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LIQUIDITY, RISK APPETITE AND EXCHANGE RATE MOVEMENTS DURING THE FINANCIAL CRISIS OF 2007-2009

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Abstract

Given the deleveraging process in the banking sector, banks were reluctant to lend funds in the interbank market because of uncertainty about their own future need for funds during the financial crisis of 2007 - 2009. Aggregate liquidity then declined. This paper investigates the impact of the market-wide liquidity risk and carry-trade incentives on exchange rate movements. The results suggest that liquidity risk measured by the spread between LIBOR and the overnight index swap rate was a significant factor affecting the exchange-rate movements of the euro, British pound and Swiss franc, while carry trades were important for the Japanese yen, Australian dollar and New Zealand dollar.

JEL classification: F31; F32; F33
Key words: Sub-prime crisis; carry trades; liquidity; leverage

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EXECUTIVE SUMMARY

- *During the crisis started in August 2007, the US dollar has seen some remarkable swings against major currencies. At the same time, banks reportedly faced severe liquidity problems. US-dollar funding shortages put intense pressure on the balance sheet capacity of the banking sector due to financial sector deleveraging. Banks were reluctant to lend funds in the interbank market because of uncertainty about their own future need for funds. Aggregate liquidity then declined.*

- *This paper investigates the impact of the market-wide liquidity risk and carry-trade incentives on exchange-rate movements. The estimation results suggest that the liquidity risk measured by the LIBOR-OIS spread was a significant factor affecting the exchange-rate movements of the euro, British pound and Swiss franc against the US dollar, while carry trades were important for the Japanese yen, Australian dollar and New Zealand dollar. The economic significance of the market-wide liquidity problem and carry trades surged after the Lehman default. This reflects that the exchange rates were more sensitive to the liquidity problem and risk appetite when the crisis deepened.*

- *The results show that the market-wide liquidity problem in the US dollar due to the financial-sector deleveraging associated with the increase in the US-dollar LIBOR-OIS spread put pressure on the US dollar to depreciate. Conversely, the liquidity problem in other currencies tended to be linked with an appreciation of the US dollar. This finding is consistent with the theory that contraction of US intermediary balance sheets will be associated with a drop in risk appetite. This drives up the market price of risk on risky assets in foreign currencies that increase their expected returns, implying a future appreciation of risky currencies (i.e. a dollar depreciation against such risky currencies).*

I. INTRODUCTION

The sub-prime crisis emerged in the United States in mid-2007 and spilled over to Europe and other economies. From mid-2007 to mid-2008, the spillovers were relatively modest. The situation began to change in mid-2008. Then, following the bankruptcy of Lehman Brothers in mid-September 2008, developments took a dramatic turn leading to a global financial crisis. During the crisis, the US dollar has seen some remarkable swings against major currencies. For example, from September 2007 to March 2008, it depreciated about 16% against the euro and yen, while between March and September 2008, it gained sharply (22%) against the euro. On the other hand, the dollar depreciated against the yen about 21% from August to December 2008, in particular after the Lehman's default (see Figure 2 below). During this crisis, banks reportedly faced severe liquidity problems. US dollar funding shortages put intense pressure on the balance sheet capacity of the banking sector due to financial-sector deleveraging. In response central banks around the world took unprecedented policy measures to supply funds to the banks (see McGuire and von Peter, 2009).

The purpose of this paper is to investigate any link between the market-wide liquidity risk caused by the deleveraging process and exchange-rate movements during the crisis. Adrian and Shin (2008) document that aggregate liquidity can be understood as the rate of growth of the aggregate financial-sector balance sheet. When asset prices increase, financial intermediaries' balance sheets generally become stronger, and, without adjusting asset holdings, their leverage declines. The financial intermediaries then hold surplus capital which they use to expand their balance sheets. On the liability side, they take on more short-term debt. On the asset side, they search for potential borrowers. Aggregate liquidity is intimately tied to how hard the financial intermediaries search for borrowers, including through the interbank market. Conversely, when asset prices decline during a financial crisis, the financial intermediaries' balance sheets contract and are thus reluctant to lend. Aggregate liquidity then declines.

Spreads of interbank interest rate over overnight index swap (OIS) in the US as well as Europe, the UK and Japan widened substantially in August 2007, and then persisted at high levels during the financial crisis in 2007 - 2009.[1] The rise in spreads could represent heightened perceived default risk or greater compensation demanded by risk-averse investors against the risk of default. Alternatively, it could represent a risk premium demanded by investors to induce them to hold comparatively illiquid assets. Schwarz (2009) constructs new microstructure measures of credit and market liquidity and find that liquidity effects explain more than two-thirds of the widening of one- and three-month euro LIBOR-OIS spreads. Taylor and Williams (2009) find that while counterparty risk is a key factor in the movements in the term-lending spreads including

1 The structure of OISs is discussed in the following section.

LIBOR-OIS spreads, they do not rule out that liquidity has been reduced by the increase in counterparty risk since the crisis began. The argument is that banks are reluctant to lend funds in the interbank market because of uncertainty about their own future need for funds, perhaps because of concerns about risk in their own balance sheet.

