strategies. He uses deep out of the money currency options to extract currency crash risk. While his main result, that disaster risk explains 30% to 40% of carry trade returns, is consistent with the findings of this paper, our approach differs in several dimensions. First, our model-based empirical strategy leads to a structural interpretation of our results. Second, our model allows us to use a variety of option strikes, including more liquid at the money options, in order to disentangle Gaussian and disaster risk premia. Finally, using at the money options, Burnside, Eichenbaum, Kleshchelski and Rebelo (2008) also find that disaster risk can account for the carry trade premium, where disaster risk comes in the form of a high value of the stochastic discount factor, rather than large carry trade losses. In contrast to our approach, in their framework the only source of risk priced in carry trade returns is disaster risk.

A related literature studies high frequency data and option pricing with jumps, following the pioneering work by Bates (1996), who shows that exchange rate jumps are necessary to explain option 'smiles'. Recent examples include Carr and Wu (2007) who find great variations in the riskiness of two currencies (the yen and the British pound) vis a vis the US dollar, and relate it to stochastic risk premia. Campa, Chang and Reider (1998) document similar results for EMS cross-rates. Bakshi, Carr and Wu (2008) find evidence that jump risk is priced in currency options. The jumps they consider, however, are high frequency jumps, whereas the disasters we have in mind are very low frequency; in the Barro (2006) study, disasters happen every 60 years. As a result, the

in the vein of Campbell and Cochrane (1999). Bansal and Shaliastovich (2008) build on the long run risk model pioneered by Bansal and Yaron (2004). Guo (2007) presents a disaster-based model with monetary frictions. Backus, Chernov and Martin (2009), Barro and Ursua (2009), Bates (2009), Gabaix (2008), Gourio (2008), Julliard and Ghosh (2008), Liu, Pan and Wang (2005), Martin (2008), Pan (2002), Santa-Clara and Yan (2009) and Wachter (2008) study disaster risk on equity and bond markets. Using swap rates, exchange rate returns, and prices of at-the-money currency options, Graveline (2006) estimates a two-country term structure model that replicates the forward premium anomaly. Barro (2009) studies the welfare costs of rare disasters.

[6]See Lewis (1995) for a recent survey. For example, Kaminsky (1993), extending the work of Engel and Hamilton (1990), considers the possibility for rare events to explain investors' expectations about exchange rates. Rare events in her model are infrequent switches from contractionary to expansionary monetary policy. She provides evidence that investors' expectations are consistent with the model. However, she does not examine the forward premium puzzle, and only considers one exchange rate (dollar-sterling) and a short time period.

economic analysis and our econometric technique are very different: we cannot directly measure disasters, as they do not happen in our sample, unlike small jumps in studies such as Bakshi et al. (2008).

Our paper is organized as follows. Section 2 presents our model and derives its main implications. Section 3 reports our empirical results and Section 4 concludes. A separate appendix reports proofs and empirical robustness checks.

2 Theory

We provide a simple model that serves as the basis for our empirical strategy. In the model, expected carry trade returns X^e correspond to the sum of two risk premia, a normal times or Gaussian risk premium π^G and a disaster risk premium π^D:

$$X^e = \pi^D + \pi^G.$$

Here and in what follows G refers to Gaussian and D refers to Disaster.

Our main objective is to devise a simple structural estimation procedure to determine π^G, π^D and the fraction of carry trade returns due to disaster risk. To accomplish this, we use additional information from hedged carry trade returns. Hedged carry trades are zero investment trades where the investor borrows in the funding currency and uses the proceeds to invest in the investment currency and to purchase protection against a large depreciation of the investment currency through currency put options.[7] In the model, we derive closed form solutions for expected returns of hedged carry trades as a function of the option strikes. The expected return X^e_{hedged} of a hedged carry trade is equal to:

$$X^e_{\text{hedged}} = (1+\Delta)\pi^G.$$

In this formula, $\Delta \in (-1,0)$ denotes the "delta" of the put option hedging the trade, which we define below. It is increasing in the option strike. This is intuitive: the further away from the money, the more depreciation risk the investor bears, the higher the expected return of the hedged carry trade. We will make use of several strikes, with corresponding "delta" equal to -0.1 for deep out of the money options, -0.25 for out of the money options and -0.5 for at the money options. Hence the expected returns of a carry trade hedged deep out of the money (10-delta), out of the

[7] In this simple overview, returns are computed in the units of the funding currency. Later in the paper, we also treat the more general case where returns are computed in the units of the investment currency.

money (25-delta) and at the money (ATM) respectively are:

$$X^{e}_{\text{hedged, 10-delta}} = 0.9\pi^{G}, \quad X^{e}_{\text{hedged, 25-delta}} = 0.75\pi^{G}, \quad X^{e}_{\text{hedged, ATM}} = 0.5\pi^{G}.$$

To the best of our knowledge, this simple decomposition of hedged and un-hedged returns is novel.

The rest of the section is devoted to setting up a model and deriving this result. Our modeling strategy follows Backus et al. (2001): we specify a stochastic discount factor for each country. These stochastic discount factors incorporate both a traditional log-normal component as in Lustig et al. (2008) and a disaster component as in Farhi and Gabaix (2008). This is enough to compute all relevant quantities, returns and asset prices.

2.1 Model Set-Up

We focus on two countries, Home and Foreign, and develop a two-period model. In order to develop our empirical application, in section 3 we explain how to incorporate this building block in a multi-country, multi-period extension. There, we introduce a state variable Ω_t which describes the state of the world. The parameters of our two-country, two-period model depend on Ω_t. All the results in this section should be understood as returns conditional on Ω_t, but for notational simplicity, we do not make this dependence explicit. In particular, all the expectations in this section are conditional on Ω_t.

We assume that financial markets are complete, but that some frictions prevent perfect risk-sharing across countries.[8] Because we only have data for options on nominal exchange rates, we choose to consider only nominal returns. Therefore, our SDFs should be thought of as nominal SDFs (i.e., in units of local currency).[9]

In the home country, the log SDF evolves as:

$$\begin{aligned} \log M_{t,t+\tau} &= -g\tau + \varepsilon\sqrt{\tau} - \frac{1}{2}\operatorname{var}(\varepsilon)\,\tau \\ &\quad + \left\{ \begin{array}{ll} 0 & \text{if there is no disaster at time } t+\tau \\ \log(J) & \text{if there is a disaster at time } t+\tau \end{array} \right\}. \end{aligned}$$

[8] The assumption of complete markets is not necessary. Technically, our theory only requires the absence of arbitrage, and that risk-free bonds and options with enough strikes be traded. In other words, we rely on the existence of SDFs but do not need these SDFs to be unique.

[9] The link with real pricing kernels is well-known. If $Q_{t,t+\tau}$ is the change in the quantity of real goods bought by one unit of the local currency, and $M^{R}_{t,t+\tau}$ is the real SDF, then the nominal SDF is $M_{t,t+\tau} = M^{R}_{t,t+\tau} Q_{t,t+\tau}$.

We use a star to denote foreign variables. The log of SDF in the foreign country evolves as:

$$\log M^{\star}_{t,t+\tau} = -g^{\star}\tau + \varepsilon^{\star}\sqrt{\tau} - \frac{1}{2}\operatorname{var}(\varepsilon^{\star})\,\tau + \left\{ \begin{array}{ll} 0 & \text{if there is no disaster at time } t+\tau \\ \log(J^{\star}) & \text{if there is a disaster at time } t+\tau \end{array} \right\}.$$

Note that the SDFs have two components. The first one, $-g\tau + \varepsilon\sqrt{\tau} - \frac{1}{2}\operatorname{var}(\varepsilon)\,\tau$, is a country-specific Gaussian risk, with an arbitrary degree of correlation across countries. The second component, $\log(J)$, captures the impact of a disaster on the country's SDF.

The probability of a disaster between t and $t+\tau$ is given by $p\tau$. Note that disasters are perfectly correlated across the two countries: disasters are world disasters. Here, g and $g^{\star}$ are constants. The random variables $(\varepsilon, \varepsilon^{\star})$ are jointly normally distributed with mean 0 and may be correlated. However, $(\varepsilon, \varepsilon^{\star})$ are independent of the nonnegative random variables J and $J^{\star}$, which measure the magnitudes of the disaster event. All these variables are independent of the realization of the disaster event.

The "disaster" can have several interpretations. One, championed by Rietz (1988) and Barro (2006), is that of a macroeconomic drop in aggregate consumption, perhaps due to a war or a major economic crisis that affects many countries. Another interpretation is that of a financial crisis or stress, which would affect participants in world financial markets, perhaps via a drastic liquidity shortage and a violent drop in asset valuations. Both interpretations have merit, and we do not need to take a stand on the precise nature of a disaster.

This model is extremely tractable. Indeed, it yields closed form solutions for a number of key moments of interest. However, this tractability does not come for free. It relies on a few important assumptions: ϵ and ϵ^* are jointly normal and independent of the realization of the disaster. As we shall see shortly, our model implies that, conditional on no disasters, the change in the exchange rate between home and foreign is an affine transformation of $\epsilon^* - \epsilon$. In Section 3, we show that the hypothesis that the distribution of monthly log exchange rate changes conditional on no disaster being lognormal cannot be rejected in our sample.[10] This validates the assumption that $\epsilon^* - \epsilon$ is normally distributed and independent of the realization of disasters. Yet, our model presumes not only that $\epsilon^* - \epsilon$ is normal, but also that ϵ and ϵ^* are both normal.[11] This assumption on pricing kernels is harder to confront directly with the data. Section 3.2 provides an overall test of the fit of the model, and fails to reject it. This validates our overall strategy of building a simple and

[10] At very high frequencies, exchange rates exhibit fat-tailed distributions. In line with the central limit theorem, however, monthly changes in exchange rates very often appear Gaussian.

[11] In Section 3, we return to this issue and discuss how relaxing this hypothesis could potentially help us reduce the sensitivity of the estimated disaster risk premium on the strikes of the options used for the estimation.

parsimonious model that is consistent with the data.

2.2 Interest Rates and Exchange Rates

In a complete markets economy such as ours, the change in the (nominal) exchange rate is given by the ratio of the SDFs (Backus et al., 2001):

$$\frac{S_{t+\tau}}{S_t} = \frac{M^{\star}_{t,t+\tau}}{M_{t,t+\tau}},$$

where S is measured in home currency per foreign currency. An increase in S represents an appreciation of the foreign currency. The exchange rate moves both in normal times and in disasters. In normal times, the exchange rate increases following a good realization of the home Gaussian risk ε or a bad realization of the foreign Gaussian risk $\varepsilon^{\star}$. In disasters, the exchange rate increases following a good realization of J or a bad realization of $J^{\star}$.

It is important to note that a low realization of $J^{\star}$ corresponds to a depreciation of the foreign currency. Hence, a country's exposure to disaster risk increases when the distribution of $J^{\star}$ decreases in the first order stochastic dominance sense. Actually, we will see shortly that a summary statics for the foreign country's exposure to disaster risk is $-pE[J^{\star} - 1]$.

The home interest rate r is determined by the Euler equation $1 = E\left[M_{t,t+\tau}e^{r\tau}\right]$:

$$r = g - \log\left(1 + p\tau E\left[J - 1\right]\right)/\tau. \tag{1}$$

A similar expression determines the foreign interest rate. In the limit of small time intervals, this expression takes a very simple form.

Proposition 1. *In the limit of small time intervals $\tau \to 0$, the interest rate r in the home country is given by:*

$$r = g - pE\left[J - 1\right].$$

A similar formula holds for the foreign interest rate. Ceteris paribus, if the foreign country has a higher average disaster risk, or lower $pE\left[J^{*} - 1\right]$, then it also has a higher interest rate. This higher interest can be understood as a compensation for the risk of holding a currency that tends to depreciate in disasters, when the SDF is high.

2.3 Options

To determine the payoffs of hedged carry trades, we need to specify some option related notation. We denote by $P_{t,t+\tau}\left(K\right)$ and $C_{t,t+\tau}\left(K\right)$ the prices of one period puts and calls on the home-foreign currency pair: $P_{t,t+\tau}(K)$ is the home currency price of a put yielding $\left(K - \frac{S_{t+\tau}}{S_t}\right)^+$ in home currency, and $C_{t,t+\tau}(K)$ is the home currency price of a call yielding $\left(\frac{S_{t+\tau}}{S_t} - K\right)^+$ in the home currency.[12]

The Black-Scholes formula. Our closed form solutions for hedged carry trade returns build on a version of the Black-Scholes formula. This formula, developed originally in Black and Scholes (1973) in the context of stocks, was adapted to a foreign exchange setting by Garman and Kohlhagen (1983). We denote by $V^P_{BS}(S, K, \sigma, r, r^\star, \tau)$ and $V^C_{BS}(S, K, \sigma, r, r^\star, \tau)$ the Black-Scholes price for a put and a call, respectively, when the spot is S, the strike is K, the volatility is σ, the time to maturity is τ, the home interest rate is r and the foreign interest rate is $r^\star$. For example, the Black-Scholes price of a put is given by

$$V^P_{BS}(S, K, \sigma, r, r^\star, \tau) = Ke^{-r\tau}\mathbb{N}(-d_2) - Se^{-r^\star\tau}\mathbb{N}(-d_1),$$

where $\mathbb{N}$ is the cumulative distribution function of a Gaussian, and

$$d_1 = \frac{\log(S/K) + (r - r^\star + \sigma^2/2)\tau}{\sigma\sqrt{\tau}}, \qquad d_2 = d_1 - \sigma\sqrt{\tau}.$$

The Black-Scholes formula has a simple scaling property with respect to the time to maturity τ and the interest rates r and $r^\star$:

$$V^P_{BS}(S, K, \sigma, r, r^\star, \tau) = V^P_{BS}(Se^{-r^\star\tau}, Ke^{-r\tau}, \sigma\sqrt{\tau}, 0, 0, 1).$$

This scaling property allows us to always use the formula when the time to maturity is equal to 1 and both interest rates are 0. For notational convenience, we will omit the arguments 0 and 1 and simply write

$$V^P_{BS}(S, K, \sigma) \equiv V^P_{BS}(S, K, \sigma, 0, 0, 1).$$

The "delta" of options. The delta of an option is the sensitivity (or the partial derivative) of the option price to a change in the underlying exchange rate. The delta of a put is negative because the value of a put increases when the underlying currency depreciates. The delta increases with the strike of the put: a deep out-of-the-money put has a delta close to 0, while a deep-in-the-money

[12] We use the notation:

$$y^+ \equiv \max(0, y).$$

has a delta close to $-e^{-r^\star\tau}$. For example in the Black-Scholes model, the delta of a put is given by

$$\partial V^P_{BS}(S, K, \sigma, r, r^\star, \tau)/\partial S = -e^{-r^\star\tau}\mathbb{N}(-d_1).$$

We will often consider the limit of short time to maturity. The delta of the option then has a simple interpretation. It is the probability that the put will be exercised. More formally, the delta of a put option with time to maturity τ and strike $Se^{\kappa\sqrt{\tau}}$ has the following limit:[13]

$$\Delta^P_{BS}(\kappa) \equiv \lim_{\tau\to 0} \partial V^P_{BS}(S, Se^{\kappa\sqrt{\tau}}, \sigma, r, r^\star, \tau)/\partial S = -\mathbb{N}(\kappa/\sigma) \in (-1, 0),$$

where the partial derivative is taken with respect to the first argument.

For example, for at-the-money options, $\kappa = 0$, so the delta of an at the money put is $-1/2$.

2.4 Hedged and Unhedged Carry-Trade Returns

We compute returns in units of the home currency. However, we want to allow for the possibility that home might be both the funding currency (if $r < r^\star$)and the investment currency (if $r > r^\star$.) We therefore define two carry-trade payoffs X and Y, which correspond to these two cases:

$$X_{t,t+\tau} = e^{r^\star\tau}\frac{S_{t+\tau}}{S_t} - e^{r\tau} \ ,$$

$$Y_{t,t+\tau} = -X_{t,t+\tau}.$$

The payoff $X_{t,t+\tau}$ corresponds to the following trade: at date t, borrow 1 unit of the home currency, at rate r, and invest the proceeds in the foreign currency, at rate $r^\star$. At the end of the trade, at date $t+\tau$, convert the proceeds back into the home currency. The payoff $Y_{t,t+\tau} = -X_{t,t+\tau}$ corresponds to the opposite trade.

In the main text, we treat the case where the home currency is the funding currency ($r < r^*$). The corresponding derivations can be found in Appendix A. In Appendix B, we derive the corresponding results for the case where home is the investment currency.

We now construct the hedged carry-trade returns, $X_{t,t+\tau}(K)$. The return $X_{t,t+\tau}(K)$ is the payoff of the following zero investment trade: borrow one unit of the home currency at interest rate r , use the proceeds to buy $\lambda^P_{t,t+\tau}(K)$ puts with strike K protecting against a depreciation in the foreign currency, and invest the remainder $\left(1 - \lambda^P_{t,t+\tau}(K)P_{t,t+\tau}(K)\right)$ in the foreign currency at interest rate $r^\star$, where $P_{t,t+\tau}(K)$ is the home currency price of a put yielding $\left(K - \frac{S_{t+\tau}}{S_t}\right)^+$ in the

[13] In this equation, κ is a normalized measure of the moneyness of the option.

home currency:

$$X_{t,t+\tau}(K) = \left(1 - \lambda^P_{t,t+\tau}(K)\, P_{t,t+\tau}(K)\right) e^{r^\star \tau} \frac{S_{t+\tau}}{S_t} + \lambda^P_{t,t+\tau}(K) \left(K - \frac{S_{t+\tau}}{S_t}\right)^+ - e^{r\tau},$$

where we choose the hedge ratio $\lambda^P_{t,t+\tau}(K)$ to eliminate disaster risk:

$$\lambda^P_{t,t+\tau}(K) = e^{r^\star \tau} / \left(1 + P(K)\, e^{r^\star \tau}\right).$$

Of foremost interest to us is the annualized expected returns, conditional on no disasters, of two strategies: the unhedged carry trade, X^e, and the hedged carry trades at strike $e^{\kappa\sqrt{\tau}}$ over short horizons τ, $X^e(\kappa)$. These returns correspond to the following limiting cases:

$$X^e = \lim_{\tau \to 0} E^{ND}\left[X_{t,t+\tau}\right]/\tau,$$
$$X^e(\kappa) = \lim_{\tau \to 0} E^{ND}\left[X_{t,t+\tau}\left(e^{\kappa\sqrt{\tau}}\right)\right]/\tau.$$

To summarize our notation: $X_{t,t+\tau}$ denotes the carry-trade return, while X^e is its expected value; $X_{t,t+\tau}(e^{\kappa\sqrt{\tau}})$ denotes the hedged carry trade return with strike $K = e^{\kappa\sqrt{\tau}}$, while $X^e(\kappa)$ is the expected value of that hedged carry trade return. E^{ND} denotes expectations under the assumption of no disaster.

The following proposition offers a decomposition of these returns in terms of disaster and Gaussian risk premia.

Proposition 2. *In the limit of small time intervals ($\tau \to 0$), carry trade expected returns (conditional on no disasters) are given by the following equation:*

$$X^e = pE\left[J - J^\star\right] + \mathrm{cov}\left(\varepsilon, \varepsilon - \varepsilon^\star\right). \tag{2}$$

In the same limit, hedged carry trade expected returns (conditional on no disasters) are given by:

$$X^e(\kappa) = -pE\left[(J^\star - J)^+\right] + \mathrm{cov}\left(\varepsilon, \varepsilon - \varepsilon^\star\right)\left(1 + \Delta^P_{BS}(\kappa)\right). \tag{3}$$

The first term in equation (2) is the risk premium associated with disaster risk:

$$\pi^D \equiv pE\left[J - J^\star\right].$$

If the foreign country is riskier, then $E\left[J - J^\star\right] > 0$ and the expected return due to disaster risk is positive. The second term, is the risk premium associated with "Gaussian risk"a la Backus et al.

(2001):[14]

$$\pi^G \equiv \text{cov}\left(\varepsilon, \varepsilon - \varepsilon^\star\right).$$

It is the covariance between the home SDF and the bilateral exchange rate $S_{t+\tau}/S_t$. In our model, the expected return of the carry trade compensates for the exposure to these two sources of risk.

The purchase of a protection against extreme depreciation affects the loading of the carry-trade payoff on the two sources of risk in the model. This is reflected in the expression for the expected value of the hedged carry trade return in equation (3). The disaster risk premium π^D is reduced to $pE\left[(J^\star - J)^+\right]$, which equals zero if $J > J^\star$ almost surely. The Gaussian risk premium π^G is reduced to $\text{cov}\left(\varepsilon, \varepsilon - \varepsilon^\star\right)\left(1 + \Delta^P_{BS}(\kappa)\right)$. This can be understood as follows: since the put option has a sensitivity to currency changes equal to the "option delta" $\Delta^P_{BS}(\kappa)$, hedging reduces the risk premium corresponding to Gaussian risk by $\text{cov}\left(\varepsilon, \varepsilon - \varepsilon^\star\right)|\Delta^P_{BS}(\kappa)|$. We will expand on the intuition for this term below, in section 2.5.

Implied volatilities. To put Proposition 2 to work, we use implied volatilities. The implied volatility $\hat{\sigma}_{t,t+\tau}(K)$ of a put with strike K is defined implicitly as the volatility that would make the Black-Scholes price match the observed price of the option:

$$P_{t,t+\tau}(K) = e^{-r^*\tau} V^P_{BS}\left(1, Ke^{(r^\star - r)\tau}, \hat{\sigma}_{t,t+\tau}(K)\sqrt{\tau}\right).$$

A similar definition stands for call options. By the put-call parity formula, the implied volatility of a put and a call of same strike and maturity are equal. We now state a Lemma that will simplify the empirical analysis.

Lemma 1. *In the limit of small time intervals ($\tau \to 0$), the Black-Scholes implied volatility $\hat{\sigma}_{t,t+\tau}\left(e^{\kappa\sqrt{\tau}}\right)$ of a put or a call with strike $e^{\kappa\sqrt{\tau}}$ is given by* $\text{var}\left(\varepsilon^\star - \varepsilon\right)^{1/2}$.