According to the theory in Adrian and Shin (2008), when the asset prices declined during the crisis, banks were reluctant to lend in the interbank market. This in turn would reduce market liquidity and require a higher risk premium (i.e. higher aggregate price of risk) for lending with longer maturity (which is more illiquid). Their reluctance to lend to each other in money markets at longer maturity should also contribute to the rise in spreads between the term and overnight interbank lending. The LIBOR-OIS spread is therefore an appropriate measure of the market-wide liquidity risk. Figure 1 shows the negative relationship between the leverage of US banks and the spread of three-month US dollar LIBOR over OIS during 2007 - 2008.

The abrupt escalation of the crisis during 2008 marked an important turning point for the exchange rates of many currencies. Traders, bankers, and economists often attribute these exchange rate movements to a decline in risk appetite (i.e. an increase in market-wide risk premium of holding risky assets), in particular due to the unwinding of carry trades (i.e. decline in "carry-trade incentives"). As the market-wide liquidity problem due to US-dollar funding shortages also occurred during this period, the risk spreads of interbank interest rate over OIS should also explain these exchange-rate movements, if the theory in Adrian and Shin (2008) is correct. Against this background, this paper investigates the contribution of the market-wide liquidity risk on the one hand, and "carry-trade incentives" on the other, to the value of the US dollar against several currencies during the crisis.

A related paper by Hattori and Shin (2009) studies the conjunction of deteriorating credit conditions in the US and the weakness of the dollar against the yen in the early stages of the credit crisis of 2007 - 2008. They argue that the carry trade should be viewed in the broader context of global credit conditions. Both can be thus seen as consequences of financial sector deleveraging in the US. However, our paper makes a distinction between exchange-rate movements that are caused by market-wide liquidity risk (itself a consequence of the deleveraging process) and those that were due to carry trades. We view the latter as being the result of changes in risk appetite of participants in the foreign exchange market. We include the exchange rate movements of the euro, British pound, Swiss Franc, Japanese yen, Australian dollar and New Zealand dollar against the US dollar in the study.

The remainder of this paper is organised as follows. The next section describes the measures of market-wide liquidity risk and carry-trade incentives. Section III discusses the data used and the model specification. Section IV presents the estimation results and discusses the related issues. Section V concludes.

II. LIBOR-OIS SPREADS AND CARRY-TRADE INCENTIVES

An OIS is an interest rate swap in which the floating leg is linked to an index of daily overnight rates. The two parties agree to exchange at maturity, on an agreed notional amount, the difference between interest rate accrued at the agreed fixed rate and interest accrued at the floating index rate over the life of the swap. The fixed rate is a proxy for expected future overnight interest rates. As overnight interest rates generally bear lower credit and liquidity risks, the credit risk and liquidity risk premiums contained in the OIS rates should be small. Therefore, the spread of the three-month interbank rate (LIBOR) relative to three-month overnight index swap rate generally reflects the credit and liquidity risks of the interbank market. Since the emergence of the crisis in August 2007, risk premiums in short-term money market rates, as represented by the spreads between LIBOR and OIS rates, increased significantly in most major currencies (see Figure 2).

The LIBOR-OIS spreads indirectly measure the availability of funds in the interbank market. It is generally viewed as reflecting two types of risk. The first is related to liquidity. The spread reflects the different interbank funding costs (the liquidity premiums paid by banks) of term (say three-month) lending and overnight lending rolled over for three months. A second component of the spreads stems from counterparty default risk. Schwarz (2009) finds that both credit and liquidity effects are important in explaining the widening of LIBOR-OIS spreads, but that market liquidity explains a greater share. This finding is consistent with that in McAndrews et al. (2008) who find that there is a substantial and time-varying liquidity component in LIBOR-OIS spreads. Michaud and Upper (2008) also find a significant role for liquidity in explaining money market spreads. While Taylor and Williams (2009) find a much smaller role for liquidity in LIBOR-OIS spreads, they argue that the LIBOR can be pushed up as the lender demands compensation for taking on default risk, due to poor market liquidity, or because of other factors, especially at times of market stress. In view of these findings, the LIBOR-OIS spreads of an economy's currency should be an appropriate measure and broad representation of market-wide liquidity risk in its financial system which is a main source of funding of its currency.

In the currency carry trade, an investor borrows in a low-yielding currency and invests in a high-yielding currency. Empirically, it is observed that carry trades do well when currency volatility is low.[2] To realise the carry in a carry trade, investors are

[2] Empirical studies of carry trades are examined by Brunnermeier et at. (2008), Gagnon and Chaboud (2008) and Burnside et al. (2007).

required to hold the position for some time. If the foreign rate is r_{FC} and the domestic rate is *r*, then the return to the carry trade is proportional to $(r_{FC} - r)T$, where *T* is the holding period. The risk to the carry trade is an adverse price movement in the level of the exchange rate. Bhansali (2007) argues that carry trades are essentially short volatility and documents that option based carry trades yield excess returns. The carry per unit of volatility, also know as the carry-to-risk ratio, $\left[(r_{FC} - r)/\sigma_{imp}\right]$, where σ_{imp} is the option-implied volatility, determines the relative attractiveness of entering into the carry trade. When this ratio is large in absolute terms (i.e. the difference between r_{fc} and *r* is large or σ_{imp} is small), the carry trade is attractive (true option cost is low). Otherwise, the carry trade is unattractive (true option cost is high). This ratio is used as a measure of "carry-trade incentives" to estimate the link between carry trades and the swings in exchange rates during the crisis.