Lemma 1 states that, in the limit of small time intervals, the implied volatility is equal to the physical Gaussian volatility of the bilateral exchange rate, $\text{var}\left(\varepsilon^\star - \varepsilon\right)^{1/2}$. This is true even though our model contains both normal times risk and disaster risk. The intuition is the following: for options close to the money, the value of the option due to disasters is proportional to $p\tau$, the

[14] Backus et al. (2001) show that, when markets are complete and SDFs are log normal, then expected log currency excess returns are equal to $E(\log R^e) = 1/2Var(\log M) - 1/2Var(\log M^\star)$. We focus here instead on the log of expected currency excess returns, but the two expressions are naturally consistent. Starting from Backus et al. (2001), we obtain:

$$\begin{aligned}\log E(R^e) &= E(\log R^e) + \frac{1}{2}Var(R^e) = \frac{1}{2}Var(\varepsilon) - \frac{1}{2}Var(\varepsilon^\star) + \frac{1}{2}Var(\varepsilon - \varepsilon^\star) \\ &= Var(\varepsilon) - Cov(\varepsilon, \varepsilon^\star).\end{aligned}$$

probability that the disaster will occur during the lifetime of the option, τ. This is very small compared to the value of the option due to normal times volatility, which is proportional to $\sqrt{\tau}$. Hence, for small maturities and strikes close to the money, most of the value of the option comes from Gaussian risk rather than disaster risk. Correspondingly, the implied volatility of the option is well approximated by the physical volatility of the exchange rate.

In the case of short-dated options with close to the money strikes, Lemma 1 implies that we can use the Black-Scholes implied volatilities $\hat{\sigma}_{t,t+\tau}\left(e^{\kappa\sqrt{\tau}}\right)$ instead of the physical Gaussian volatility $\text{var}\left(\varepsilon^\star - \varepsilon\right)^{1/2}$ when computing $\Delta^P_{BS}(\kappa)$ in equation (3). This is true even though the assumptions of the Black-Scholes model do not hold due to the presence of disasters.

Hence, we do not have have to forecast future volatility country by country (which is hard given that market participants have more information than we do). We can instead rely on option-implied volatilities. The quality of this approximation deteriorates for out-of-the-money options. Then, the implied volatility will be larger than the physical volatility. Our procedure will then bias our estimates of option deltas away from 0, leading to an overestimation of Gaussian risk premia and an underestimation of disaster risk premia.

In practice, traders routinely use the Black-Scholes delta of the underlying option rather than its strike, which is a conventional quantity computed as follows

$$-e^{-r^*\tau}\mathbb{N}\left(\frac{\kappa\sqrt{\tau} + \left(r - r^* - \hat{\sigma}^2/2\right)\tau}{\hat{\sigma}\sqrt{\tau}}\right).$$

Note that this quantity might differ from the true sensitivity of the option with respect to the fundamental. However, it converges to $\Delta^P_{BS}(\kappa) = -e^{-r^*\tau}\mathbb{N}(-d_1)$ in the limit of small time intervals.

Using Lemma 1 therefore provides us with a useful simplification: the conventional deltas that traders use to quote currency options coincide, in the limit of small time intervals, both with the true deltas of the options and with the quantity $\Delta^P_{BS}(\kappa)$ featured in our model.

In practice, this approximation is valid when the disaster risk premium $p(J^* - J)\tau$ is small in absolute value compared to the option price, which is of order $\xi\sigma\sqrt{\tau}$, where $\xi > 0$ depends on κ. Therefore, for our approximation to be valid, we need $\tau \ll \left(\xi\sigma/\left(p\left|J - J^\star\right|\right)\right)^2$. Numerically, with yearly units, volatility is about 10%, so $\sigma \simeq 0.1$. The disaster part of the carry trade risk premium is, in order of magnitude, 1.5%, so $p\left|J^* - J\right| \simeq 0.015$.[15] Thus we need $\tau \ll 44\xi^2$. For at-the-money options, $\xi = 1/\sqrt{2\pi}$, and the condition is $\tau \ll 44\xi^2 = 6.9$ years. As we use one-month options ($\tau = 1/12$), our approximation can be expected to be valid in practice. Furthermore, in practice, the ratio of the implied volatility of 10 and 25-delta options to the implied volatility of ATM options typically lies between 1 and 1.2. Hence, using the volatility ATM rather than the implied volatility

[15] To do this analysis, we do not need to decompose the relative contributions of p and $J^* - J$, as Farhi and Gabaix (2008) do. Only the value of the disaster risk premium, $p(J^\star - J)\tau$, matters.

at 10-delta would change the factor $1+\Delta$ of 10 delta options from 0.9 to 0.94. For the 25-delta options, the $1+\Delta$ factor would be equal to 0.79 instead of 0.75.[16] These corrections would imply only trivial modifications to our empirical estimates, much below their reported standard errors.

2.5 Estimating the Contribution of Disasters

The expected return of the unhedged carry trade in equation (2) can be re-expressed as:

$$X^e = \pi^D + \pi^G. \tag{4}$$

Assume that $J^\star < J$ almost surely: this means that the exchange rate of the foreign country will depreciate vis a vis the home country in case of a disaster. A put option protects the investor against this depreciation in case of disaster, and also against more modest depreciations resulting from Gaussian risk. As a consequence, the hedged carry trade is less risky and commands a lower risk-premium. The further out of the money the put option is, the more risk the investor bears, and the higher the hedged carry-trade return. Indeed, we can re-express (3) as:

$$X^e(\kappa) = \pi^G \left(1 + \Delta^P_{BS}(\kappa)\right).$$

For instance, take the carry trade hedged with at the money options ($\kappa = 0$). Then, $\Delta^P_{BS}(\kappa) = -1/2$, and $X^e(\kappa) = 0.5\pi^G$. The expected return of the carry trade hedged at the money is equal to half of the no-disaster risk premium π^G.[17]

The intuition is that the hedge eliminates all the disaster risk and half the Gaussian risk. The fact that exactly half of the Gaussian risk is eliminated might seem surprising, given that the SDF puts more weight on depreciations of the foreign currency than on its appreciations. The intuition is as follows. In the limit of small time horizons $\tau \to 0$, the "shape" of the distribution is a Gaussian with standard deviation $\sigma\sqrt{\tau}$, while the adjustments for risk that govern the difference between the physical and risk-adjusted probability are much smaller, of the order of magnitudes of τ. Together with the fact that the Gaussian distribution is symmetric around 0, this implies $X^e(0) = 0.5\pi^G$.

Next, take the carry trade hedged with put option at "25-delta". In the language of currency traders, that means that the strike is such that the delta of the put is -0.25. There, $X^e(\kappa) = 0.75\pi^G$. Likewise, for the carry trade hedged at 10-delta, we get $X^e(\kappa) = 0.9\pi^G$. Again, the

[16] With an upper bound of 1.1, the numbers are 0.92 and 0.77. With an upper bound of 1.3, they are 0.95 and 0.81.

[17] An informal intuition is as follows. The carry trade has a "disaster beta" of 1, and a "Gaussian risk" beta of 1. Hence, its risk premium is $\pi^D + \pi^G$. On the other hand, the carry trade hedged at the money has a zero disaster beta, and a Gaussian risk beta of 1/2 (as we saw earlier, it eliminates half the Gaussian risk). Hence, its risk premium is $0.5\pi^G$. Likewise, the carry trade hedged at 10-delta has a zero disaster risk beta, and a Gaussian risk beta of 0.9 (as it eliminates 10% of the Gaussian risk), hence it has a risk premium of $0.9\pi^G$.

intuition is that, given that the hedge uses a relatively deep out of the money put, investors bear much of the Gaussian risk, but not all of it: they bear 90% of the risk, so that the expected return of the carry trade at 10-delta is 0.9 times the Gaussian risk premium.

The strategy underlying our estimation procedure is to use expected returns of different strategies with different loadings on disaster and Gaussian risks to infer π^G and π^D. Alternatively, option prices can also be used directly to make some inference about those premia. We turn to this issue in the next section.

2.6 Risk Reversals

Roughly speaking, if the foreign currency is riskier than the home currency, then out of the money put prices on the currency pair (home, foreign) should be higher than out of the money call prices, as the price of protection against a devaluation of the foreign currency should be high. In this section, we construct a simple metric – risk reversals – to measure the gap between the out of the money puts and out of the money calls.

One tradition is to construct risk reversals as the implied volatility of an out of the money put, minus the implied volatility of a symmetric out of the money call. A more theoretically appealing definition for our purposes is to look at the difference between the prices of put and calls, rather than between their implied volatilities. More precisely, we call $\mathcal{F} = e^{(r-r^*)\tau}$ the forward rate of bilateral exchange rate $S_{t+\tau}/S_t$. We use k, which in practice is close to 1, in order to indicate the moneyness of the options. For instance, for puts and calls corresponding to movements of 10 percent from the forward rate, $k = 1.1$. We define the risk reversal to be:

$$RR(\mathcal{F}k) = P\left(\mathcal{F}k^{-1}\right) - k^{-1}C\left(\mathcal{F}k\right). \tag{5}$$

Risk reversals are the price of one put with strike $\mathcal{F}k^{-1}$ minus k^{-1} calls with strike $\mathcal{F}k$, which is symmetric with respect to the money forward, $\mathcal{F}$. For instance, in the previous case where $k = 1.1$, the risk reversal is the price of a put protecting against a 10 percent depreciation of the foreign currency, minus 0.9 units of a call paying off symmetrically, i.e. if the foreign currency appreciates by 10 percent.

The next lemma gives the reason for the definition in equation (5): if there is only Gaussian risk, then the risk reversal is exactly 0.

Lemma 2. *If there is no disaster risk, then the risk reversal is exactly 0, for all strikes:* $RR\left(\mathcal{F}k\right) = 0$ *for all* $k > 0$*.*

On the other hand, if there is disaster risk, the risk reversal is basically the price of an out-of-the-money put (e.g., in the previous example, protecting against a 10 percent depreciation of the foreign currency), minus the price of a symmetric call (e.g., protecting against a 10 percent appreciation of the foreign currency). Hence, if the foreign country has more crash risk than the home country, its risk reversal is positive.

In the next proposition, we characterize the limit price of risk reversals for strikes in the parametric class $e^{\kappa\sqrt{\tau}}$.

Proposition 3. *In the limit of small time intervals, the price of risk reversals is given by the following equation*

$$\lim_{\tau\to 0} RR(\mathcal{F}e^{\kappa\sqrt{\tau}})/\tau = pE\left[(J-J^{\star})^{+} - (J^{\star}-J)^{+}\right] + 2(1+\Delta_{BS}^{P}(\kappa))pE\left[(J^{\star}-J)\right]. \tag{6}$$

Consider a risk reversal at-the-money forward ($\kappa = 0$), in the case where $J > J^{\star}$ almost surely. Then, $\Delta_{BS}^{P}(0) = -1/2$, and $\lim_{\tau\to 0} RR(\mathcal{F}e^{\kappa\sqrt{\tau}})/\tau = 0$. In other words, disaster risk generates non-trivial risk reversals only for strikes away from the money.

Risk reversals on the currency pair (home, foreign) essentially capture the relative loadings on disaster risk of the home currency and the foreign currency in the following sense. If the distribution of $J^{\star}$ decreases in a first order stochastic dominance sense (if the foreign currency bears more crash risk), then the value of the risk reversal is weakly higher ($\lim_{\tau\to 0} RR(\mathcal{F}e^{\kappa\sqrt{\tau}})/\tau$ is weakly higher).

We can also consider strikes that do not scale as $\kappa\sqrt{\tau}$ in the limit of short time horizons. If instead the strike is constant at $K > 0$, the delta of the corresponding put option is equal to -1. The price of deep out-of-the money risk reversals is then:

$$\lim_{\tau\to 0} RR(K)/\tau = pE\left[\left(K^{-1}J - J^{\star}\right)^{+} - \left(K^{-1}J^{\star} - J\right)^{+}\right]. \tag{7}$$

We conclude with a Proposition linking risk reversals to interest rates.

Proposition 4. *In the domain where the foreign country has more disaster risk than the home country ($J > J^{*}$), ceteris paribus, the more the foreign country is exposed to disaster risk (the lower is $J^{\star}$ in first order stochastic dominance sense), the higher are the interest rate differential $r^{*} - r$ and the short-maturity risk reversal.*

Proposition 4 is natural. Riskier countries should have higher interest rates as we saw above, and they should have higher prices of put premia, as they bear important crash risk: their risk reversals are higher. An analogous proposition naturally holds if the foreign country has less disaster risk than the home country.

3 Estimation

The theoretical results presented in the previous section guide our empirical work on carry trade returns. From a methodological perspective, the model has two main implications: currency excess returns increase with interest rates, and currency options allow the estimation of disaster risk premia. We follow these two insights. Because the forward premium puzzle implies that risk premia are time-varying, we build *portfolios* of currency excess returns by sorting countries on their interest rates. By doing so, we obtain currency excess returns that are significantly different from zero and capture *expected* excess returns from currency markets. We apply this methodology to unhedged and hedged currency excess returns. As a result, we obtain the empirical counterparts to the expected excess returns described in the previous section. Using the closed-form expressions derived in the previous section, we estimate the market compensation for crash risk.

3.1 Data

We first describe our dataset and how we build currency portfolios, and then turn to our results on disaster risk premia. We start off with spot, forward and option contracts on currency markets.

Spot, forward and currency options. All exchange rates in our sample are in US dollar per foreign currency. As a result, an increase in the exchange rate corresponds to an appreciation of the foreign currency and a decline of the US dollar. For each currency, our sample presents spot and forward exchange rates at the end of the month and implied volatilities from currency options for the same dates. We consider one-month forward rates and options with one-month maturity. Longer term contracts are available but much less traded. We construct foreign interest rates using forward currency rates and the US LIBOR, assuming that the covered interest rate parity condition holds.[18]

Options are quoted using their Black and Scholes implied volatilities for five different deltas.[19] Our sample comprises far out-of-the money puts (denoted 10-delta puts), out-of-the money puts (denoted 25-delta puts), at-the-money puts and calls, out-of-the money calls (denoted 25-delta calls) and far out-of-the money calls (denoted 10-delta calls) for the 1996-2008 period.[20] Figure 4

[18] In normal conditions, forward rates satisfy the covered interest rate parity condition (CIP): forward discounts, e.g. the log differences between forward and spot rates, equal the interest rate differentials between two countries. Akram, Rime and Sarno (2008) study high frequency deviations from CIP. They conclude that CIP holds at daily and lower frequencies.

[19] Jorion (1995), Carr and Wu (2007) and Corte, Sarno and Tsiakas (2009) study the features of these currency options.

[20] By using data from the Chicago Mercantile Exchange, we could have extended the sample to 1986 for three currencies (Canadian dollar, Swiss franc and yen) and to 1994 for two others (Australian dollar and British pound). Unfortunately CME data do not provide at each date a constant variety of option strikes, which is crucial for our estimation procedure.

presents, for example, the implied volatilities of the currency options in our sample at the end of August 2008. If the underlying risk-neutral distributions of exchange rates were purely lognormal, these lines would be flat: implied volatilities would not differ across strike prices. This is clearly not the case here. Note for example that the implied volatility curve is decreasing for Australia or New Zealand - two high interest rate countries at that time, and increasing for Japan or Switzerland - two low interest rate countries. These curves signal departures from the normality assumption. Let us take a simple example. A high implied volatility for an out-of-the money call option implies that the probability of a foreign currency appreciation is higher than in a normal distribution. At the end of August 2008, option prices reflect large probabilities of appreciation for the Japanese yen and Swiss franc, and large probabilities of depreciation for the Australian and New Zealand dollars. These expected changes actually occurred in the next months.

Using these spot, forward and option contracts, we now build unhedged and hedged currency excess returns following the definitions presented in section 2.4.

Portfolios of unhedged and hedged currency excess returns. For each individual currency, we construct the corresponding excess return from the perspective of a US investor. We consider two cases: the US investor goes either long or short on the foreign currency. In each case, we build the hedged excess return obtained by buying protection on the option market against an unfavorable change in the foreign currency. When the US investor is long on the foreign currency, he buys a put contract, thereby protecting himself against a depreciation of the foreign currency. When he is short, he buys a call contract. Again, the strike price of these options contracts is either far out of the money (at 10-delta), out of the money (at 25-delta) or at the money.

We sort currencies on their forward discounts and allocate them into three portfolios, rebalancing every month. The first portfolio contains the lowest interest rate currencies, while the last portfolio contains the highest interest rate currencies. By sorting currencies on their risk characteristics, we focus on sources of risk and we average out idiosyncratic variations. When computing portfolio averages, we use equal weights for all currencies. We obtain average currency excess returns, average implied volatilities, and average risk reversals for each portfolio.[21]

The connection with the theory developed in Section 2 is as follows. The different countries are indexed by $i \in I$. A state variable Ω_t describes the state of the world at date t. This state variable follows an arbitrary stationary stochastic process. All the parameters of the model are arbitrary functions of Ω_t: p, g_i, J_i, $\mathrm{cov}(\varepsilon_i, \varepsilon_j)$. Correspondingly all the computed variables r_i, X_i^e, $X^e(\kappa)_i$,

[21] Note that the hedge strategy requires buying one option for every currency in the portfolio. In essence, this amounts to buying protection against adverse movements of every currency in the portfolio against the US dollar. Another potentially interesting strategy consists in buying a single option to protect against an adverse movement of the basket of currencies in this portfolio. However, we do not have data on basket options. Therefore, we do not pursue that route.

π_i^D, π_i^G depend on Ω_t. Underlying our portfolios are three state-dependent sets, $I_1(\Omega_t)$, $I_2(\Omega_t)$, and $I_3(\Omega_t)$.

High interest rates r_i can be due to high values of g^i or low values of $pE[J_i - 1]$. If disaster risk is an important determinant of cross-country variations in interest rates, then a portfolio formed by selecting countries with high interest rates will on average select countries that feature high disaster risk, $-E[J_i]$. The empirical analysis below will indeed confirm that this is the case.

Sample. Our data set comes from JP Morgan. It contains 32 currencies: Argentina, Australia, Brazil, Canada, Switzerland, Chile, China, Columbia, Czech Republic, Denmark, Euro Area, United Kingdom, China Hong Kong, Indonesia, Israel, India, Japan, South Korea, Mexico, Malaysia, Norway, New Zealand, Peru, Philippines, Poland, Sweden, Singapore, Thailand, Turkey, Taiwan, Venezuela, and South Africa. Following the World Economic Outlook (IMF, 2008) classification, we split the sample between advanced countries and emerging countries.[22]

There are two main reasons to focus on advanced countries: the higher liquidity of their option markets and the normality of their returns. We focus here on normality tests and investigate later the impact of transaction costs.

Our model implies that, as long as a currency crash does not occur in sample, changes in exchange rate are conditionally normally distributed. We check this implication in our data, limiting first our attention to the 1/1996 - 8/2008 period. We exclude the last four months of our sample because, during the fall of 2008, high interest rate currencies depreciated and low interest rate currencies appreciated sharply. Carry trades thus paid very badly in the fall of 2008, when world wide stock markets tumbled and liquidity dried up. We take the view that this period represents an example of disasters in our sample and will pay special attention to this particular period in the next section. For now, we exclude it from our sample.

Table 9 in Appendix C reports higher moments of changes in exchange rates, and the standard Jarque and Bera (1980) and Lilliefors (1967) normality tests for each currency available over this period. The left panel focuses on advanced countries. Bootstrapping the skewness and kurtosis statistics, we find that the sample values are not significantly different to the Gaussian ones for all countries, except for South Korea and Singapore. The Lilliefors test leads to the same conclusion. The Jarque-Bera test rejects normality more often (adding UK and Japan to the list above), but the test is known to over-reject in short samples. The comparison with the right panel, which focuses on emerging countries, is striking. There, most exchange rate distributions differ from normality. Most rejections come from high kurtosis.[23] If we include fall 2008 in our sample, the recent large

[22]The Word Economic Outlook classification combines three criteria: (i) per capita GDP, (ii) export diversification, and (iii) global integration into the global financial system.

[23]We also report, in Appendix C, higher moments and normality tests for our portfolios of currency excess returns. In

changes in exchange rates lead to rejection of the normal distribution even for many advanced countries.

Our model implies that *conditional* changes in exchange rates are normal. Yet, the normality tests reported so far are unconditional, and exchange rates tend to exhibit time-varying volatility. To take into account such heteroscedasticity, we estimate a GARCH(1,1) model for each currency. We then run normality tests on exchange rate changes normalized by their volatility. To save space, we report results in Table 10 in Appendix C. After the GARCH(1,1) correction, all advanced countries, except South Korea, exhibit conditionally Gaussian exchange rates in our sample. Most emerging countries, however, still fail normality tests.

As a result, we focus here on our sample of advanced countries (excluding South Korea) over the 1/1996-8/2008 period.[24] We turn now to our main empirical results. Note that results obtained with the whole sample of advanced and emerging countries are reported in Appendix C as robustness checks. We also consider, in the appendix, a smaller sample of the nine most advanced countries as in Jurek (2008).

3.2 Results

We first present the key characteristics of our currency portfolios and then focus on measures of disaster risk premia.

Portfolio Characteristics. Forming portfolios is a way to compute moments conditional on the three sets I_1, I_2 and I_3. Of particular interest to us will be three of these moments: the return of carry trade, and the corresponding disaster and Gaussian risk premia. For instance, the expected return on portfolio k is simply the average return over the countries in the portfolio:

$$\overline{X}_k^e = E\left[\frac{\sum_{i \in I_k(\Omega_t)} X_i^e(\Omega_t)}{\# I_k(\Omega_t)}\right].$$

Similarly, the expected hedged return on portfolio k is:

$$\overline{X}_k^e(\kappa) = E\left[\frac{\sum_{i \in I_k(\Omega_t)} X_i^e(\Omega_t)(\kappa)}{\# I_k(\Omega_t)}\right].$$

Table 1 reports average currency excess returns that are either unhedged, hedged at 10-delta,

our benchmark sample of advanced countries, the Lilliefors test cannot reject the normality assumption for any of our portfolios. In our large sample of advanced and emerging countries, however, the high interest rate portfolios exhibit fat tails and thus clearly depart from normality.

[24]Our sample thus comprises Canada, Switzerland, Czech Republic, Denmark, Euro Area, United Kingdom, Israel, Japan, Norway, New Zealand, Poland, Sweden, Singapore, Thailand.

hedged at 25-delta or hedged at the money. Average currency excess returns increase monotonically from the first to the last portfolio. This is not a surprise: we know from the empirical literature on the uncovered interest rate parity that high interest rate currencies tend to appreciate on average. As a result, investors in high interest rate currencies gain both the interest rate differential and the foreign exchange rate appreciation. Hedging downside risks decreases average returns. An hedge at 10-delta protects the investor against large drops in foreign currencies, while an hedge at the money protects the investor against any depreciation of the foreign currency: the latter insurance is obviously more expensive because it covers more states of nature and thus leads to lower excess returns.

For each portfolio, we also report in Table 2 the average implied volatility at different strikes. One result stands out: the average implied volatility of high interest rate currencies (eg portfolio 3) is much higher for out-money put options than for other strikes and other portfolios. Option markets price a large depreciation risk for high interest rate currencies. The same insight is apparent in risk reversals.

The last panel of Table 2 presents average risk reversals at 10 and 25-deltas:

$$\overline{RR}_k = E\left[\frac{\sum_{i \in I_k(\Omega_t)} RR_i(\Omega_t)}{\# I_k(\Omega_t)}\right].$$

Recall that risk reversals correspond to positions that are long put and short call options. As a result, higher risk reversals indicate higher probabilities of depreciation for the foreign currency. We report risk reversals quoted in implied volatilities. As in the model, risk reversals increase monotonically with interest rates. Higher interest rate currencies have higher probabilities of depreciation. This result is in line with the premises of our model which introduces the risk of large depreciations in currency markets.

The strong link between interest rates and risk reversals suggests a comparable sorting, using risk reversals instead of interest rates. Underlying this construction are three different portfolio sets, with their corresponding conditional moments. Here again, we obtain a monotonically increasing cross-section of excess returns. Table 3 reports hedged and unhedged average excess returns. Countries with higher risk reversals tend to offer higher currency returns on average. The difference between the last and first portfolio returns is lower than in our previous portfolios, but it is still clearly significant.

We now turn to the direct estimation of the market's compensation for bearing disaster risk.

Disaster risk premia. In order to estimate disaster risk premia, we focus on a zero-investment strategy that goes long on high interest rate currencies and short on low interest rate currencies.

This strategy corresponds to usual currency carry trades.

The expected return of the carry trade is: $\overline{X}^e = \overline{X}_3^e - \overline{X}_1^e$. It can be decomposed as the sum of a disaster risk premium $\overline{\pi}^D$ and a Gaussian risk premium $\overline{\pi}^G$. The disaster risk premium is the difference between the average disaster risk premium in portfolio 3 and the average disaster risk premium in portfolio 1:

$$\overline{\pi}^D = E\left[\frac{\sum_{i \in I_3(\Omega_t)} \pi_i^D(\Omega_t)}{\# I_3(\Omega_t)}\right] - E\left[\frac{\sum_{i \in I_1(\Omega_t)} \pi_i^D(\Omega_t)}{\# I_1(\Omega_t)}\right].$$

Similarly, the Gaussian risk premium is the difference between the average disaster Gaussian premium in portfolio 3 and the average Gaussian risk premium in portfolio 1:

$$\overline{\pi}^G = E\left[\frac{\sum_{i \in I_3(\Omega_t)} \pi_i^G(\Omega_t)}{\# I_3(\Omega_t)}\right] - E\left[\frac{\sum_{i \in I_1(\Omega_t)} \pi_i^G(\Omega_t)}{\# I_1(\Omega_t)}\right].$$

The average unhedged return of this strategy is equal to 6.5 percent per year in our sample. It corresponds to the sum of the average return on the third portfolio in the left panel of Table 1 (when the investor is long on the foreign currency) and the first portfolio in the right panel (when the investor is short on the foreign currency). We also report hedged carry trades at 10-delta, 25-delta and at the money. They correspond to $\overline{X}^e(\kappa) = \overline{X}_3^e(\kappa) - \overline{X}_1^e(\kappa)$. The first panel of Table 4 presents these average carry excess returns and their standard errors. The latter are obtained by bootstrapping the monthly excess returns under the assumption that they are i.i.d. As a result, these standard errors take into account the short sample size. Carry excess returns that are either unhedged or hedged at 10-delta and 25-delta are statistically different from zero. Carry hedged at the money are positive but not significant. The differences between unhedged and hedged returns are all positive and significant.

The second panel of Table 4 reports structural estimates of the disaster risk component ($\overline{\pi}^D$) and the Gaussian risk component ($\overline{\pi}^G$). We start with simple estimates that only requires computing averages, and then we turn to GMM estimates.

Unhedged excess returns correspond to the sum of $\overline{\pi}^D$ and $\overline{\pi}^G$. As derived in the previous section, hedged excess returns are approximately equal to $\overline{\pi}^G$ multiplied by a correction factor related to the delta of the option. To estimate $\overline{\pi}^D$ and $\overline{\pi}^G$, we first correct each average hedged return for its delta component:

$$\widetilde{X^e(\kappa)} = \overline{X}^e(\kappa)/(1 + \Delta_\kappa),$$

where $\overline{X}^e(\kappa)$ corresponds to the average carry return hedged at delta κ ($\kappa = 10$, 25 or at the money) and Δ_κ denotes the option delta (respectively equal to -0.1, -0.25 and -0.5). Section

2.5 shows that the expected value of each $\widetilde{X^e(\kappa)}$ is simply $\overline{\pi}^G$. So, we form our estimate of the Gaussian risk premium as a simple, weighted average of the delta-corrected hedged carry trade returns:[25]

$$\widehat{\pi}^G = \frac{\sum_{\kappa \in I} \widetilde{X^e(\kappa)}}{\# I}, \tag{8}$$

where $\# I$ is the number of hedged excess returns considered. For instance, when we use at the money options only, $\# I = 1$, while when we use 10-delta, 25-delta and at the money options, $\# I = 3$.

As warranted by the analysis in section 2.5, our estimate of the disaster risk premium is the average unhedged carry trade return, $\overline{X}^e$, minus the estimate of the no-disaster premium:

$$\widehat{\pi}^D = \overline{X}^e - \widehat{\pi}^G. \tag{9}$$

We report four sets of estimates obtained using the methodology above and four different sets I of hedged returns: 10-delta (first column), 25-delta (second column), at-the-money (third column) hedged returns, along with the previous three hedged returns combined together (fourth column). Note that we estimate two risk premia, $\overline{\pi}^D$ and $\overline{\pi}^G$, using either 2 (first, second and third columns), or 4 moments (fourth column). Again, standard errors are obtained by bootstrapping the monthly excess returns under the assumptions that they are i.i.d. Depending on the specification, Gaussian risk premia range from 3.4 to 5.3 percent. Disaster risk premia amount to 1.2 to 3.1 percent annually. They account for approximately 20 percent to 50 percent of the average carry trade returns in our sample. The lower estimate is obtained when using only far out-of-the-money options. Disaster risk premia are significantly different from zero in all cases, except when using solely at the money options.

Our previous estimates of disaster risk premia, obtained with simple averages, correspond to the minimization of the sum of squared differences between empirical and theoretical excess returns. We now turn to Hansen (1982)'s GMM estimates of disaster risk premia. We use all the available unhedged and hedged excess returns and thus have four moments to estimate two parameters. The other cases reported before are just-identified with two moments to determine two parameters.[26]

[25] This estimate corresponds to the minimization of:

$$(\overline{X}^e - \overline{\pi}^D - \overline{\pi}^G)^2 + \sum_{\kappa \in I} (\widetilde{X^e(\kappa)} - \overline{\pi}^D)^2.$$

[26] This estimate corresponds to the minimization of $g_T' W^{-1} g_T$, where W is the variance covariance matrix of all hedged and un-hedged returns, and g_T describes all moment conditions: $g_T = [(\overline{X}^e - \overline{\pi}^D - \overline{\pi}^G), (\widetilde{X^e(\kappa_1)} - \overline{\pi}^D), ..., (\widetilde{X^e(\kappa_3)} - \overline{\pi}^D)]$. If $W^{-1} = A'A$, the estimate minimizes $g_T' A' A g_T$. This corresponds to the 'square' of linear combinations of our original moments. As a result, the minimization does not imply that $\overline{X}^e = \overline{\pi}^D + \overline{\pi}^G$. The J-statistic is equal to $g_T var(g_T)^{-1} g_T \sim \chi^2(\# moments - \# parameters)$, cf Cochrane (2005).

In order to weight the different moments, we use the covariance matrix of all hedged and unhedged returns. We do not use a spectral density matrix because of the short length of our sample. We obtain a disaster risk premium of 1 percent (with a standard error of 0.36), and a Gaussian risk premium of 4.77 (with a standard error of 1.92). The disaster risk premium obtained with all hedged returns is close to the one obtained with 10-delta returns. This happens because the standard deviation of delta-corrected at the money-hedged returns is much higher than the other ones. As a result, the GMM estimation under-weights this moment, which previously delivered the higher estimate of disaster risk premia. Note also that the GMM estimation does not impose that unhedged excess returns are the sum of disaster and Gaussian risk premia.

We check our results on different portfolios, which use either different sorts or different countries. We obtain similar results on portfolios of currency excess returns sorted on risk reversals. Recall that these portfolios deliver a monotonic cross-section of returns, offering a carry excess return of 3.2 percent annually. Table 5 reports estimates of the corresponding Gaussian and disaster risk premia. The former varies from 1.3 to 1.7 percent. The latter range from to 1.5 to 1.9 percent. Again, all estimates, except the one using solely at the money options, are statistically significant. Disaster risk premia account for approximately 40 to 60 percent of the long-short returns on these risk-reversal-based portfolios.

As robustness checks, we consider two additional samples: either all the developed and emerging countries in our dataset, or a subset of nine developed countries (Australia, Canada, Switzerland, Euro area, United Kingdom, Japan, Norway, New Zealand, and Sweden). We obtain very similar estimates on this small sample of developed countries as before on our larger sample of advanced countries. We report them in Table 13. Using GMM, we obtain a disaster risk premium of 1.1 percent, which accounts for 25% of the carry trade returns. We obtain somehow lower disaster risk premia on our large sample of advanced and emerging countries. Table 14 in Appendix C reports average currency excess returns across portfolios when we sort countries on interest rates. Table 15 presents implied volatilities and risk reversals. Table 16, also in Appendix C, reports estimates of disaster risk premia. Disaster risk accounts for 5 to 25 percent of the average carry trade, less than in the sample with only advanced countries. Emerging markets, however, present lower liquidity and higher bid-ask spreads. As we show below, taking these transaction costs into account helps reconcile the results obtained on both samples.

We view these estimates of disaster risk premia as the main empirical contribution of this paper because they are derived within a theoretical framework that allows us to incorporate a variety of options. We draw two clear conclusions from this experiment. First, disaster risk is priced on currency markets. Second, there are significant differences in the amounts of disaster risk across countries. If all countries bore the same amount of disaster risk, it would cancel out in our long-short excess returns.

The estimate of disaster risk premia $\overline{\pi}^D$ is higher when using at-the-money options rather than out-of-the money options. In light of the model, out-of the-money options seem "too cheap" compared to at-the-money options. Note, however, that differences in disaster risk premia across these options are not statistically significant. The GMM estimate is clearly very close to the 10-delta one. Take for example the latter as benchmark. The other estimates, obtained using simple averages, differ by 0.47, 1.94 and 0.80 percentage points (cf Table 4). But the corresponding standard errors on these differences are 0.59, 1.50 and 0.69 percentage points. Therefore, the estimates of disaster premia are not statistically different across strikes. With this caveat in mind, we turn to potential explanations for these different point estimates. We see three possible explanations: illiquidity, counterparty risk, and model misspecification.

The illiquidity explanation goes as follows: the JP Morgan market maker simply gives indicative prices by using the Black-Scholes formula (which generates a low option price), but there is little trading of out of the money options. If someone wanted to aggressively buy these options, he would move prices against him, and pay higher prices. So the potential trading prices are higher than the indicative prices we have in our data for currencies.

In the counterparty risk explanation, the seller of a put might actually default during a disaster. Put premia take that risk into account, and are lower than in the model. This issue, of course, affects not only currency options, but also stock options, credit default swaps and the like. We expand on this issue in section 3.4.

Finally, the model may simply be misspecified. The model might generate too small a risk-neutral probability for small depreciations. One way to incorporate this possibility in our model would be to allow for two kinds of disasters: large disasters and small disasters. In such a specification, out-of-the money options offer no protection against small disasters, and would therefore be cheaper compared to at the money options.

We do not attempt to enrich the model to capture liquidity and counterparty risks or small disasters. We leave this for future research. In this paper, we focus on the most simple model that is not rejected by the data. We can formally test if the model is rejected with our GMM estimation. Following Hansen (1982), we compute the J-test of the model's pricing errors. This statistic is distributed as a Chi-square with two degrees of freedom. The J-statistic is 2.51, leading to a p-value of 0.28. The model is thus not rejected in our sample.

3.3 Transaction Costs

So far, our estimates of disaster risk premia do not take into account bid-ask spreads on currency markets. Transaction costs on forward and spot contracts would reduce unhedged excess returns.

Transaction costs on currency options would increase insurance costs against disasters. As a result, these costs would increase the share of disaster risk premia. In this respect, the numbers previously reported in this paper constitute a lower bound.

Bid and ask spreads are not available in the JP Morgan dataset. For the spot and forward markets, we rely on Reuters daily quotes available on Datastream. Measured in our sample, these quotes imply average spreads (divided by the mid rate) of 9 basis points for forwards and 8 basis points for spot rates. When implementing carry trades through forward markets, investors who go long on high interest rate currencies buy forward contracts at the ask price. When they receive the corresponding foreign currencies at the end of the contract, they convert their proceeds back into US dollars at the bid price. As a result, they incur half the bid-ask spread on both the forward and spot contracts. Assuming a spread of 8 basis points and 12 trades per year, the annual cost is equal to around 100 basis points or 1%. Gilmore and Hayashi (2008) argue that such spreads overstate transaction costs on currency markets because investors might roll over their positions each month instead of closing them to re-open them the next day. With an example based on the South African rand, they show that forward markets imply an annual carry cost of 192 basis points, whereas rolling over positions would cost only 13 basis points, eg 15 times less (cf Appendix 2 of their paper). This estimate, however, assumes that a given currency remains in the carry portfolio for five years, and thus underestimates the costs due to portfolio rebalancing. As a result, we assume that the average actual transaction costs on our unhedged carry portfolio are in between these two estimates. We take an annual value of 0.25% for advanced countries and 2% for emerging countries.

In order to assess transaction costs on currency option markets, we unfortunately do not have access to time-series of bid-ask spreads on these markets. To obtain an order of magnitude, we collected bid-ask spreads on November 10, 2008 and January 20, 2009 for different currency pairs.[27] Table 12 presents these bid-ask spreads on currency options quoted in terms of implied volatilities. Due to the subprime mortgage crisis, implied volatilities are much higher than in the rest of our sample. For most currency pairs, implied volatilities in November 2008 are more than twice their sample means. According to market participants, bid-ask spreads in November 2008 are also much higher than in our sample. These spreads reach 30 percent of the underlying mid-point (mean of bid and ask) values for out-of-the money options on emerging market currencies. Bid-ask spreads are much tighter for the currencies of the most advanced countries. In January 2009, most implied volatilities are lower, but spreads remain around 10 percent. According to market participants, these spreads are abnormally large. To estimate the impact of transaction costs on our results, we assume bid ask spreads of 5 percent for advanced countries and 10 percent for the others. As a result, spreads widen when implied volatilities increase, but not fully to the levels observed during fall

[27] We thank the Bank of France for sharing these data with us.

2008. We convert these implied volatilities spreads into bid-ask prices and estimate again hedged excess returns.

We test the robustness of our results to the inclusion of these transaction costs. As expected, transaction costs increase the share of disaster risk; the results are reported in Table 6 . Gaussian risk premia now range from 2.8 to 5.7 percent. Disaster risk premia range from 1.3 to 4.4 percent annually, accounting for approximately 25 percent to 70 percent of the average carry trade in our sample. All these estimates are significantly different from zero. Using GMM, we obtain a disaster risk premium of 1.3 percent. It represents one-fourth of the carry trade excess returns. We consider this value as our best estimate of the compensation for disaster risk considering the data available. It is, however, a lower bound because it does not take into account default probabilities on option markets.

3.4 Counterparty Risk

So far we have assumed that there is no counterparty risk for options. However, it is reasonable to think that the seller of a put might default with some probability ϕ if a disaster occurs. In that case, an agent engaging in hedged carry trade still bears some disaster risk. Indeed, the expected excess return of the hedged carry trade is then:

$$X^e_{\text{hedged}} = (1+\Delta)\pi^G + \phi\pi^D.$$

Since with probability ϕ the agent is exposed to disasters, the compensation for the disaster risk is then $\phi\pi^D$.

Our estimation to uncover disaster risk premia needs to be amended as follows:

$$\pi^D = \frac{\overline{X}^e - \overline{X}^e(\kappa)/(1+\Delta_\kappa)}{1-\phi/(1+\Delta_\kappa)} \tag{10}$$

For instance, take the case of deep out of the money options ($\Delta = -0.1$). Equation (10) shows that the estimate of π^D that does not take into account counterparty risk needs now to be multiplied by approximately $1/(1-1.1\phi)$. When $\phi = 0.1$, π^D is multiplied by 1.12. When $\phi = 0.25$, it is multiplied by 1.38.

This section demonstrates that counterparty risk can substantially increase our estimate of disaster risk premia. However, we lack data to pin down default probabilities on option markets. As a result, our estimate of disaster risk premia should be considered as a lower bound. One approach to estimate default probabilities could be to use information from the credit default swap or corporate bond markets, but it is beyond the scope of this paper and we leave it for further research. Instead, we now compare our estimate of disaster risk premia to the macroeconomic literature on disasters, starting with a case study of fall 2008.

3.5 Fall 2008 and Comparison with Barro and Ursua (2008)

We view this recent period as the unique example of disaster in our data. As noted earlier, its inclusion in our sample is enough to reject the normality assumption for many countries. In this section, we provide a brief description of what happened in currency markets. Both spot and option markets support the characterization of this period as a financial disaster.

Fall 2008 In our sample, fall 2008 stands out as the worst time for carry traders. This is obvious for specific currencies, but also holds for currency portfolio returns. We start with a simple example using two bilateral exchange rates; the New Zealand dollar is a high interest currency, while the Japanese yen is a low interest rate one. Figure 5 plots monthly changes in these exchange rates vis-a-vis the US dollar. We start our graph at the beginning of the subprime crisis; the sample period is thus 7/2007 - 12/2008. Clearly, the Japanese yen appreciated and the New Zealand dollar depreciated during that period, with both movements hurting carry traders. The same figure also reports the return index on a carry trade strategy that borrows in yen to invest in the New Zealand dollar. The index starts at 100 in July 2007. At the end of December 2008, the index is slightly above 60, and most of the losses have occurred in the last four months of the sample. These losses are not specific to the New Zealand dollar - Japanese Yen pair. We obtain similar results with our baskets of currencies. The average return of our carry trade strategy was -4.5 percent in the fall 2008, for a cumulative decline from September to December that amounts to 17.8 percent. This is a large drop, as the standard deviation of monthly returns over the whole sample is just 2 percent. Almost all of the 17.8 percent decline is due to losses on high interest rate currencies, which depreciated sharply.

Similar conclusions arise form currency options. Large changes in exchange rates triggered exercise of currency options that some carry traders might have bought. Figure 6 plots the frequency of call and put options exercised on currencies allocated in the first and last portfolios, respectively. At each point in time, the frequency is obtained as the number of options exercised divided by the number of currencies in the portfolio at that time. Recall that the first portfolio contains low interest rate currencies, and thus funding currencies. Investors want to buy call options to insure themselves against large appreciations of such currencies. The last portfolio contains high interest rate currencies. There, investors consider put options. The figure shows clearly that the frequency of 10-delta put options exercised reaches an all-time high in the fall of 2008. The proportion of call options triggered was also high, but not at its maximum value in the sample.

These very low returns on currency markets occurred in bad times for US investors. During fall 2008, the US stock market declined by 33 percent, according to the MSCI index.[28] Figure 7 compares equity and currency excess returns over our sample. The correlation between these excess returns is particularly high, reaching 0.7 since the start of the subprime mortgage crisis in July 2007.

Standard risk measures beyond those from equity markets point in the same direction in our sample: the equity option-implied volatility index VIX, its bond equivalent MOVE and credit spreads were at an all-time high in the fall of 2008. Figure 8 presents all these variables in a standardized way: currency returns and risk measures are all demeaned and divided by their standard deviations. The events of fall 2008 represent up to five standard deviations in these series. Very low excess returns (five standard deviation below their means) happened exactly when volatilities and credit spreads were high (five standard deviation above their means), eg in bad times. Our sample in this paper is short, but our findings are in line with the literature. As Lustig et al. (2008) show, carry trades tend to pay poorly during times of crises, exactly when stock markets tank. This high correlation between stock and currency markets also occurred during the 1987 stock market crash and the Mexican, Asian and Russian crises. These market-based indices offer real-time measures of risk that complement less financial approaches to the investors' marginal utilities, linked to real consumption growth rates. Figure 9 focuses on consumption growth and the same conclusion emerges here. Preliminary estimates of US national account statistics point towards an annualized decrease of 4.3 percent in real personal consumption expenditures in the fourth quarter of 2008, after an annualized decrease of 3.8 percent in the third quarter. These shocks represent more than three-standard deviation declines in the mean consumption growth rate. As reported in Lustig and Verdelhan (2007) on an earlier sample, low carry trade excess returns tend to occur in times of low consumption growth.

Finally, note that the link between risk reversals and subsequent currency appreciations differs during crisis and normal times. In normal times, according to the model, high risk reversals should predict foreign currency appreciations. Using actual data, we did not find significant predictability though. During crisis, high risk reversals should predict foreign currency depreciations. This is what happens during the fall of 2008: foreign currency depreciations seem to follow high risk reversals. This behavior is line with the model, if we interpret the fall of 2008 as a disaster. The evidence is of course very limited because we have only one disaster in our sample. As a consequence, we do not attempt to quantify this point, but simply present, in Figure 10, exchange rate appreciations and risk reversals for each month and each currency in the fall of 2008.

[28]The closest event to this very strong decline in equity and currency returns is the 1987 stock market crash. From September to November 1987, the US stock market lost 32.6 percent. This period is not in our sample since we do not have currency option data before January 1996.

According to many markets and risk factors, the fall of 2008 constitutes a disaster. We use this example to connect our findings to the previous macroeconomic literature on disasters.

A Comparison with Barro and Ursua (2008) In a disaster, the SDF is multiplied by an amount J. To relate it to more primitive economic quantities, we use the model of Farhi and Gabaix (2008). In that model, $J = B^{-\gamma}F$, where $B^{-\gamma}$ is the growth of real marginal utility during a disaster, and F is the growth of the value of one unit of the local currency in terms of international goods during the same disaster. Hence, $\overline{\pi}^D = \overline{pE[J]}_1 - \overline{pE[J]}_3 = \overline{pE[B^{-\gamma}(F)]}_1 - \overline{pE[B^{-\gamma}(F)]}_3$. Therefore, the disaster risk premium depends on the probability of disasters p, the relative value of the SDF $B^{-\gamma}$ and the payoff of the carry trade in disasters through the sufficient statistic $\overline{pE[B^{-\gamma}(F)]}_1 - \overline{pE[B^{-\gamma}(F)]}_3$. Using the episode of fall 2008 to calibrate the value of $\overline{F}_1 - \overline{F}_3$ and assuming away a potential correlation between $B^{-\gamma}$ and $\overline{F}_1 - \overline{F}_3$ we can shed some light on the typical value of $pB^{-\gamma}$. This exercise should be viewed as a back of the envelope calculation rather than a rigorous estimate, since our inference of $\overline{F}_1 - \overline{F}_3$ relies on a single disaster, which is still unfolding at the time of the writing of this paper. As a result, we cannot observe the full path to recovery, and as Gourio (2008) shows, we might overestimate the impact of disasters. With this caveat in mind, if we retain a value of $\overline{F}_1 - \overline{F}_3$ of 20%, a value of $\overline{pE[B^{-\gamma}]}$ of 6.5% is necessary to generate the disaster risk premium $\overline{\pi}^D$ that we estimate in the data (1.3%).

We compare this value to Barro and Ursua (2008b)'estimates. These authors use long samples of consumption series for a large set of countries.[29] Their findings are broadly consistent with the estimates from Barro (2006), which are based on GDP disasters. Barro and Ursua (2008b) estimate a probability of disasters p equal to 3.63%. A coefficient of relative risk aversion $\gamma = 3.5$ then implies $\overline{E[B^{-\gamma}]} = 3.88$, leading to a value of $\overline{pE[B^{-\gamma}]}$ equal to 14%. They show that these values can rationalize the equity premium.

Using a value of 14% for $\overline{pE[B^{-\gamma}]}$ and a value of 20% for $\overline{F}_1 - \overline{F}_3$ leads to a disaster risk premium of $0.14 \times 0.2 = 2.8\%$, which is higher but still comparable to our point estimate of 1.3%. Therefore, we view our estimates as broadly consistent with Barro and Ursua (2008b)'s findings. We end this paper with a review of the link between volatility smiles, risk reversals and exchange rates.

[29] Note, however, that interpreting our pricing kernel strictly as a simple function of consumption growth would open a large debate that is beyond the scope of this paper. Constant relative risk aversion and complete markets imply, for example, a very high correlation between consumption growth and exchange rates, which is not in the data (Backus and Smith, 1993).

3.6 Volatility Smiles, Risk Reversals and Exchange Rates

We first provide a simple calibration of the model that simultaneously accounts for the volatility smile observed in the data and the disaster risk premium that we have estimated. We then test the contemporaneous relationship between risk reversals and exchange rates, and the predictive content of risk reversals for currencies.

Accounting for the smile In this section, we examine the implications of our model for the volatility smile, that is, the relationship between the implied volatility and the strike of currency options. The exact value of a put with strike K is given by:

$$
\begin{aligned}
P_{t,t+\tau}(K) &= (1-p\tau)\, e^{-g^{*}\tau} V_{BS}^{P}\left(1, Ke^{-(g-g^{*})\tau}, \sigma\sqrt{\tau}\right) \\
&+ p\tau e^{-g^{*}\tau} E\left[J^{*} V_{BS}^{P}\left(1, Ke^{-(g-g^{*})\tau} J/J^{*}, \sigma_{t,t+\tau}\sqrt{\tau}\right)\right],
\end{aligned}
$$

where $\sigma_{t,t+\tau} = \sqrt{var(\varepsilon - \varepsilon^{*})}$ and the expectation operator E is over the joint distribution of J and J^{*}.

The implied volatility $\widehat{\sigma}_{t,t+\tau}$ is computed by solving the following implicit equation:

$$
P_{t,t+\tau}(K) = e^{-r^{*}\tau} V_{BS}^{P}\left(1, Ke^{-(r-r^{*})\tau}, \widehat{\sigma}_{t,t+\tau}\sqrt{\tau}\right),
$$

where $r = g - \log(1 + p\tau E[J-1])/\tau$ and $r^{*} = g^{*} - log(1 + p\tau E[J^{*}-1])/\tau$. Recall that when quoting options, traders routinely use the delta of the underlying option rather than its strike, which is a conventional quantity computed as follows:

$$
-e^{-r^{*}\tau}\mathbb{N}\left(\frac{\log(K) - \left(r - r^{*} + \widehat{\sigma}_{t,t+\tau}^{2}/2\right)\tau}{\widehat{\sigma}_{t,t+\tau}\sqrt{\tau}}\right).
$$

Note that this quantity might differ from the true sensitivity of the option with respect to the fundamental.

All our currency options are options on exchange rates vis a vis the US dollar. It is therefore most natural to attempt to calibrate our model to fit the average volatility smile of a given portfolio. We choose to focus on portfolio 3: it represents a carry trade where the funding currency is the US dollar. To calibrate the model, we choose the parameters as follows. We take J and J^{*} to be deterministic. We assume that the values of p and J for the US are consistent with the estimation of Barro and Ursua: $J = B^{-\gamma} = 3.88$ and $p = 3.63\%$. We choose J^{*} to match our estimate of $\pi^{D} = 1.6\%$. It implies that $J^{*} = J\left(1 - \pi^{D}/(pB^{-\gamma})\right)$. We choose the physical volatility of the exchange rate to match an implied volatility at the money in portfolio 3 of 10%. This leads us to pick $\sigma_{t,t+\tau} = 9.6\%$. We pick $g = 13.4$ and $g^* = 14.6\%$, in order to match the average US interest rate $r = 3\%$ and the average interest rate in portfolio 3, $r^* = 5.8\%$. over the sample.

The resulting implied volatilities as a function of the "delta" of the option in this calibration are as follows. For a 10-delta put, the implied volatility is 11.4%. For a 25-delta put, the implied volatility is 10.4%. At the money, the implied volatility is 10.0%. For a 25-delta call, the implied volatility is 9.9%. Finally, for a 10-delta call, the implied volatility is 9.8%.

This is to be compared to the implied volatilities for portfolio 3 in the data. For a 10-delta put, the implied volatility is 11.5%. For a 25-delta put, the implied volatility is 10.6%. At the money, the implied volatility is 10.0%. For a 25-delta call, the implied volatility is 10.02%. Finally, for a 10-delta call, the implied volatility is 10.39%. The overall fit of our model is quite good. It is better for out of the money puts than for out of the money calls. Yet, note that we obtain these values by assuming constant J and $J^\star$. The fit could be further improved by choosing an appropriate probability distribution for J and J^*.

Risk reversals and exchange rates The model implies that (i) increases in risk reversals are associated with *contemporaneous* exchange rate depreciations, (ii) high levels of risk-reversal *predict* future currency returns. We test these predictions both on panel data and on portfolio series.

In order to test for the first prediction, we first regress monthly changes in bilateral nominal exchange rates on monthly changes in risk reversals. We use risk reversals measured in prices at 10 and 25 deltas. Because these deltas imply different deviations from forward rates across countries, we also check our findings on risk reversals that are normalized: these risk reversals correspond to strikes which are 5 or 10 percent away from forward rates. We demean both the regressor and the dependant variable so as to remove the central role played by the US dollar. All panel specifications include currency fixed effects, and standard errors are obtained by bootstrap. The results on portfolios are reported in Table 7. Tables 18 and 19 in Appendix C report panel results for advanced economies and the whole sample, respectively. We find a highly robust negative correlation between changes in risk reversals and changes in exchange rates. This negative relationship is robust to alternative risk-reversal measures and to controlling for the effect of the dollar.[30] Within portfolios, R^2s range from 30% to 45%. In our panel estimates using demeaned country-level exchange rates, R^2s are close to 5%. In both cases, risk reversals are statistically significant. Their effect is also economically significant: a one standard deviation change in risk reversals is associated with a 1% to 2.3% variation in exchange rates, which is slightly below the monthly standard deviation of nominal exchange rate changes (2.8%).

[30] Carr and Wu (2007) also report high contemporaneous correlation between currency excess returns and risk reversals for the Yen and British Pound vis-a-vis the US dollar.

In order to test for the second prediction, we augment standard UIP regressions with risk reversals. Equivalent regressions start off excess returns instead of changes on exchange rates. The null hypothesis of UIP not being rejected is a coefficient of 1 for the interest differential - defined as the difference between domestic and foreign interest rate - in the specification with exchange rate change and a coefficient of zero in the specification with excess returns. Adding risk reversals to the usual UIP regressions does not improve exchange rate one-month-ahead forecasts, and no risk reversal significantly predicts currency excess returns or changes in nominal exchange rates in panel data. To save space, we report the results in Tables 20 and 21 in Appendix C. Currency portfolios offer a slightly different view on risk reversals. They suggest a clear positive relationship between average currency excess returns and average risk reversals over the sample period. As previously noted, the last panel of Table 2 reports an increase in average risk reversals from the first portfolio (-0.46 basis point) to the last portfolio (3.95 basis points). Equivalent results are obtained for other measures of risk reversals and for the whole sample of advanced and emerging countries (cf Table 15). However, within portfolios, there is no one-month ahead predictability of risk reversals on currency excess returns as shown in Table 8.

Overall, we find strong evidence in favor of a contemporaneous link between exchange rates and risk reversals, but more limited evidence of exchange rate predictability.

4 Conclusion

The objective of this paper is to provide a simple model-based estimation of the share of carry trade returns that can be attributed to disaster risk. Our main empirical result shows that disaster premia explain one-fourth of carry trade returns. This result suggests that the introduction of a time-varying disaster risk in exchange rate models, as in Farhi and Gabaix (2008), is empirically relevant.

While we find that disaster risk plays a significant role in explaining currency returns, we fall short of fully solving the carry trade puzzle though disasters. In fact, our findings suggest that a typical investor can still obtain significant carry trade returns while being hedged against large currency crashes. Several interpretations of these hedged excess returns are possible. First, the investor naturally expects a compensation for the remaining Gaussian, non-disaster risk. High interest rate currencies tend to depreciate and low interest rate currencies tend to appreciate in bad times. Second, out-of-the money options might be relatively cheap in our sample. These options are not default-free, and counterparty risk might push their prices downward.

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Table 1: Excess Returns: Advanced Countries Sorted on Interest Rates

Portfolios	1	2	3	1	2	3
		Going Long			Going Short	
			Panel I: Unhedged			
Mean	−1.37	1.45	5.13	1.37	−1.45	−5.13
	[2.08]	[2.25]	[2.08]	[2.02]	[2.14]	[1.99]
Sharpe Ratio	−0.19	0.19	0.71	0.19	−0.19	−0.71
			Panel II: Hedged at 10-delta			
Mean	−2.30	0.65	4.06	0.74	−1.58	−5.33
	[1.93]	[1.99]	[1.90]	[1.86]	[1.94]	[1.87]
Sharpe Ratio	−0.33	0.09	0.60	0.11	−0.23	−0.81
			Panel III: Hedged at 25-delta			
Mean	−2.14	0.59	3.03	0.62	−1.21	−4.68
	[1.72]	[1.82]	[1.66]	[1.48]	[1.59]	[1.53]
Sharpe Ratio	−0.36	0.09	0.51	0.12	−0.21	−0.86
			Panel IV: Hedged ATM			
Mean	−1.33	0.61	1.68	0.02	−0.86	−3.47
	[1.27]	[1.40]	[1.26]	[1.07]	[1.13]	[1.10]
Sharpe Ratio	−0.31	0.13	0.39	0.00	−0.21	−0.91

Notes: This table reports average currency excess returns that are unhedged, hedged at 10-delta, at 25-delta and at-the-money for our four portfolios. In the left section, we assume that the US investor goes long the foreign currency. In the right section, we assume that the US investor goes short the foreign currency. In each case, we report the mean excess return, its standard error and the corresponding Sharpe ratio. The mean and standard deviations are annualized (multiplied respectively by 12 and $\sqrt{12}$). The Sharpe ratio corresponds to the ratio of the annualized mean to the annualized standard deviation. Standard errors are obtained by bootstrapping the monthly excess returns under the assumptions that they are i.i.d. Portfolio 1 contains currencies with the lowest interest rates. Portfolio 3 contains currencies with the highest interest rates. The horizon of the excess returns and the option maturity are one month. Data are monthly, from JP Morgan. The sample period is 1/1996 - 8/2008.

Table 2: Implied Volatilities and Risk Reversals: Advanced Countries Sorted on Interest Rates

Portfolios	1	2	3
		Panel I: Implied Volatilities	
$10\delta-$Put	9.78	10.09	11.50
	[0.14]	[0.17]	[0.20]
$25\delta-$Put	9.38	9.56	10.60
	[0.15]	[0.16]	[0.17]
ATM	9.33	9.31	10.02
	[0.14]	[0.16]	[0.17]
25δ-Call	9.78	9.55	10.02
	[0.15]	[0.16]	[0.15]
10δ-Call	10.51	10.05	10.39
	[0.16]	[0.17]	[0.16]
		Panel II: Risk Reversals (Implied Volatilities)	
Mean RR10	−0.73	0.05	1.12
	[0.06]	[0.05]	[0.06]
Mean RR25	−0.40	0.01	0.58
	[0.03]	[0.03]	[0.03]

Notes: This table reports average implied volatilities and risk reversals by portfolios. The first panel reports average implied volatilities on put and call contracts for strike prices 10-, 25-delta and at-the-money. The last two panels reports risk reversals at 10- and 25-deltas. The second panel corresponds to differences in implied volatilities. They are quoted in annual percentages. Standard errors are obtained by bootstrapping the monthly excess returns under the assumptions that they are i.i.d. Portfolio 1 contains currencies with the lowest interest rates. Portfolio 3 contains currencies with the highest interest rates. The horizon of the excess returns and the option maturity are one month. Data are monthly, from JP Morgan. The sample period is 1/1996 - 8/2008.

Table 3: Excess Returns: Advanced Countries Sorted on Risk Reversals

Portfolios	1	2	3	1	2	3
	Going Long			Going Short		
			Panel I: Unhedged			
Mean	0.48	1.22	3.70	−0.48	−1.22	−3.70
	[2.10]	[2.11]	[1.95]	[2.06]	[2.05]	[1.87]
Sharpe Ratio	0.06	0.16	0.54	−0.06	−0.16	−0.54
			Panel II: Hedged at 10-delta			
Mean	−0.38	0.47	2.57	−1.00	−1.39	−3.96
	[2.02]	[2.05]	[1.83]	[1.98]	[1.90]	[1.76]
Sharpe Ratio	−0.05	0.07	0.39	−0.14	−0.20	−0.62
			Panel III: Hedged at 25-delta			
Mean	−0.21	0.05	1.83	−0.68	−1.29	−3.45
	[1.68]	[1.70]	[1.51]	[1.66]	[1.61]	[1.45]
Sharpe Ratio	−0.03	0.01	0.33	−0.12	−0.23	−0.65
			Panel IV: Hedged ATM			
Mean	−0.03	−0.09	1.17	−0.53	−1.33	−2.55
	[1.28]	[1.31]	[1.10]	[1.12]	[1.16]	[1.06]
Sharpe Ratio	−0.01	−0.02	0.29	−0.13	−0.32	−0.69

Notes: This table reports average currency excess returns that are unhedged, hedged at 10-delta, at 25-delta and at-the-money for our four portfolios. In the left section, we assume that the US investor goes long the foreign currency. In the right section, we assume that the US investor goes short the foreign currency. In each case, we report the mean excess return, its standard error and the corresponding Sharpe ratio. The mean and standard deviations are annualized (multiplied respectively by 12 and $\sqrt{12}$). The Sharpe ratio corresponds to the ratio of the annualized mean to the annualized standard deviation. Standard errors are obtained by bootstrapping the monthly excess returns under the assumptions that they are i.i.d. Portfolio 1 contains currencies with the lowest risk reversals at 10-delta. Portfolio 3 contains currencies with the highest risk reversals at 10-delta. The horizon of the excess returns and the option maturity are one month. Data are monthly, from JP Morgan. The sample period is 1/1996 - 8/2008.

Table 4: Disaster Risk Premia - Advanced Countries Sorted on Interest Rates

Panel I: Carry Excess Returns					
	Unhedged Carry	Hedged at 10 δ	Hedged at 25 δ	Hedged ATM	
Mean	6.50	4.80	3.65	1.70	
	[1.88]	[1.59]	[1.41]	[1.12]	
Mean Spread		1.70	2.85	4.80	
		[0.41]	[0.85]	[1.32]	

Panel II: Estimations					
	10δ	25δ	ATM	10δ, 25δ, *and* ATM	GMM 2^{nd} $Stage$
$\overline{\pi}^D$	1.16	1.63	3.10	1.96	1.01
	[0.41]	[0.87]	[1.68]	[0.93]	[0.36]
$\overline{\pi}^G$	5.33	4.87	3.40	4.53	4.77
	[1.79]	[1.87]	[2.21]	[1.87]	[1.92]
$\overline{\pi}^D - \overline{\pi}^G$	−4.17	−3.23	−0.30	−2.57	−3.76
	[1.90]	[2.31]	[3.51]	[2.35]	[2.02]

Notes: This first panel of this table reports average returns on hedged and unhedged currency carry trades and their standard errors. We use the currency portfolios presented in Table 1. Carry trades correspond to returns on the last minus returns on the first portfolio. We consider different hedges: 10-delta, 25-delta and at-the-money. We also report the average difference between unhedged and hedged carry trades. The second panel reports structural estimates. $\overline{\pi}^D$ denotes the part of the carry excess return linked to disaster risk. $\overline{\pi}^G$ corresponds to the Gaussian, non-disaster part of the same excess return. These estimates are obtained using hedged returns at 10-delta (first column), 25-delta (second column), at-the-money (third column) or 10-, 25-delta and at-the-money (fourth and fifth columns). Standard errors are obtained by bootstrapping the monthly excess returns under the assumptions that they are i.i.d. Data are monthly, from JP Morgan. The sample period is 1/1996 - 8/2008.

Table 5: Disaster Risk Premia - Advanced Countries - Sorted on Risk Reversals

Panel I: Carry Excess Returns				
	Unhedged Carry	Hedged at 10 δ	Hedged at 25 δ	Hedged ATM
Mean	3.22	1.57	1.15	0.64
	[1.66]	[1.53]	[1.29]	[1.14]
Mean Spread		1.65	2.07	2.58
		[0.36]	[0.80]	[1.32]

Panel II: Estimations					
	10δ	25δ	ATM	10δ, 25δ, and ATM	GMM 2^{nd} $Stage$
$\overline{\pi}^D$	1.48	1.68	1.94	1.70	1.41
	[0.36]	[0.87]	[1.72]	[0.94]	[0.32]
$\overline{\pi}^G$	1.74	1.54	1.28	1.52	1.67
	[1.67]	[1.74]	[2.11]	[1.74]	[1.78]
$\overline{\pi}^D - \overline{\pi}^G$	-0.26	0.14	0.66	0.18	-0.27
	[1.79]	[2.22]	[3.49]	[2.28]	[1.90]

Notes: This first panel of this table reports average returns on hedged and unhedged currency carry trades and their standard errors. We use the currency portfolios presented in Table 3. Carry trades correspond to returns on the last minus returns on the first portfolio. We consider different hedges: 10-delta, 25-delta and at-the-money. We also report the average difference between unhedged and hedged carry trades. The second panel reports structural estimates. $\overline{\pi}^D$ denotes the part of the carry excess return linked to disaster risk. $\overline{\pi}^G$ corresponds to the Gaussian, non-disaster part of the same excess return. These estimates are obtained using hedged returns at 10-delta (first column), 25-delta (second column), at-the-money (third column) or 10-, 25-delta and at-the-money (fourth and fifth columns). Standard errors are obtained by bootstrapping the monthly excess returns under the assumptions that they are i.i.d. Data are monthly, from JP Morgan. The sample period is 1/1996 - 8/2008.

Table 6: Disaster Risk Premia - Advanced Countries Sorted on Interest Rates - With Transaction Costs

Panel I: Carry Excess Returns					
	Unhedged Carry	Hedged at 10 δ	Hedged at 25 δ	Hedged ATM	
Mean	6.50	4.46	3.08	1.03	
	[1.76]	[1.65]	[1.37]	[1.13]	
Mean Spread		2.04	3.42	5.47	
		[0.41]	[0.82]	[1.28]	
Panel II: Estimations					
	10δ	25δ	ATM	10δ, 25δ, and ATM	GMM 2^{nd} $Stage$
$\overline{\pi}^D$	1.54	2.39	4.44	2.79	1.27
	[0.40]	[0.87]	[1.71]	[0.94]	[0.38]
$\overline{\pi}^G$	4.95	4.11	2.06	3.71	4.36
	[1.80]	[1.87]	[2.25]	[1.88]	[1.96]
$\overline{\pi}^D - \overline{\pi}^G$	-3.41	-1.72	2.39	-0.91	-3.09
	[1.89]	[2.29]	[3.57]	[2.36]	[2.04]

Notes: This first panel of this table reports average returns on hedged and unhedged currency carry trades and their standard errors. We use the currency portfolios presented in Table 1. Carry trades correspond to returns on the last minus returns on the first portfolio. We consider different hedges: 10-delta, 25-delta and at the money. We also report the average difference between unhedged and hedged carry trades. The second panel reports structural estimates. $\overline{\pi}^D$ denotes the part of the carry excess return linked to disaster risk. $\overline{\pi}^G$ corresponds to the Gaussian, non-disaster part of the same excess return. These estimates are obtained using hedged returns at 10-delta (first column), 25-delta (second column), at-the-money (third column) or 10-, 25-delta and at-the-money (fourth and fifth columns). Standard errors are obtained by bootstrapping the monthly excess returns under the assumptions that they are i.i.d. Data are monthly, from JP Morgan. The sample period is 1/1996 - 8/2008. We assume annual transaction costs of 0.25% on unhedged returns and bid-ask spreads of 5% on implied volatilities.

Table 7: Changes in Risk Reversals and Exchange Rates: Contemporaneous Specifications within Portfolios

Dependant Variable:	Exchange Rates					
	Panel I: Raw Variables			Panel II: Demeaned Variables		
Portfolios	P1	P2	P3	P1	P2	P3
Risk Reversals	-126.63	-131.82	-105.18	-119.95	-132.09	-145.43
Strike: Delta 10	[12.93]***	[24.22]***	[28.46]***	[27.30]***	[18.09]***	[17.87]***
Observations	155	155	155	155	155	155
R^2	0.4	0.28	0.41	0.37	0.42	0.35
Risk Reversals	-77.56	-62.66	-49.29	-54.95	-62	-74.57
Strike: Delta 25	[8.46]***	[18.28]***	[16.76]***	[19.08]***	[17.25]***	[14.26]***
Observations	155	155	155	155	155	155
R^2	0.38	0.25	0.36	0.32	0.36	0.31
Risk Reversals	-61.64	-39.38	-30.31	-96.83	-45.76	-69.08
Strike: Forward +/- 10%	[14.66]***	[36.52]	[13.61]**	[60.45]	[12.88]***	[30.00]**
Observations	96	125	133	96	125	133
R^2	0.22	0.14	0.28	0.05	0.25	0.16
Risk Reversals	-40.08	-48.97	-46.8	-50.99	-52.8	-47.9
Strike: Forward +/- 5%	[4.69]***	[6.05]***	[7.66]***	[7.51]***	[5.08]***	[6.80]***
Observations	147	155	144	147	155	144
R^2	0.39	0.3	0.46	0.42	0.44	0.32

Notes: This table documents contemporaneous relationships between changes in nominal exchange rates and changes in risk reversals. Constant terms are included but not reported. Panel I presents results based on raw variables. Panel II uses cross-sectionally demeaned variables to control for the specific role of the US Dollar. Changes in exchange rates correspond to monthly log changes. Changes in risk reversals correspond to first differences. Each horizontal panel presents the results of regressions including a different risk-reversal measure. Standard errors obtained from bootstrap procedures using 1000 replications are presented below the point estimates. The symbols ***, ** and * indicate statistical significance at 1, 5 and 10 percent confidence levels. The sample comprises currencies from advanced countries excluding observations with non floating exchange rate according to the IMF De Facto Classification. Data are monthly, from JP Morgan. The sample period is 02/1996 -08/2008.

Table 8: Risk Reversals, Exchange Rate Changes and Currency Excess Returns: Predictive Specifications within Portfolios

Dependant Variable:	Panel I: Exchange Rates			Panel II: Currency Excess Returns		
Portfolios	P1	P2	P3	P1	P2	P3
Interest Rate Differentials	-1.27	-4.16	-0.97	-2.27	-5.17	-1.97
	[1.52]	[1.77]**	[1.08]	[1.49]	[1.74]***	[1.06]*
Risk Reversals: (+/- 10%)	13.1	-1.12	-3.7	13.11	-1.14	-3.72
	[13.36]	[37.33]	[19.30]	[14.94]	[40.95]	[19.38]
Observations	109	129	138	109	129	138
R^2	0.02	0.04	0.01	0.04	0.06	0.03
Interest Rate Differentials	-2.78	-3.49	-0.96	-3.78	-4.5	-1.97
	[1.28]**	[1.72]**	[1.15]	[1.27]***	[1.79]**	[1.16]*
Risk Reversals: (+/-5 %)	0.81	-2.37	-3.44	0.81	-2.39	-3.47
	[5.52]	[9.54]	[7.53]	[5.55]	[9.69]	[7.26]
Observations	109	129	138	109	129	138
R^2	0.03	0.04	0.01	0.05	0.06	0.02
Interest Rate Differentials	-2.5	- 3.48	-0.7	-3.5	-4.49	-1.71
	[1.21]**	[1.71]**	[1.02]	[1.22]***	[1.65]***	[1.06]
Risk Reversals: Delta 10	4.18	-8.18	-7.39	4.17	-8.23	-7.44
	[16.66]	[25.22]	[18.81]	[17.10]	[26.06]	[18.55]
Observations	155	155	155	155	155	155
R^2	0.02	0.04	0.01	0.05	0.06	0.02
Interest Rate Differentials	-2.51	-3.49	-0.76	-3.52	-4.5	-1.76
	[1.26]**	[1.69]**	[1.07]	[1.23]***	[1.68]***	[1.12]
Risk Reversals: Delta 25	0.39	-5.32	-5.06	0.38	-5.35	-5.09
	[9.31]	[13.27]	[10.02]	[9.41]	[14.19]	[10.90]
Observations	155	155	155	155	155	155
R^2	0.02	0.04	0.01	0.05	0.06	0.02

Notes: This table presents results of predictability tests. We regress monthly changes in nominal exchange rates (panel I) or monthly currency excess returns (panel II) on risk reversals and interest differentials. The interest differential is defined as the difference between the domestic and the foreign interest rate. The null hypothesis of UIP not being rejected is a coefficient of 1 for the interest rate differential in panel I and a coefficient of zero in panel II. Constant terms are included but not reported. Standard errors obtained from a bootstrap procedure using 1000 replications are presented below their respective point estimates. ***,**,* indicates statistical significance at 1, 5, 10 percent confidence levels. The sample comprises currencies from advanced countries excluding observations with non floating exchange rate according to the IMF De Facto Classification. Data are monthly, from JP Morgan. The sample period is 01/1996 -08/2008.

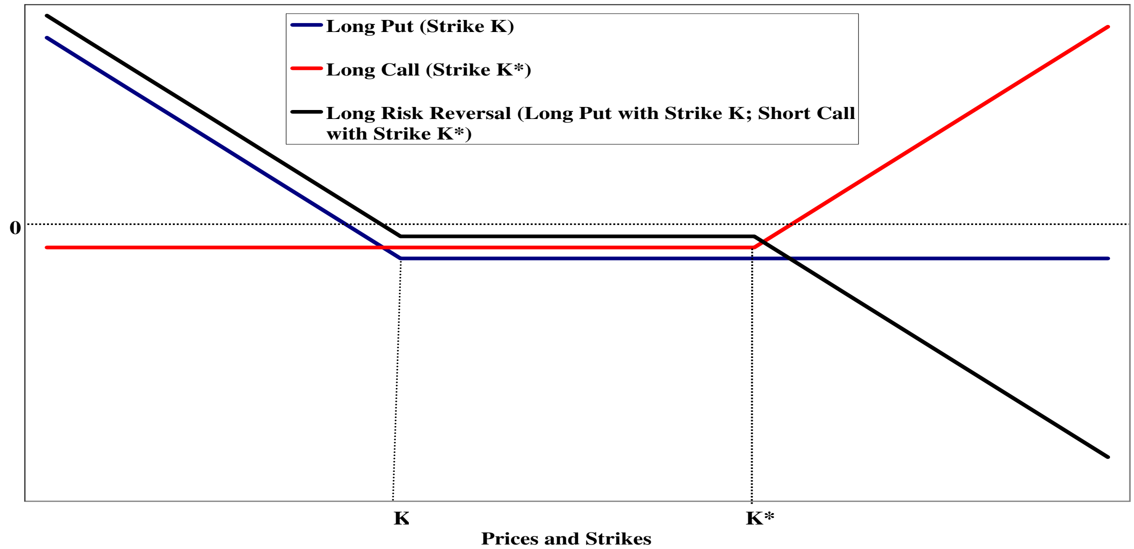

Figure 1: Option Payoffs

This figure presents the payoffs of different option investments as a function of the underlying asset prices and strikes. We consider the payoff of buying a call (with strike $K^{\star}$) or buying a put option (with strike K). Finally, we consider a risk reversal that corresponds to selling a call (with strike $K^{\star}$) and simultaneously buying a put (with strike K).

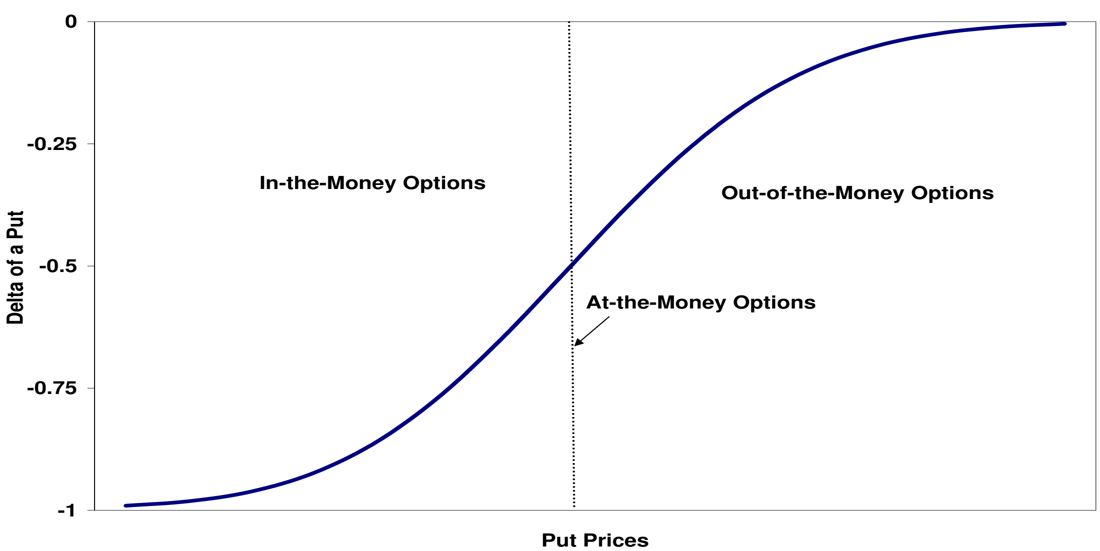

Figure 2: Deltas

This figure presents the deltas of put options as a function of their prices. The delta of an option is defined as the rate of change of the option price with respect to the price of the underlying asset. The delta of a put varies between -1 for extremely in the money options to 0 for extremely out of the money options.

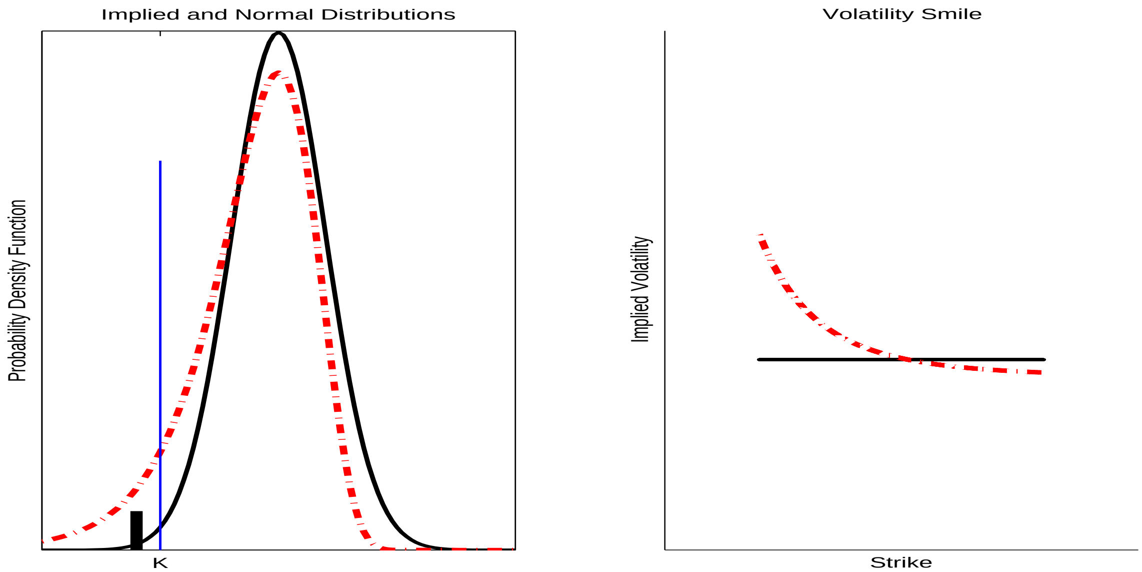

Figure 3: Implied distributions and implied volatility smiles

This figure relates implied distributions to implied volatility smiles. The left panel presents two theoretical distributions. They do not correspond to our data and are used here only as examples. The first one (in black) corresponds to a Gaussian distribution. The second one (in red) has the same mean and standard deviation as the Gaussian distribution but exhibits a left, fat tail. The probability of an exchange rate depreciation is here larger than in a Gaussian distribution. This second distribution can be thought of as the sum of a Gaussian distribution and some large but rare disasters (represented here in a black rectangle). Note that buying an option with strike κ (blue vertical line) offers protection against these disasters, but also against all the negative exchange rate changes implied by the Gaussian distribution to the left of the blue line. The right panel presents two implied volatility curves as function of strikes. The implied volatility is defined as the volatility necessary to match the observed option price using a standard Black-Scholes formula. If the distribution of the underlying exchange rate is Gaussian, the implied volatility is unique; it does not vary with the option strike. It corresponds to the black line. If the underlying distribution has a left fat tail, for example, the implied volatility varies with the option strike (red curve); in this case, the implied volatility for low strikes is higher than for a Gaussian distribution.

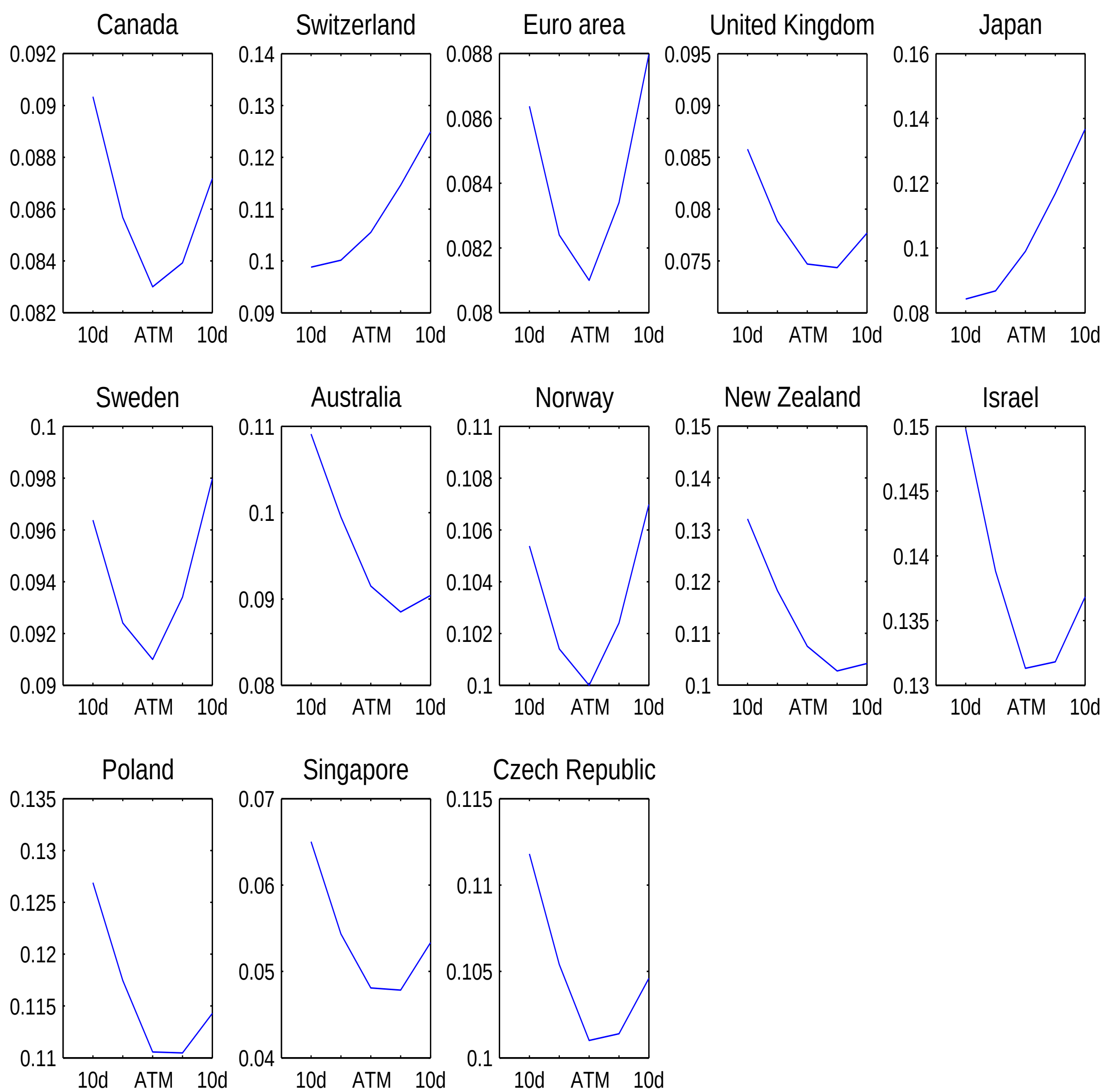

Figure 4: One-Month Option-Implied Volatility Smiles - August 2008.

This figure plots, for each currency in our sample, implied volatilities for different strike prices. Implied volatilities are in percentages. Strike prices are scaled by spot rates.

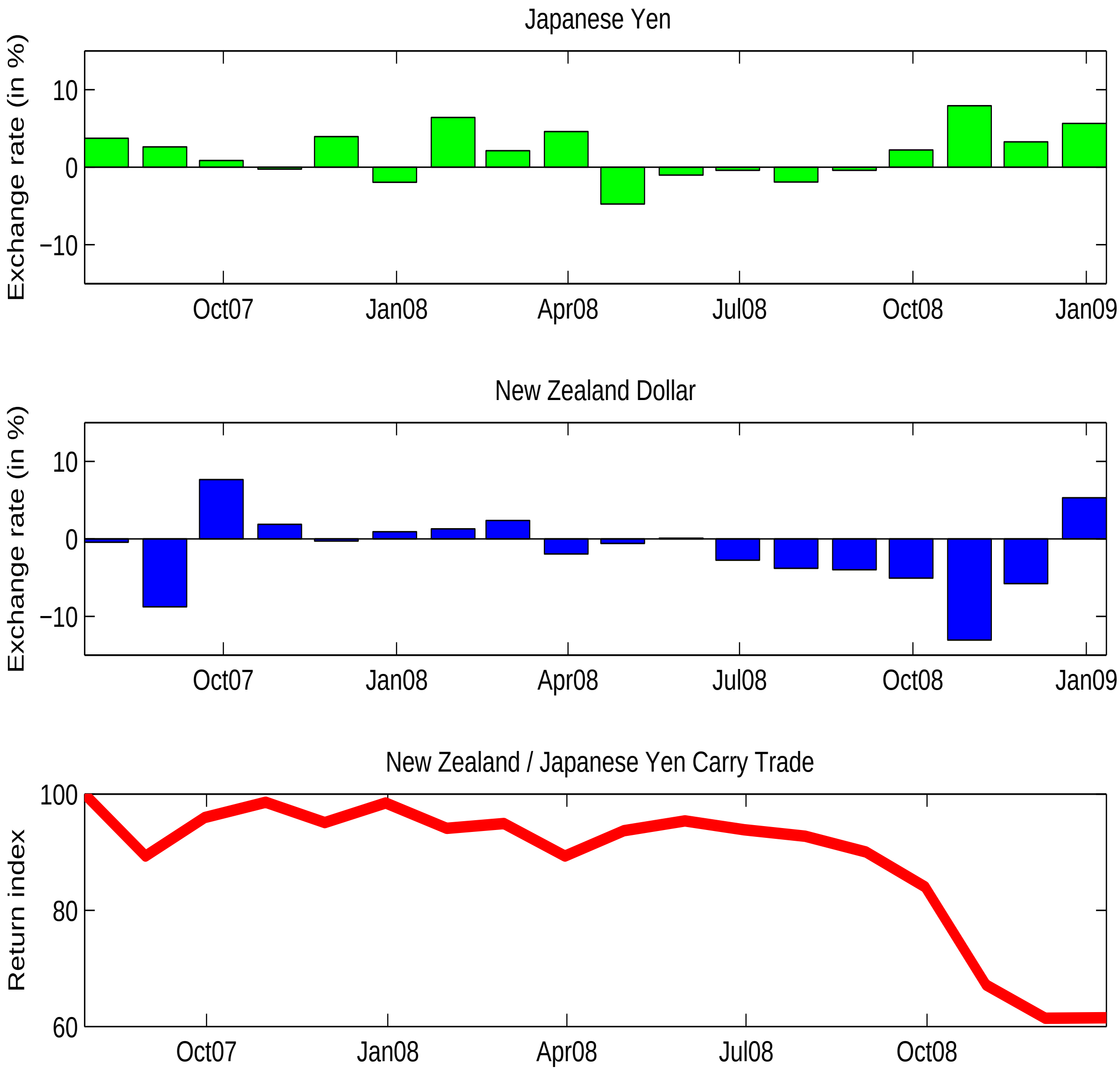

Figure 5: New Zealand Dollar and Japanese Yen

This figure plots monthly changes in exchange rates for the New Zealand Dollar and Japanese Yen and the return index on a carry trade strategy that borrows in Yen to invest in New Zealand Dollar. The sample period is 7/2007 - 12/2008.

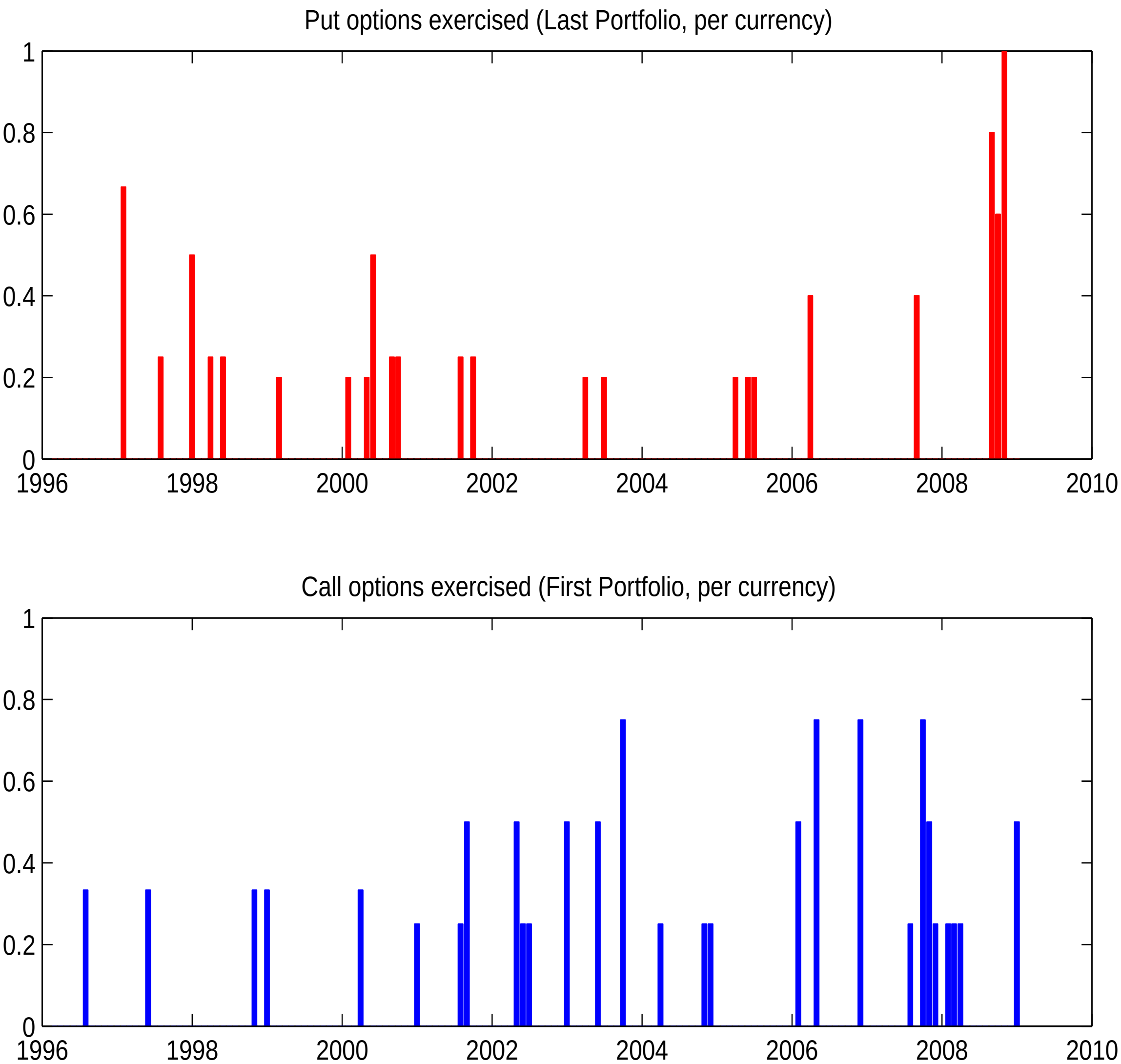

Figure 6: Options Exercised

This figure plots the frequency of call and put options exercised respectively in the first and last portfolios. At each point in time, the frequency is obtained as the number of options exercised divided by the number of currencies in the portfolio at that time. We consider only options at 10-delta. The sample period is 2/1996 - 12/2008.

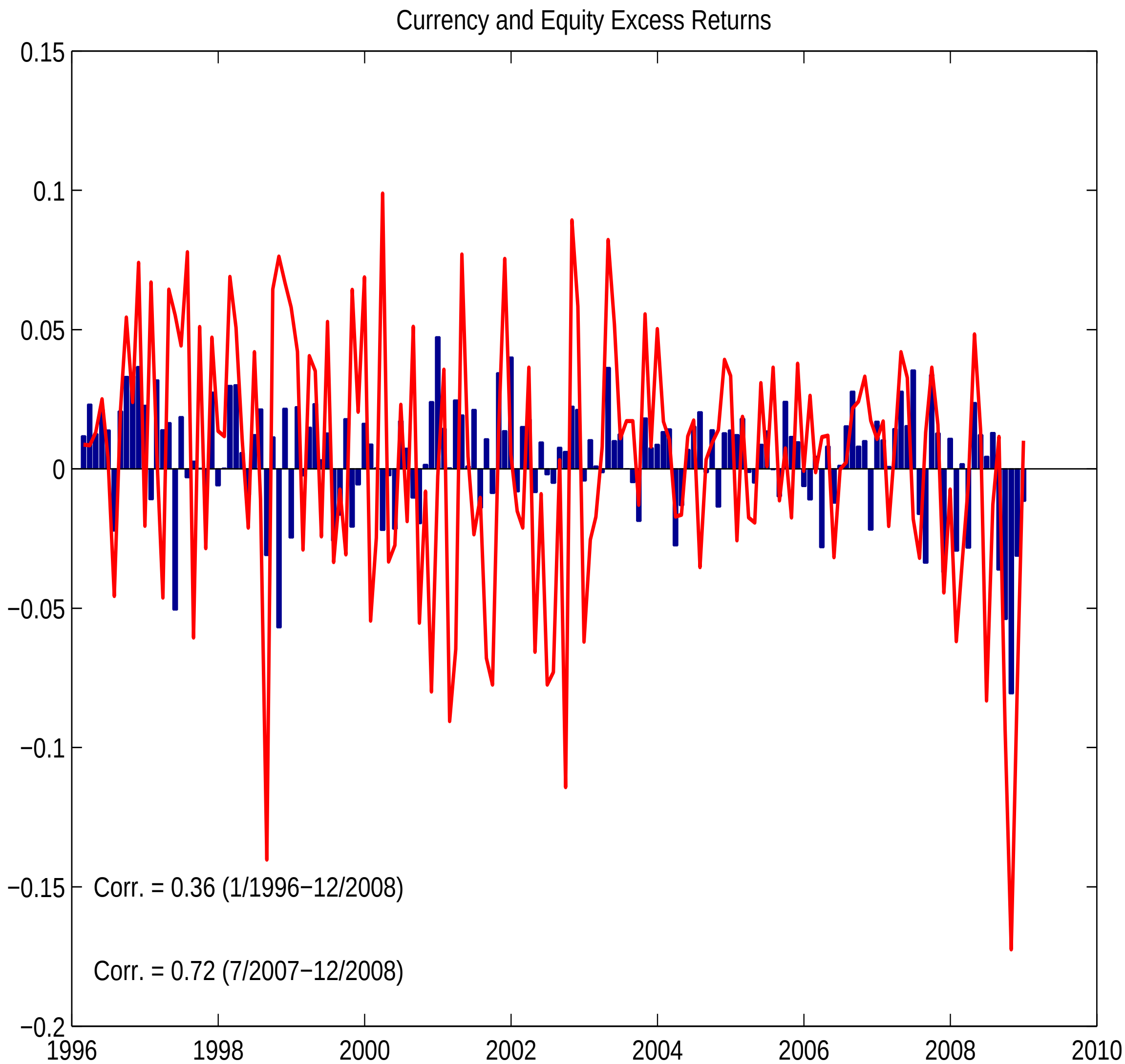

Figure 7: Currency Carry Trades and Equity Returns.

This figure plots monthly currency carry trades and US equity returns. Carry excess returns (blue bars) correspond to our sample of advanced countries. Data are monthly, from JP Morgan (IMF). Equity returns (red line) correspond to the US MSCI index. The sample period is 2/1996 - 12/2008.

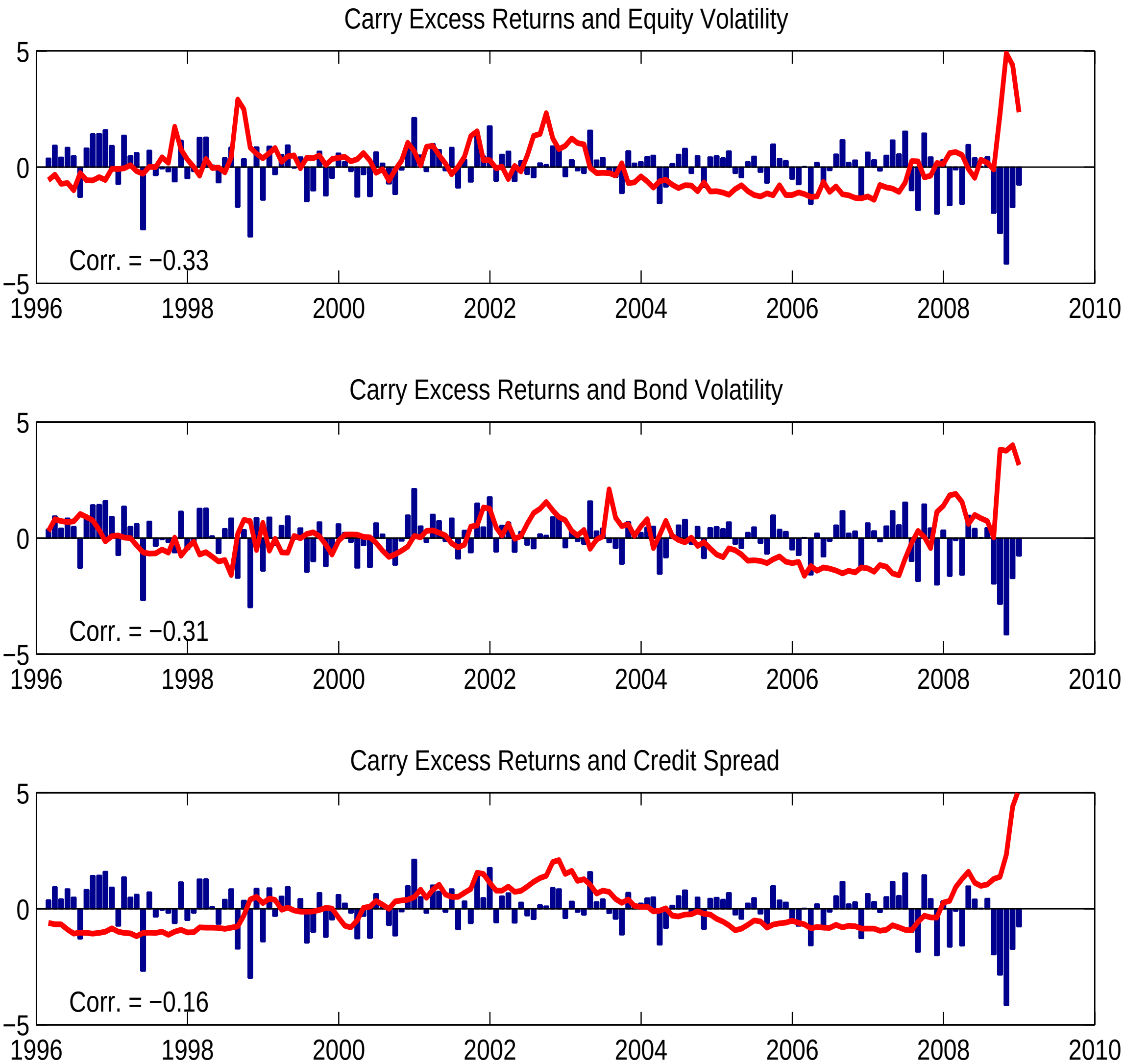

Figure 8: Carry Returns and Risk Measures

This figure plots carry excess returns and different risk measures. The upper panel uses the equity option-implied volatility index VIX; below are the bond option-implied volatility MOVE index and the credit spread (measured as the yield spreads between BAA and 10-year US Treasury bonds). Currency returns (blue bars) and risk measures (red lines) are all demeaned and divided by their standard deviations. The sample period is 2/1996 - 12/2008.

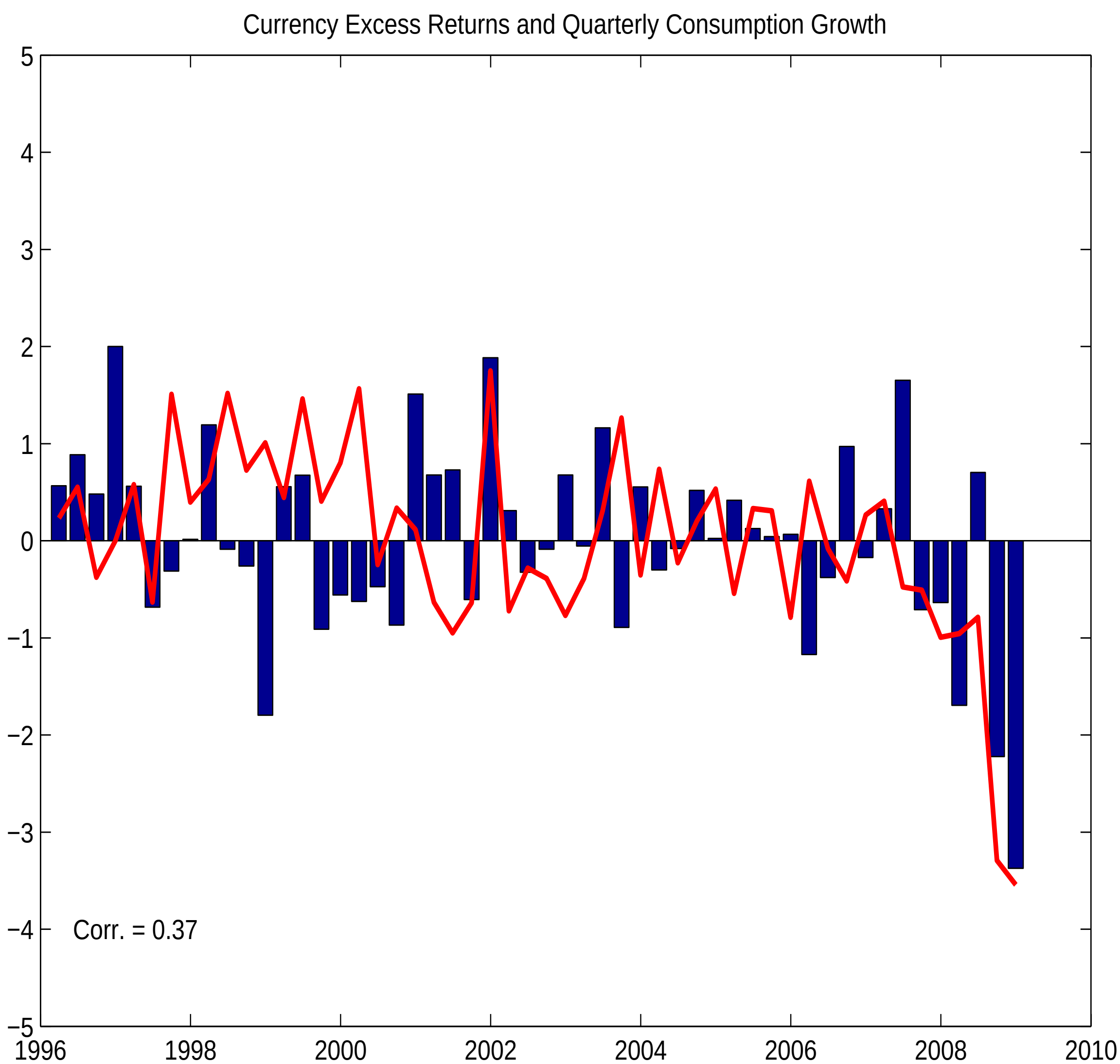

Figure 9: Carry Returns and Consumption Growth

This figure presents quarterly carry excess returns and real consumption growth per capita. Currency returns (blue bars) and consumption growth (red line) are all demeaned and divided by their standard deviations. The sample period is 2/1996 - 12/2008.

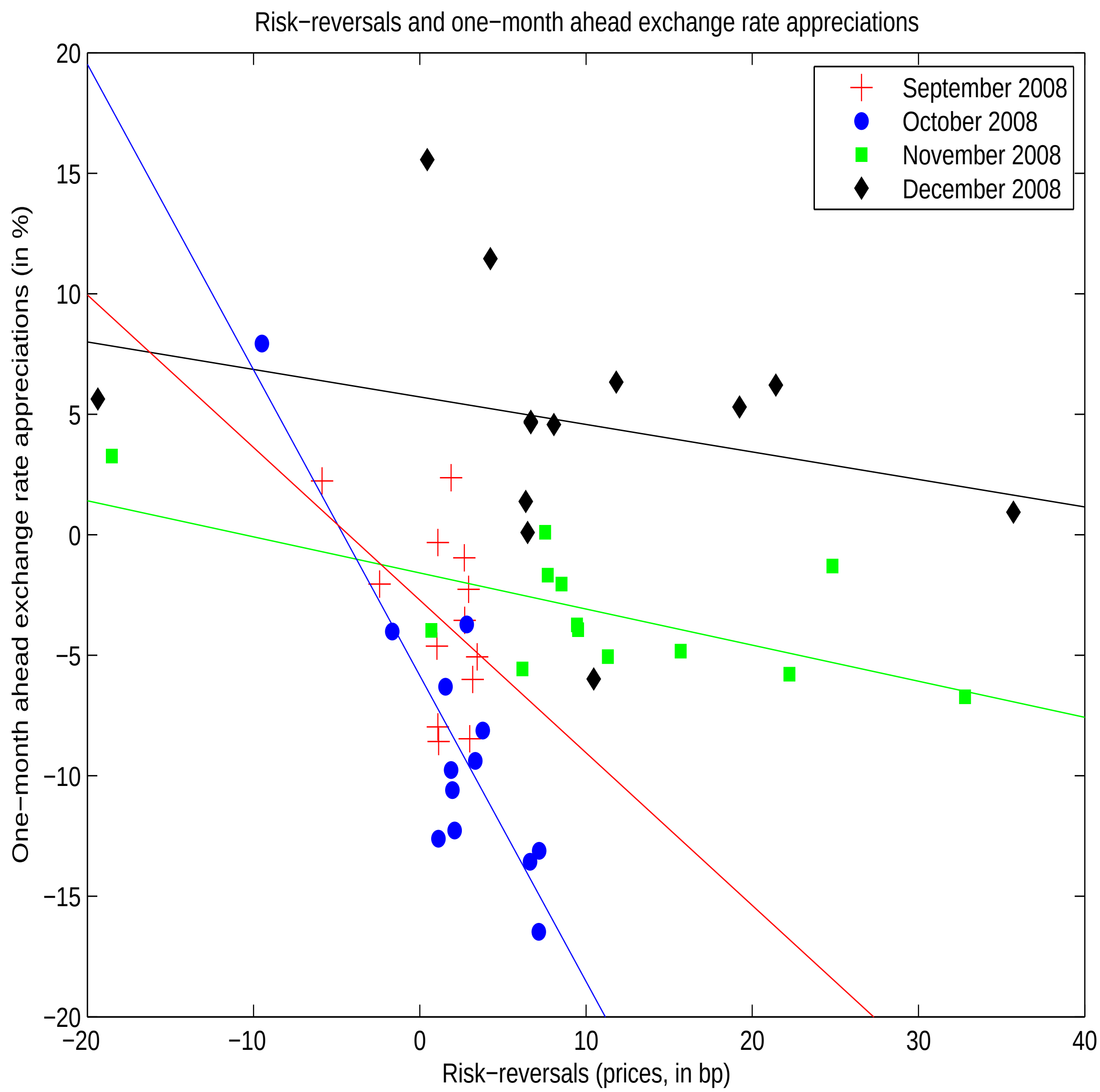

Figure 10: Risk Reversals and Changes in Exchange Rates - Fall 2008

This figure plots risk reversals at 10-delta and subsequent one-month changes in exchange rates for each month of fall 2008. Risk reversal prices are in basis points. Changes in exchange rates are in percentages. Increases in exchange rates correspond to depreciations of the US dollar. Exchange rate changes between date t and $t+1$ are dated $t+1$. The sample period focuses on advanced countries and covers the period from 9/2008 to 12/2008.

Crash Risk in Currency Markets
- Supplementary Appendix -

5 Appendix A: Derivations

5.1 Some Useful Lemmas

We start with a well-known Lemma, whose proof we provide for completeness.

Lemma 3. *(Discrete-time Girsanov's lemma) Suppose that* (x, y) *are jointly Gaussian distributed random variables under probability measure* P. *Consider the measure* Q *such that* $dQ/dP = \exp(x - E[x] - \mathrm{var}(x)/2)$. *Then, under* Q, y *is Gaussian, with distribution*

$$y \sim^Q \mathcal{N}(E[y] + \mathrm{cov}(x, y), \mathrm{var}(y)), \tag{11}$$

where $E[y], \mathrm{cov}(x, y), \mathrm{var}(y)$ *are calculated under* P.

Proof. We calculate that the characteristic function of y. For a purely imaginary number k, $E^Q\left[e^{ky}\right]$ is given by

$$E\left[e^{x-E[x]-\sigma_x^2/2}e^{ky}\right] = \exp\left(kE[y] + \frac{k^2\sigma_y^2}{2} + k\,cov(x, y)\right) = \exp\left(k(E[y] + \mathrm{cov}(x, y)) + \frac{k^2\sigma_y^2}{2}\right).$$

That is indeed the characteristic function of distribution (11). $\square$

Lemma 4. *For* $\ln X$, $\ln Y$ *jointly Gaussian distributed,*

$$\begin{aligned} E\left[(X-Y)^+\right] &= V_{BS}^C\left(E[X], E[Y], \mathrm{var}(\ln X - \ln Y)^{1/2}\right) \\ &= V_{BS}^P\left(E[Y], E[X], \mathrm{var}(\ln X - \ln Y)^{1/2}\right), \end{aligned}$$

where the convention is $V_{BS}^C(S_0, K, \sigma)$ *and* $V_{BS}^P(S_0, K, \sigma)$ *are the Black-Scholes call and put prices with interest rate 0 and horizon* 1.

Proof. Observe that our Black-Scholes functions are:

$$V_{BS}^P(S, K, \sigma) = E\left[\left(K - Se^{\sigma u - \sigma^2/2}\right)^+\right], \qquad V_{BS}^C(S, K, \sigma) = E\left[\left(Se^{\sigma u - \sigma^2/2} - K\right)^+\right],$$

where u is a normal with mean 0 and variance 1.

Write $X = E[X]\, e^{x-\text{var}(x)/2}$ and $Y = E[Y]\, e^{y-\text{var}(y)/2}$, where (x, y) are jointly Gaussian distributed with mean 0 and respective variance $\text{var}(\ln X)$ and $\text{var}(\ln Y)$. Use Lemma 3, calling P the underlying probability measure, and defining measure $dQ/dP = \exp(x - E[x] - \text{Var}(x)/2)$,

$$\begin{aligned} E\left[(X-Y)^+\right] &= E\left[\left(E[X]\, e^{x-\text{var}(x)/2} - E[Y]\, e^{y-\text{var}(y)/2}\right)^+\right] \\ &= E\left[e^{x-\text{var}(x)/2}\left(E[X] - E[Y]\, e^z\right)^+\right] \\ &= E^Q\left[\left(E[X] - E[Y]\, e^z\right)^+\right], \end{aligned}$$

with $z = y - \text{var}(y)/2 - x + \text{var}(x)/2$. Applying Lemma 3, $z \sim^Q \mathcal{N}\left(E^Q[z], \text{var}(y-x)\right)$, with:

$$\begin{aligned} E^Q[z] &= -\text{var}(y)/2 + \text{var}(x)/2 + \text{cov}(x, y-x) \\ &= -\text{var}(y-x)/2, \end{aligned}$$

and

$$z \sim^Q \mathcal{N}(-\text{var}(y-x)/2, \text{var}(y-x)).$$

So

$$E\left[(X-Y)^+\right] = V_{BS}^P\left(E[Y], E[X], \text{var}(\ln X - \ln Y)^{1/2}\right).$$

The same reasoning shows that $E\left[(X-Y)^+\right] = V_{BS}^C\left(E[X], E[Y], \text{var}(\ln X - \ln Y)^{1/2}\right)$. ☐

Lemma 5. *For $\ln X$, $\ln Y$, $\ln Z$ jointly Gaussian distributed,*

$$\begin{aligned} \text{cov}\left(Z, (X-Y)^+\right) &= V_{BS}^C\left(E[ZX], E[ZY], \text{var}(\ln X - \ln Y)^{1/2}\right) \\ &\quad - E[Z]\, V_{BS}^C\left(E[X], E[Y], \text{var}(\ln X - \ln Y)^{1/2}\right) \\ &= V_{BS}^P\left(E[ZY], E[ZX], \text{var}(\ln X - \ln Y)^{1/2}\right) \\ &\quad - E[Z]\, V_{BS}^P\left(E[Y], E[X], \text{var}(\ln X - \ln Y)^{1/2}\right). \end{aligned}$$

Proof. It comes directly from the previous Lemma. ☐

5.2 Proofs

5.2.1 Proof of Proposition 1

Call $H = pE[J-1]$. We have:

$$e^{-r\tau} = E[M_{t,t+\tau}] = e^{-g\tau}(1 + H\tau).$$

Taking logs,

$$-r\tau = -g\tau + \ln(1 + H\tau) = -g\tau + H\tau + o(\tau),$$

so $r = g - H + o(1)$.

5.2.2 Proof of Proposition 2

Unhedged Returns The trade has return X in domestic currency, and does not require any investment, so $E[M_{t,t+\tau} X_{t,t+\tau}] = 0$. Hence:

$$\begin{aligned} 0 &= (1 - p\tau) E^{ND}[M_{t,t+\tau} X_{t,t+\tau}] + p\tau E^{D}[M_{t,t+\tau} X_{t,t+\tau}] \\ &= (1 - p\tau)\left(E^{ND}[M_{t,t+\tau}] E^{ND}[X_{t,t+\tau}] + cov^{ND}(M_{t,t+\tau}, X_{t,t+\tau})\right) + p\tau E^{D}[M_{t,t+\tau} X_{t,t+\tau}]. \end{aligned}$$

Hence

$$E^{ND}[X_{t,t+\tau}] = \frac{-p\tau E^{D}[M_{t,t+\tau} X_{t,t+\tau}] - (1 - p\tau) cov^{ND}(M_{t,t+\tau}, X_{t,t+\tau})}{(1 - p\tau) E^{ND}[M_{t,t+\tau}]}.$$

Note that

$$E^{ND}[M_{t,t+\tau}] = 1 + o(1),$$

$$cov^{ND}(M_{t,t+\tau}, X_{t,t+\tau}) = cov^{ND}(\varepsilon, \varepsilon^{\star} - \varepsilon)\tau + o(\tau),$$

and

$$E^{D}[M_{t,t+\tau} X_{t,t+\tau}] = E[(J^{\star} - J)] + o(1).$$

Therefore,

$$E^{ND}[X_{t,t+\tau}]/\tau = pE[J - J^{\star}] - \mathrm{cov}(\varepsilon, \varepsilon^{\star} - \varepsilon) + o(1).$$

Hedged returns By the same reasoning as above, and using $\lambda^{P}_{t,t+\tau} = 1 + o(1)$, $\lambda^{C}_{t,t+\tau} = 1 + o(1)$,

$$\begin{aligned} E^{ND}[X_{t,t+\tau}(K)] &= p\tau E[J - J^{\star}] - p\tau E\left[(KJ - J^{\star})^{+}\right] \\ &\quad - cov^{ND}\left[M_{t,t+\tau}, \left(K - \frac{S_{t+\tau}}{S_t}\right)^{+}\right] - cov^{ND}\left[M_{t,t+\tau}, \frac{S_{t+\tau}}{S_t}\right]. \end{aligned}$$

We see that

$$\begin{aligned} cov^{ND}\left[M_{t,t+\tau}, \frac{S_{t+\tau}}{S_t}\right] &= \mathrm{cov}\left(\varepsilon\sqrt{\tau}, (\varepsilon^{\star} - \varepsilon)\sqrt{\tau}\right) + o(\tau) \\ &= \mathrm{cov}(\varepsilon, \varepsilon^{\star} - \varepsilon)\tau + o(\tau). \end{aligned}$$

Call $Z = M_{t,t+\tau}$, $X = K$, $Y = S_{t+\tau}/S_t$, so that

$$E[Z] = e^{-g\tau},\ E[Y] = e^{(-g^{\star} + g - cov(\varepsilon, \varepsilon^{\star} - \varepsilon))\tau},\ E[ZY] = e^{-g^{\star}\tau}.$$

We use Lemma 5. We have:

$$
\begin{aligned}
cov^{ND}\left[M, \left(e^{\kappa\sqrt{\tau}} - \frac{S_{t+\tau}}{S_t}\right)^+\right] &= V_{BS}^P\left(e^{g^\star\tau}, e^{\kappa\sqrt{\tau}}e^{g\tau}, \mathrm{var}\left(\varepsilon^\star - \varepsilon\right)^{1/2}\sqrt{\tau}\right) \\
&\quad - V_{BS}^P\left(e^{g^\star\tau + \mathrm{cov}(\varepsilon,\varepsilon^\star-\varepsilon)\tau}, e^{\kappa\sqrt{\tau}}e^{g\tau}, \mathrm{var}\left(\varepsilon^\star - \varepsilon\right)^{1/2}\sqrt{\tau}\right) \\
&= \Delta_{BS}^P(\kappa)\,\mathrm{cov}\left(\varepsilon, \varepsilon^\star - \varepsilon\right)\tau + o(\tau).
\end{aligned}
$$

We conclude:

$$
\lim_{\tau\to 0} E^{ND}\left[X\left(e^{\kappa\sqrt{\tau}}\right)\right]/\tau = pE\left[J - J^\star\right] - pE\left[\left(KJ - J^\star\right)^+\right] - \mathrm{cov}\left(\varepsilon, \varepsilon^\star - \varepsilon\right)\left(1 + \Delta_{BS}^P(\kappa)\right).
$$

5.2.3 Proof of Lemma 1

It follows directly from the calculations done in the proof of Proposition 3. The disaster risk premium is proportional to $p\tau$, while the disaster risk premium is proportional to $\sqrt{\tau}$. So in the limit of small times, the option price is equal to its no-disaster component up to smaller $O(\tau)$ terms.

5.2.4 Proof of Lemma 2

We have

$$
E\left[M_{t,t+\tau}\right] = e^{-r\tau} \text{ and } E\left[M_{t,t+\tau}^\star\right] = e^{-r^\star\tau}.
$$

Also, define $\sigma = \mathrm{var}\left(\varepsilon^\star - \varepsilon\right)^{1/2}$. So, the call price is:

$$
\begin{aligned}
C(K) = E\left[M_{t,t+\tau}\left(\frac{S_{t+\tau}}{S_t} - K\right)^+\right] &= E\left[\left(M_{t,t+\tau}^\star - KM_{t,t+\tau}\right)^+\right] \\
= V_{BS}^C(E\left[M_{t,t+\tau}^\star\right], E\left[KM_{t,t+\tau}\right], \sigma\sqrt{\tau}) &\text{ by Lemma 4} \\
= V_{BS}^C(e^{-r^\star\tau}, Ke^{-r\tau}, \sigma\sqrt{\tau}).&
\end{aligned}
$$

The price of a put with strike $\widetilde{K}$ is:

$$
\begin{aligned}
P\left(\widetilde{K}\right) = E\left[M_{t,t+\tau}\left(\widetilde{K} - \frac{S_{t+\tau}}{S_t}\right)^+\right] &= E\left[\left(\widetilde{K}M_{t,t+\tau} - M_{t,t+\tau}^\star\right)^+\right] \\
= V_{BS}^C(\widetilde{K}E\left[M_{t,t+\tau}\right], E\left[M_{t,t+\tau}^\star\right], \sigma\sqrt{\tau}) &\text{ by Lemma 4} \\
= V_{BS}^C(\widetilde{K}e^{-r\tau}, e^{-r^\star\tau}, \sigma\sqrt{\tau}).&
\end{aligned}
$$

so, when $\widetilde{K} = K^{-1}e^{2(r-r^\star)\tau}$,

$$\begin{aligned}
P\left(\widetilde{K}\right) &= V_{BS}^C(K^{-1}e^{2(r-r^\star)\tau}e^{-r\tau}, e^{-r^\star\tau}, \sigma\sqrt{\tau}) \\
&=^{(a)} K^{-1}e^{(r-r^\star)\tau}V_{BS}^C(e^{-r^\star\tau}, Ke^{-r\tau}, \sigma\sqrt{\tau}) \\
&= K^{-1}e^{(r-r^\star)\tau}C(K),
\end{aligned}$$

where $=^{(a)}$ is because $V_{BS}^C(S, k, \sigma\sqrt{\tau})$ is homogenous of degree 1 in (S, k). So indeed,

$$RR = P\left(K^{-1}e^{2(r-r^\star)\tau}\right) - K^{-1}e^{(r-r^\star)\tau}C(K) = 0.$$

5.2.5 Proof of Proposition 3

We start with a lemma characterizing the price of puts for slightly more general strikes given by $e^{\kappa\sqrt{\tau}+\alpha\tau}$. The price of a put with strike $e^{\kappa\sqrt{\tau}+\alpha\tau}$ is by definition

$$C\left(e^{\kappa\sqrt{\tau}+\alpha\tau}\right) = E\left[M_{t,t+\tau}(\frac{S_{t+\tau}}{S_t} - e^{\kappa\sqrt{\tau}+\alpha\tau})^+\right] = C^D\left(e^{\kappa\sqrt{\tau}+\alpha\tau}\right) + C^{ND}\left(e^{\kappa\sqrt{\tau}+\alpha\tau}\right),$$

where

$$C^D\left(e^{\kappa\sqrt{\tau}+\alpha\tau}\right) = p\tau E^D\left[M_{t,t+\tau}(\frac{S_{t+\tau}}{S_t} - e^{\kappa\sqrt{\tau}+\alpha\tau})^+\right],$$

and

$$C^{ND}\left(e^{\kappa\sqrt{\tau}+\alpha\tau}\right) = (1-p\tau)\,E^{ND}\left[M_{t,t+\tau}(\frac{S_{t+\tau}}{S_t} - e^{\kappa\sqrt{\tau}+\alpha\tau})^+\right].$$

Let $\sigma = \mathrm{var}\,(\varepsilon^\star - \varepsilon)^{1/2}$.

Lemma 6. *We have*

$$C^{ND}\left(e^{\kappa\sqrt{\tau}+\alpha\tau}\right) = e^{\kappa\sqrt{\tau}}V_{BS}^C\left(e^{-\kappa\sqrt{\tau}}, 1, \sigma\sqrt{\tau}\right) + \Delta_{BS}^C(\kappa)\,(r - r^\star - \alpha)\,\tau + o\,(\tau)\,,$$

and

$$P^{ND}\left(e^{-\kappa\sqrt{\tau}+\beta\tau}\right) = V_{BS}^C\left(e^{-\kappa\sqrt{\tau}}, 1, \sigma\sqrt{\tau}\right) + \Delta_{BS}^C(\kappa)\,(r^\star - r + \beta)\,\tau + o\,(\tau)\,.$$

Proof. We first calculate the value of the call. By Lemma 4, we have

$$\begin{aligned}
C^{ND}\left(e^{\kappa\sqrt{\tau}+\alpha\tau}\right) &= (1-p\tau)\,V_{BS}^C\left(e^{-r^\star\tau}, e^{(-r+\alpha)\tau+\kappa\sqrt{\tau}}, \sigma\sqrt{\tau}\right) \\
&= (1-p\tau)\,e^{(-r+\alpha)\tau+\kappa\sqrt{\tau}}V_{BS}^C\left(e^{(r-r^\star-\alpha)\tau-\kappa\sqrt{\tau}}, 1, \sigma\sqrt{\tau}\right) \\
&= e^{\kappa\sqrt{\tau}}\,(1 + (-r-p+\alpha)\,\tau + o\,(\tau)) \\
&\quad \left[V_{BS}^C\left(e^{-\kappa\sqrt{\tau}}, 1, \sigma\sqrt{\tau}\right) + \Delta_{BS}^C(\kappa)\,(r - r^\star - \alpha)\,\tau + o\,(\tau)\right],
\end{aligned}$$

by Taylor expansion. We observe that $V_{BS}^{C}\left(e^{-\kappa\sqrt{\tau}},1,\sigma\tau^{1/2}\right)=O\left(\sqrt{\tau}\right)$, so

$$C^{ND}\left(e^{\kappa\sqrt{\tau}+\alpha\tau}\right)=e^{\kappa\sqrt{\tau}}V_{BS}^{C}\left(e^{-\kappa\sqrt{\tau}},1,\sigma\sqrt{\tau}\right)+\Delta_{BS}^{C}(\kappa)\left(r-r^{\star}-\alpha\right)\tau+o\left(\tau\right).$$

□

The derivation of the put price is similar.

Lemma 7. $P\left(e^{-\kappa\sqrt{\tau}+\beta\tau}\right)-e^{-\kappa\sqrt{\tau}+\gamma\tau}C\left(e^{\kappa\sqrt{\tau}+\alpha\tau}\right)$ *is given by the following formula*

$$\begin{aligned}&p\tau E^{D}\left[\left(Je^{-\kappa\sqrt{\tau}+\beta\tau}-J^{\star}\right)^{+}-\left(e^{-\kappa\sqrt{\tau}+\gamma\tau}J-J^{\star}e^{(\alpha+\gamma)\tau}\right)^{+}\right]\\&+\Delta_{BS}^{C}(\kappa)\left(2\left(r-r^{\star}\right)+\beta+\alpha\right)\tau+o\left(\tau\right).\end{aligned}$$

Proof. Clearly $P^{ND}\left(e^{-\kappa\sqrt{\tau}+\beta\tau}\right)-e^{-\kappa\sqrt{\tau}+\gamma\tau}C^{ND}\left(e^{\kappa\sqrt{\tau}+\alpha\tau}\right)$ is given by

$$\begin{aligned}&\left\{V_{BS}^{C}\left(e^{-\kappa\sqrt{\tau}},1,\sigma\sqrt{\tau}\right)+\Delta_{BS}^{P}(\kappa)\left(r^{\star}-r+\beta\right)\tau\right\}\\&-e^{-\kappa\sqrt{\tau}+\gamma\tau}\left\{e^{\kappa\sqrt{\tau}}V_{BS}^{C}\left(e^{-\kappa\sqrt{\tau}},1,\sigma\sqrt{\tau}\right)+\Delta_{BS}^{C}(\kappa)\left(r-r^{\star}-\alpha\right)\tau+o\left(\tau\right)\right\}\\&=\Delta_{BS}^{C}(\kappa)\left(2\left(r^{\star}-r\right)+\beta+\alpha\right)\tau+o\left(\tau\right).\end{aligned}$$

The result follows. □

With those two lemmas, the result in the proposition can be derived by taking $\alpha=\beta=\gamma=r-r^{\star}$.

5.2.6 Proof of Proposition 4

The impact of risk on interest rate comes from 1, written for the foreign country (with starred variables). By examining (6) and (7), one sees that it increases when $F^{\star}$ decreases.

6 Appendix B: Results when the Home Currency is the Investment Currency

We define the hedged carry-trade returns $Y_{t,t+\tau}(K)$ as the payoff corresponding to the following zero investment trade: invest one in home at interest r, buy $\lambda_{t,t+\tau}^{C}(K)$ calls with strike K protecting against an appreciation of the foreign currency and, in order to finance these investments, borrow $\left(1+\lambda_{t,t+\tau}^{C}(K)C_{t,t+\tau}(K)\right)$ in the foreign currency at interest rate $r^{\star}$. Once again, we choose the hedge ratio $\lambda_{t,t+\tau}^{C}(K)$ to eliminate tail risk.

$$Y_{t,t+\tau}(K)=e^{r\tau}-\left(1+\lambda_{t,t+\tau}^{C}C_{t,t+\tau}(K)\right)e^{r^{\star}\tau}\frac{S_{t+\tau}}{S_{t}}+\lambda_{t,t+\tau}^{C}\left(\frac{S_{t+\tau}}{S_{t}}-K\right)^{+},$$

where $P_{t,t+\tau}(K)$ is the home currency price of a put yielding $\left(K - \frac{S_{t+\tau}}{S_t}\right)^+$ in the home currency, and $C_{t,t+\tau}(K)$ is home currency price of a call yielding $\left(\frac{S_{t+\tau}}{S_t} - K\right)^+$ in the home currency, and:

$$\lambda^C_{t,t+\tau} = \frac{e^{r^\star \tau}}{1 - C_{t,t+\tau}(K) e^{r^\star \tau}}.$$

Proposition 5. *In the limit of small time intervals ($\tau \to 0$), the carry trade expected returns (conditional on no disasters) are given by the following equation*

$$\lim_{\tau \to 0} E^{ND}\left[Y_{t,t+\tau}\right]/\tau = -\lim_{\tau \to 0} E^{ND}\left[X\right]/\tau.$$

In the same limit, the hedged carry trade expected returns (conditional on no disasters) are given by

$$\lim_{\tau \to 0} E^{ND}\left[Y_{t,t+\tau}\left(e^{\kappa\sqrt{\tau}}\right)\right]/\tau = -pE\left[(J - J^\star)^+\right] - \operatorname{cov}\left(\varepsilon, \varepsilon - \varepsilon^\star\right)\left(1 - \Delta^C_{BS}(\kappa)\right),$$

where

$$\Delta^C_{BS}(\kappa) = \partial V^C_{BS}\left(s, e^\kappa, \operatorname{var}\left(\varepsilon^\star - \varepsilon\right)^{1/2}\right)/\partial s|_{s=1} \in (0, 1)$$

are the Black-Scholes deltas of the call.

7 Appendix C: Robustness Checks

In this Appendix we report additional results obtained on the whole sample of advanced and emerging countries.

- Table 9 reports higher moments and normality tests for country-by-country changes in exchange rates. Table 10 reports the same tests after GARCH(1,1) corrections. Table 11 reports equivalent results for portfolios of currency excess returns.
- Table 12 presents some examples of bid-ask spreads on advanced and emerging countries.
- Table 13 reports estimates of disaster risk premia for a subset of nine advanced countries.
- Table 14 reports average currency excess returns across portfolios using advanced and emerging countries. Table 15 reports implied volatilities and risk reversals for the same sample. Table 16 reports estimates of disaster risk premia. Table 17 takes into account bid ask spreads.
- Tables 18 and 20 report (contemporaneous and predictive) regressions on risk reversals, exchange rates and currency excess returns for advanced countries. Tables 19 and 21 report equivalent tests for advanced and emerging countries.
- Table 22 reports predictability tests on bilateral exchange rates for advanced countries.

Table 9: Higher Moments of Bilateral Exchange Rates - All Countries

Advanced Countries					Emerging Countries				
	Skew.	Kurt.	J.B	LL		Skew.	Kurt.	J.B	LL
Canada	0.06	3.09	0.15	0.04	Argentina	−5.79	40.88	5231.20	0.35
	[0.19]	[0.34]	0.50	0.50		[1.66]	[14.64]	0.00	0.00
Switzerland	0.22	2.30	4.23	0.06	Brazil	−0.25	7.31	90.07	0.09
	[0.12]	[0.18]	0.09	0.22		[0.71]	[1.16]	0.00	0.02
Euro area	0.18	2.81	0.77	0.06	Chile	−0.06	2.88	0.13	0.05
	[0.17]	[0.27]	0.50	0.35		[0.23]	[0.39]	0.50	0.50
United Kingdom	−0.33	3.89	7.69	0.04	Columbia	−0.42	5.00	20.86	0.13
	[0.30]	[0.74]	0.03	0.50		[0.42]	[0.74]	0.00	0.00
Japan	1.24	7.89	189.15	0.07	Indonesia	−0.43	15.38	847.09	0.24
	[0.62]	[2.96]	0.00	0.04		[1.50]	[3.67]	0.00	0.00
Sweden	0.26	2.88	1.73	0.05	India	0.53	10.38	317.38	0.18
	[0.16]	[0.29]	0.36	0.41		[0.97]	[2.42]	0.00	0.00
Australia	−0.06	2.84	0.25	0.05	Mexico	−0.97	6.03	81.21	0.09
	[0.19]	[0.33]	0.50	0.47		[0.45]	[1.69]	0.00	0.01
Norway	0.18	3.27	1.26	0.06	Malaysia	1.36	13.71	284.82	0.21
	[0.19]	[0.31]	0.48	0.14		[1.87]	[4.67]	0.00	0.00
New Zealand	−0.20	3.25	1.41	0.07	Peru	−1.44	12.28	531.58	0.18
	[0.18]	[0.32]	0.44	0.07		[0.96]	[3.40]	0.00	0.00
Israel	0.22	3.26	0.83	0.06	Philippines	−2.07	13.45	699.72	0.22
	[0.27]	[0.44]	0.50	0.50		[0.86]	[3.39]	0.00	0.00
Poland	−0.16	3.08	0.44	0.05	Thailand	1.16	14.55	768.74	0.14
	[0.23]	[0.41]	0.50	0.50		[1.32]	[4.91]	0.00	0.00
Singapore	0.37	6.31	72.46	0.08	Turkey	−0.44	3.57	4.17	0.11
	[0.54]	[1.34]	0.00	0.02		[0.30]	[0.71]	0.08	0.01
Czech Republic	0.04	2.96	0.04	0.06	Taiwan	−0.08	8.00	148.30	0.11
	[0.20]	[0.33]	0.50	0.40		[0.73]	[1.65]	0.00	0.00
South Korea	−2.52	23.41	2522.75	0.17	Venezuela	−0.15	2.44	0.18	0.19
	[1.73]	[7.97]	0.00	0.00		[0.56]	[0.87]	0.50	0.31
					South Africa	−0.13	3.19	0.62	0.05
						[0.18]	[0.33]	0.50	0.50

Notes: This table reports the skewness, kurtosis, and Jarque and Bera (1980) and Lilliefors (1967) normality tests of changes in exchange rates. The Jarque-Berra and Lilliefors's null hypothesis is a joint hypothesis of the skewness being zero and the excess kurtosis being 0. For the skewness and kurtosis, the table reports between brackets the standard error obtained by bootstrapping. For the Jarque-Berra and Lilliefors tests, the table reports the p-values. The sample exclude China, Hong Kong and Denmark whose exchange rate regimes are non-floating over the full sample period. The left panel focuses on advanced countries. The sample period is 1/1996 - 8/2008.

Table 10: Higher Moments of Bilateral Exchange Rates - GARCH(1,1) Correction - Advanced Countries

Advanced Countries				
	Skew.	Kurt.	J.B	LL
Canada	0.11	2.90	0.36	0.00
	[0.18]	[0.33]	0.50	0.50
Switzerland	0.22	2.30	4.23	0.00
	[0.12]	[0.18]	0.09	0.22
Euro area	0.16	2.83	0.72	0.00
	[0.16]	[0.27]	0.50	0.38
United Kingdom	−0.33	3.89	7.68	0.00
	[0.30]	[0.76]	0.03	0.50
Japan	1.14	7.18	142.95	0.00
	[0.57]	[2.63]	0.00	0.08
Sweden	0.26	2.88	1.73	0.00
	[0.15]	[0.30]	0.36	0.41
Australia	−0.14	2.73	0.93	0.00
	[0.17]	[0.30]	0.50	0.23
Norway	0.18	3.27	1.25	0.00
	[0.20]	[0.31]	0.49	0.14
New Zealand	−0.28	3.19	2.15	0.00
	[0.18]	[0.32]	0.28	0.06
Israel	−0.03	3.28	0.27	0.00
	[0.28]	[0.37]	0.50	0.48
Poland	−0.22	3.01	0.78	0.00
	[0.23]	[0.44]	0.50	0.50
Singapore	−0.16	3.62	3.03	0.00
	[0.24]	[0.39]	0.16	0.31
Czech Republic	0.09	2.89	0.25	0.00
	[0.21]	[0.32]	0.50	0.50
South Korea	−0.58	4.45	19.51	1.00
	[0.28]	[0.63]	0.00	0.01

Notes: This table reports the skewness, kurtosis, and Jarque and Bera (1980) and Lilliefors (1967) normality tests of *normalized* changes in exchange rates. In order to obtain these normalized series, we first estimate a GARCH(1,1) model for each country's exchange rate (in log differences) and then divide the exchange rate by the standard deviation. The Jarque-Berra and Lilliefors's null hypothesis is a joint hypothesis of the skewness being zero and the excess kurtosis being 0. For the skewness and kurtosis, the table reports between brackets the standard error obtained by bootstrapping. For the Jarque-Berra and Lilliefors tests, the table reports the p-values. The sample exclude China, Hong Kong and Denmark whose exchange rate regimes are non-floating over the full sample period. The left panel focuses on advanced countries. The sample period is 1/1996 - 8/2008.

Table 11: Higher Moments of Portfolio Currency Excess Returns

Panel I: Advanced Countries				
Portfolios	1	2	3	
Skewness	0.47	0.28	-0.60	
	[0.16]	[0.19]	[0.40]	
Kurtosis	2.90	3.28	5.04	
	[0.39]	[0.35]	[1.16]	
Jarque-Berra	5.64	2.40	35.33	
p-value	0.05	0.23	0.00	
Lilliefors	6.19	6.02	5.80	
p-value	0.17	0.20	0.25	

Panel II: All Countries				
Portfolios	1	2	3	4
Skewness	0.32	0.21	-2.23	1.26
	[0.18]	[0.21]	[0.95]	[0.85]
Kurtosis	3.01	3.64	15.29	10.73
	[0.37]	[0.35]	[5.26]	[3.61]
Jarque-Berra	2.55	3.63	1075.17	415.57
p-value	0.21	0.11	0.00	0.00
Lilliefors	6.00	7.51	12.16	10.13
p-value	0.20	0.04	0.00	0.00

Notes: This table reports higher moments of unhedged currency excess returns. The table reports the skewness and kurtosis of each portfolio and the corresponding standard errors. These are obtained by bootstrapping the monthly excess returns under the assumptions that they are i.i.d. The table also reports the Jarque and Bera (1980) and Lilliefors (1967) normality tests and the p-value of the null hypothesis (a p-value below 5% indicates rejection of normality at the 5% significance level). The Lilliefors test statistic is multiplied by 100. Portfolio 1 contains currencies with the lowest interest rates. Portfolio 3 contains currencies with the highest interest rates. The horizon of the excess returns and the option maturity are one month. Data are monthly, from JP Morgan. The sample period is 1/1996 - 8/2008.

Table 12: Bid-Ask Spreads - Examples

	EUR/USD	USD/CHF	AUD/USD	USD/BRL
		Panel I: November 10, 2008		
Spot	1.2890	1.1730	0.6950	2.1350
10δ Call	21.19/26.67	14.81/21.87	25.59/32.53	45/52
25δ Call	20.86/23.48	14.34/17.63	27.85/31.36	48/55
ATM	20.75/23.25	14.00/17.00	30.38/34.13	34/42
25δ Put	22.01/24.72	14.95/18.30	34.02/38.26	20/24
10δ Put	23.41/28.88	16.00/22.45	36.96/44.99	23/28
		Panel II: January 20, 2009		
Spot	1.2930	1.1450	0.6580	2.3650
10δ Call	22.60/25.00	19.80/22.80	20./22.50	31.50/34.00
25δ Call	21.50/23.00	19.00/20.50	19.00/20.50	30.50/35.00
ATM	21.5/22.50	18.70/20.20	18.70/20.20	34.50/36.50
25δ Put	22.30/23.50	19.30/21.00	19.50/21.20	48/52
10δ Put	23.80/26.00	20.50/23.50	20.70/23.80	41/43

Notes: This table reports spot rates and implied volatilities at one-month horizons for different pairs of currency options. Source: Bank of France (Broker-Dealers: UBS, Citibank, Deutsche Bank, JPM Chase). Panel I corresponds to quotes on November 10, 2008. Panel II corresponds to January 20, 2009.

Table 13: Disaster Risk Premia - Nine Advanced Countries Sorted on Interest Rates

	Panel I: Carry Excess Returns				
	Unhedged Carry	Hedged at 10 δ	Hedged at 25 δ	Hedged ATM	
Mean	5.03	3.44	2.54	0.90	
	[1.64]	[1.54]	[1.41]	[1.23]	
Mean Spread		1.59	2.48	4.12	
		[0.40]	[0.84]	[1.30]	

	Panel II: Estimations				
	10δ	25δ	ATM	10δ, 25δ, and ATM	GMM 2^{nd} $Stage$
$\overline{\pi}^D$	1.21	1.64	3.22	2.02	1.06
	[0.38]	[0.92]	[1.90]	[1.01]	[0.33]
$\overline{\pi}^G$	3.82	3.39	1.81	3.01	3.38
	[1.68]	[1.85]	[2.44]	[1.89]	[1.74]
$\overline{\pi}^D - \overline{\pi}^G$	-2.61	-1.75	1.41	-0.99	-2.32
	[1.82]	[2.44]	[4.07]	[2.57]	[1.85]

Notes: This first panel of this table reports average returns on hedged and unhedged currency carry trades and their standard errors. Due to the small number of countries in this sample, we only build two portfolios, sorting countries on interest rates. Carry trades correspond to returns on the second minus returns on the first portfolio. We consider different hedges: 10-delta, 25-delta and at-the-money. We also report the average difference between unhedged and hedged carry trades. The second panel reports structural estimates. $\overline{\pi}^D$ denotes the part of the carry excess return linked to disaster risk. $\overline{\pi}^G$ corresponds to the Gaussian, non-disaster part of the same excess return. These estimates are obtained using hedged returns at 10-delta (first column), 25-delta (second column), at-the-money (third column) or 10-, 25-delta and at-the-money (fourth and fifth columns). Standard errors are obtained by bootstrapping the monthly excess returns under the assumptions that they are i.i.d. Data are monthly, from JP Morgan. The sample period is 1/1996 - 8/2008.

Table 14: Excess Returns: All countries

Portfolios	1	2	3	4	1	2	3	4
	Going Long				Going Short			
	Panel I: Unhedged							
Mean	−2.35	1.10	0.48	12.59	2.35	−1.10	−0.48	−12.59
	[1.75]	[1.83]	[2.20]	[2.75]	[1.83]	[1.81]	[2.18]	[2.79]
Sharpe Ratio	−0.36	0.17	0.06	1.30	0.36	−0.17	−0.06	−1.30
	Panel II: Hedged at 10-delta							
Mean	−3.20	0.58	0.62	11.19	1.75	−1.16	−0.52	−11.89
	[1.73]	[1.65]	[1.65]	[2.50]	[1.66]	[1.68]	[2.13]	[2.40]
Sharpe Ratio	−0.52	0.10	0.10	1.27	0.29	−0.20	−0.07	−1.37
	Panel III: Hedged at 25-delta							
Mean	−2.87	0.37	0.26	8.85	1.44	−1.03	−0.46	−10.55
	[1.50]	[1.47]	[1.43]	[2.18]	[1.41]	[1.34]	[1.79]	[2.01]
Sharpe Ratio	−0.55	0.07	0.05	1.16	0.28	−0.21	−0.07	−1.42
	Panel IV: Hedged ATM							
Mean	−1.91	0.23	0.01	5.35	0.39	−0.87	−0.47	−7.27
	[1.05]	[1.12]	[0.98]	[1.50]	[1.01]	[0.98]	[1.60]	[1.46]
Sharpe Ratio	−0.51	0.06	0.00	0.98	0.11	−0.25	−0.08	−1.38

Notes: This table reports reports average currency excess returns that are unhedged, hedged at 10-delta, at 25-delta and at-the-money for our four portfolios. The last panel reports average risk reversals at 10- and 25-delta. In the left section, we assume that the US investor goes long the foreign currency. In the right section, we assume that the US investor goes short the foreign currency. In each case, we report the mean excess return, its standard deviation and the corresponding Sharpe ratio. The mean and standard deviations are annualized (multiplied respectively by 12 and $\sqrt{12}$). The Sharpe ratio corresponds to the ratio of the annualized mean to the annualized standard deviation. Portfolio 1 contains currencies with the lowest interest rates. Portfolio 4 contains currencies with the highest interest rates. The horizon of the excess returns and the option maturity are one month. Data are monthly, from JP Morgan. The sample period is 1/1996 - 8/2008.

Table 15: Implied Volatilities and Risk Reversals: All Countries

Portfolios	1	2	3	4
		Panel I: Implied Volatilities		
$10\delta-$Put	9.64	9.90	11.26	17.44
	[0.21]	[0.20]	[0.40]	[0.66]
$25\delta-$Put	9.12	9.29	10.21	15.57
	[0.18]	[0.19]	[0.35]	[0.60]
ATM	8.91	8.79	9.31	13.99
	[0.19]	[0.18]	[0.34]	[0.59]
$25\delta-$Call	9.25	8.93	9.24	13.39
	[0.20]	[0.18]	[0.32]	[0.56]
$10\delta-$Call	9.89	9.31	9.49	13.29
	[0.20]	[0.17]	[0.34]	[0.55]
		Panel II: Risk Reversals (Implied Volatilities)		
Mean RR10	−0.25	0.59	1.77	4.15
	[0.08]	[0.06]	[0.10]	[0.17]
Mean RR25	−0.13	0.36	0.97	2.18
	[0.04]	[0.03]	[0.05]	[0.08]
		Panel III: Risk Reversals (Prices)		
Mean RR10	0.04	1.17	2.94	7.11
	[0.11]	[0.09]	[0.20]	[0.37]
Mean RR25	0.75	2.80	5.91	14.38
	[0.20]	[0.17]	[0.44]	[0.94]

Notes: This table reports average implied volatilities and risk reversals by portfolios. The first panel reports average implied volatilities on put and call contracts for strike prices 10-, 25-delta and at-the-money. The last two panels reports risk reversals at 10- and 25-deltas. The second panel corresponds to differences in implied volatilities. They are quoted in annual percentages. The third panel corresponds to differences in prices. They are quoted in basis points ($1/100^{th}$ of a percentage point). Standard errors are obtained by bootstrapping the monthly excess returns under the assumptions that they are i.i.d. Portfolio 1 contains currencies with the lowest interest rates. Portfolio 4 contains currencies with the highest interest rates. The horizon of the excess returns and the option maturity are one month. Data are monthly, from JP Morgan. The sample period is 1/1996 - 8/2008.

Table 16: Disaster Risk Premia - All Countries

	Panel I: Carry Excess Returns			
	Unhedged Carry	Hedged at 10δ	Hedged at 25δ	Hedged ATM
Mean	14.94	12.95	10.28	5.74
	[2.85]	[2.64]	[2.31]	[1.54]
Mean Spread		1.99	4.66	9.20
		[0.50]	[0.96]	[1.70]
	Panel II: Estimations			
	10δ	25δ	ATM	10δ, 25δ, ATM
$\overline{\pi}^D$	0.55	1.23	3.46	1.75
	[0.47]	[0.85]	[1.61]	[0.92]
$\overline{\pi}^G$	14.39	13.71	11.48	13.19
	[2.93]	[3.02]	[3.02]	[2.80]
$\overline{\pi}^D - \overline{\pi}^G$	-13.83	-12.48	-8.01	-11.44
	[3.08]	[3.35]	[3.94]	[3.11]

Notes: This first panel of this table reports average returns on hedged and unhedged currency carry trades and their standard errors. We use the currency portfolios presented in Table 14. Carry trades correspond to returns on the last minus returns on the first portfolio. We consider different hedges: 10-delta, 25-delta and at-the-money. We also report the average difference between unhedged and hedged carry trades. The second panel reports structural estimates. $\overline{\pi}^D$ denotes the part of the carry excess return linked to disaster risk. $\overline{\pi}^G$ corresponds to the Gaussian, non-disaster part of the same excess return. These estimates are obtained using hedged returns at 10-delta (first column), 25-delta (second column), at-the-money (third column) or 10-, 25-delta and at-the-money (fourth column). Standard errors are obtained by bootstrapping the monthly excess returns under the assumptions that they are i.i.d. Data are monthly, from JP Morgan. The sample period is 1/1996 - 8/2008.

Table 17: Disaster Risk Premia - All Countries - With Transaction Costs

Panel I: Carry Excess Returns				
	Unhedged Carry	Hedged at 10δ	Hedged at 25δ	Hedged ATM
Mean	12.79	11.09	8.02	3.34
	[2.90]	[2.71]	[2.29]	[1.58]
Mean Spread		1.70	4.77	9.44
		[0.52]	[1.00]	[1.81]
Panel II: Estimations				
	10δ	25δ	ATM	10δ, 25δ, ATM
$\overline{\pi}^D$	0.47	2.10	6.10	2.89
	[0.48]	[0.88]	[1.66]	[0.95]
$\overline{\pi}^G$	12.32	10.69	6.69	9.90
	[2.94]	[2.90]	[3.11]	[2.97]
$\overline{\pi}^D - \overline{\pi}^G$	-11.85	-8.59	-0.59	-7.01
	[3.03]	[3.27]	[4.04]	[3.31]

Notes: This first panel of this table reports average returns on hedged and unhedged currency carry trades and their standard errors. We use the currency portfolios presented in Table 14. Carry trades correspond to returns on the last minus returns on the first portfolio. We consider different hedges: 10-delta, 25-delta and at the money. We also report the average difference between unhedged and hedged carry trades. The second panel reports structural estimates. $\overline{\pi}^D$ denotes the part of the carry excess return linked to disaster risk. $\overline{\pi}^G$ corresponds to the Gaussian, non-disaster part of the same excess return. These estimates are obtained using hedged returns at 10-delta (first column), 25-delta (second column), at-the-money (third column) or 10-, 25-delta and at-the-money (fourth column). Standard errors are obtained by bootstrapping the monthly excess returns under the assumptions that they are i.i.d. Data are monthly, from JP Morgan. The sample period is 1/1996 - 8/2008. We assume annual transaction costs on unhedged returns of 0.25% and 2% on respectively advanced and emerging countries. We assume bid-ask spreads of 5% and 10% on implied volatilities (respectively for advanced or developing countries).

Table 18: Changes in Risk Reversals and Exchange Rates: Contemporaneous Specifications

Dependant Variable:	Exchange Rates							
	Panel I: Raw Variables				Panel II: Demeaned Variables			
Risk Reversals	-49.95				-41.02			
Strike: Forward +/- 10%	[9.47]***				[6.24]***			
Risk Reversals		-32.78				-26.22		
Strike: Forward +/- 5%		[2.21]***				[2.47]***		
Risk Reversals			-102.65				-41.02	
Strike: Delta 10			[7.03]***				[6.24]***	
Risk Reversals				-63.14				-30.69
Strike: Delta 25				[3.99]***				[3.95]***
Observations	1667	1759	1776	1776	1667	1759	1776	1776
R^2	0.08	0.21	0.23	0.23	0.04	0.05	0.04	0.05

Notes: This table documents contemporaneous relationships between changes in nominal exchange rates and changes in risk reversals. All specifications include currency-fixed effects. Panel I presents results based on raw variables. Panel II uses cross-sectionally demeaned variables to control for the specific role of the US Dollar. Changes in exchange rates correspond to monthly log changes. Changes in risk reversals correspond to first differences. risk reversals are normalized by spot rates. Standard errors obtained from bootstrap procedures using 1000 replications are presented below the point estimates. The symbols ***, ** and * indicate statistical significance at 1, 5 and 10 percent confidence levels. The sample comprises currencies from advanced countries. Data are monthly, from JP Morgan. The sample period is 01/1996 -08/2008.

Table 19: Risk Reversals and Exchange Rates: Contemporaneous Specifications - All Countries

Dependant Variable:	Exchange Rates							
	Panel I: Raw Variables				Panel II: Demeaned Variables			
Risk Reversals	-19.71				-19.07			
Strike: Forward +/-10%	[7.07]***				[7.35]***			
Risk Reversals		-18.23				-15.93		
Strike: Forward +/-5%		[2.76]***				[3.58]***		
Risk Reversals			-18.48				-10.28	
Strike: Delta 10			[34.78]				[33.21]	
Risk Reversals				-9.90				-6.84
Strike: Delta 25				[17.25]				[15.44]
Observations	1638	1741	1760	1760	1638	1741	1760	1760
R-squared	0.05	0.18	0.21	0.2	0.03	0.05	0.06	0.04

Notes: This table documents contemporaneous relationships between changes in nominal exchange rates and changes in risk reversals. All specifications include currency-fixed effects. Panel I presents results based on raw variables. Panel II uses cross-sectionally demeaned variables to control for the specific role of the US Dollar. Changes in exchange rates correspond to monthly log changes. Changes in risk reversals correspond to first differences. risk reversals are normalized by spot rates. Standard errors obtained from bootstrap procedures using 1000 replications are presented below the point estimates. The symbols ***, ** and * indicate statistical significance at 1, 5 and 10 percent confidence levels. The sample comprises currencies for the full sample of available countries. Data are monthly, from JP Morgan. The sample period is 01/1996 -08/2008.

Table 20: Risk Reversals, Exchange Rates and Currency Excess Returns: Predictive Specifications

Dependant Variable:	Panel I: Exchange Rates					Panel II: Currency Excess Returns				
Interest Rate Differential	-0.58	-0.61	-0.58	-0.72	-0.732	-1.58	-1.61	-1.73	-1.78	-1.74
	[0.616]	[0.626]	[0.36]	[0.41]	[0.4]*	[0.615]**	[0.37]***	[0.41]***	[0.40]***	[0.41]***
Risk Reversal		2.37					2.31			
Strike: Forward +/-10%		[6.15]					[5.86]			
Risk Reversal			-1.87					-1.82		
Strike: Forward +/-5%			[1.85]					[1.86]		
Risk Reversal				-5.4					-5.28	
Strike: Delta 10				[2.93]*					[2.89]*	
Risk Reversal					-7.1					-6.96
Strike: Delta 25					[4.45]					[4.79]
R^2	0.01	0.015	0.01	0.01	0.01	0.034	0.037	0.036	0.035	0.038
Observations	1776	1666	1738	1750	1750	1776	1738	1750	1750	1750

Notes: This table presents results of predictability tests. We regress monthly changes in nominal exchange rates (panel I) or monthly currency excess returns (panel II) on risk reversals and interest differentials. The interest differential is defined as the difference between the domestic and the foreign interest rate. The null hypothesis of UIP not being rejected is a coefficient of 1 for the interest rate differential in panel I and a coefficient of zero in panel II. All specifications include currency-fixed effects. Standard errors obtained from a bootstrap procedure using 1000 replications are presented below their respective point estimates. ***,**,* indicates statistical significance at 1, 5, 10 percent confidence levels. The sample comprises currencies from advanced countries. Data are monthly, from JP Morgan. The sample period is 01/1996 -08/2008.

Table 21: Risk Reversals, Exchange Rates and Currency Excess Returns: Predictive Specifications - All Countries

Dependant Variable:	Panel I: Exchange Rates					Panel II: Currency Excess Returns				
Interest Rate Differential	0.86	0.96	0.89	0.79	0.78	-0.13	-0.00	-0.09	-0.12	-0.09
	[0.32]***	[0.37]**	[0.34]***	[0.31]***	[0.36]**	[0.34]	[0.38]	[0.36]	[0.33]	[0.34]
Risk Reversal		2.99					3.96			
Strike: Forward +/-10%		[2.39]					[2.43]			
Risk Reversal			1.82					2.21		
Strike: Forward +/-5%			[1.18]					[1.24]*		
Risk Reversal				-2.42					0.29	
Strike: Delta 10				[5.95]					[5.57]	
Risk Reversal					-1.07					0.55
Strike: Delta 25					[3.72]					[3.4]
R-squared	0.0711	0.0788	0.075	0.0716	0.016	0.025	0.021	0.0167	0.0163	0.0167
Observations	3580	3129	3427	3576	3576	3580	3129	3427	3576	3576

Notes: This table presents results of predictability tests. We regress monthly changes in nominal exchange rates (panel I) or monthly currency excess returns (panel II) on risk reversals and interest differentials. The interest differential is defined as the difference between the domestic and the foreign interest rate. The null hypothesis of UIP not being rejected is a coefficient of 1 for the interest rate differential in panel I and a coefficient of zero in panel II. All specifications include currency-fixed effects. Standard errors obtained from a bootstrap procedure using 1000 replications are presented below their respective point estimates. ***,**,* indicates statistical significance at 1, 5, 10 percent confidence levels. The sample comprises currencies from advanced and emerging countries. Data are monthly, from JP Morgan. The sample period is 01/1996 -08/2008.

Table 22: Risk Reversals and Exchange Rate Changes: Currency by Currency Predictive Specifications

Country Code	CAN	CAN	CHE	CHE	EUR	EUR	GBR	GBR	JPN	JPN	AUS	AUS	SWE	SWE
Interest Rate Differential	-2.23	-2.23	-4.1	-3.96	-4.13	-3.96	-0.91	-0.74	-1.37	-1.28	-4.26	-4.48	-3.49	-3.18
	[1.66]	[1.64]	[1.80]**	[1.86]**	[1.68]**	[1.72]**	[1.84]	[1.82]	[1.64]	[1.65]	[1.66]**	[1.69]***	[1.37]**	[1.38]**
Risk Reversal		0.3		-4.93		-8.1		-9.8		6.44		14.03		-22.29
Strike: Delta 10		[16.89]		[18.34]		[18.84]		[15.84]		[9.72]		[24.88]		[20.57]
Observations	150	150	150	150	115	115	150	150	150	150	150	150	150	150
R-squared	0.01	0.01	0.03	0.03	0.05	0.05	0	0	0	0.01	0.04	0.05	0.04	0.05
Country Code	NOR	NOR	NZL	NZL	ISR	ISR	POL	POL	SGP	SGP	CZE	CZE	KOR	KOR
Interest Rate Differential	-2.03	-2.22	-2.5	-2.49	0.47	1.21	0.59	1.23	-0.6	-0.6	0.37	0.11	1.7	1.92
	[1.12]*	[1.13]*	[1.54]	[1.55]	[1.14]	[1.51]	[0.72]	[1.07]	[1.92]	[1.92]	[0.39]	[0.38]	[0.62]***	[0.51]***
Risk Reversals		9.65		3.11		13.28		17.23		4.14		-12.61		14.98
Strike: Delta 10		[19.17]		[22.22]		[18.99]		[17.32]		[13.44]		[8.30]		[18.16]
Observations	150	150	150	150	78	78	99	99	150	150	134	134	136	134
R-squared	0.02	0.02	0.02	0.02	0	0.01	0.01	0.01	0	0	0	0.02	0.12	0.14

Notes: This table presents results of predictability tests. We regress monthly changes in nominal exchange rates on risk reversals and interest differentials. The interest differential is defined as the difference between the domestic and the foreign interest rate. The null hypothesis of UIP not being rejected is a coefficient of 1 for the interest rate differential. Standard errors obtained from a bootstrap procedure using 1000 replications are presented below the point estimates. The symbols ***, **, * indicate statistical significance at 1, 5, and 10 percent confidence levels. We focus on advanced countries. We exclude observations that do not correspond to a floating exchange rate regime according to IMF De Facto classification. Data are monthly, from JP Morgan. The sample period is 01/1996 -08/2008.