Currency options are often used to implement strategies on the future direction of foreign exchange rate movements. Risk reversal is a directional option strategy that is the implied volatility of an out-of-the money call option minus the implied volatility an equally out-of-the-money put. If the risk-neutral distribution of the exchange rate is negatively (positively) skewed, the price of the risk-reversal is negative (positive). Hence, the risk reversal measures the combined effects of expected skewness and a skewness risk premium. The expectation of potential appreciation (depreciation) of a currency against the US dollar generates negative (positive) skewness in the conditional distribution of currency returns when the currency price is quoted as units of foreign currency per US dollar.[3] Brunnermeier et al. (2008) find a close relationship between the physical skewness measure and the option-implied skewness. As the expectation of depreciation or appreciation of currencies may affect the exchange-rate movements, this paper uses the risk reversal as a control variable for the estimations.

III. DATA AND MODEL SPECIFICATION

We collect daily nominal exchange rates to the US dollar (USD) from 9 August 2007 to 31 March 2009 for six currencies: Australian dollar (AUD), British pound (GBP), euro (EUR), Japanese yen (JPY), New Zealand dollar (NZD) and Swiss franc (CHF).[4] We denote the nominal exchange rate as units of foreign currency per US dollar. The goal of the study is to identify whether the market-wide liquidity risk and the

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[3] Both options that form the risk reversal can be priced using the Garman and Kohlhagen (1983) formula, which is a modified Black-Scholes formula taking into account that both currencies pay a continuous yield given by their respective interest rates. Inputting the implied volatility and other parameters into the Garman and Kohlhagen (1983) formula gives the option price in dollar terms, but the options are quoted in terms of implied volatility.

[4] We follow Taylor and Williams (2009) and choose 9 August 2007 to mark the inception of the turmoil, when BNP Paribas frozen redemptions for three of its investment funds.

carry-trade incentives are important factors explaining exchange rate movements during the crisis. The liquidity risk is measured by the three-month LIBOR-OIS spread. The exchange rate and interest rate data are from Bloomberg.

The carry-to-risk ratio, defined as $\left[(r_{FC} - r_{USD}) / \sigma_{imp}\right]$, is used as a proxy for carry trade incentives, where r_{USD} is USD LIBOR, r_{FC} is the foreign currency LIBOR and σ_{imp} is the at-the-money foreign exchange option-implied volatility at the three-month tenor.[5] We use data on foreign-exchange options to measure the risk-neutral skewness (risk reversal). Specifically, we obtain data on quotes of 25-delta three-month risk reversals.[6] The option data are from JPMorgan Chase. Descriptive statistics of these variables are reported in Table 1.

To identify the roles of the market-wide liquidity and carry-trade incentives for exchange rate movement during the financial crisis, we estimate the following multiple regression:[7]

$$R_t = \alpha + \beta_1 R_{t-1} + \beta_2 \Delta rr_t + \beta_3 \Delta ctr_t + \beta_4 \Delta LSS_t^{USD} + \beta_5 \Delta LSS_t^{FC} + \varepsilon_t \qquad (1)$$

with the variance equation specified as:

$$\varepsilon_t \sim N\left(0, \sigma_t^2\right)$$

$$\ln\left(\sigma_t^2\right) = \alpha + \beta \ln\left(\sigma_{t-1}^2\right) + \gamma \frac{\varepsilon_{t-1}}{\sigma_{t-1}} + \eta\left(\left|\frac{\varepsilon_{t-1}}{\sigma_{t-1}}\right| - \sqrt{2/\pi}\right), \qquad (2)$$

where R_t is the daily log-return of the foreign exchange rate (as unit of foreign currency per US dollar), rr_t is the risk-reversal prices, ctr_t is the carry-to-risk ratio, LSS_t^{USD} and LSS_t^{FC} are the LIBOR-OIS spreads for USD and the foreign currency (FC) respectively. The first lag of the daily return of the exchange rate is included in the estimation to remove the serial correlation of the residuals, and the EGARCH(1,1) model proposed by Nelson (1991) is employed to capture the clustering and asymmetry in volatility, which are typical characteristics of financial time series during a turmoil period. The model is then

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[5] As in Brunnermeier et at. (2008), the carry-to-risk ratio here does not correspond to the typical carry-trade position (say AUD-JPY pair) taken by market participants. However, this definition allows a more systematic discussion in the context of multi-currency analysis.

[6] Taking the derivative of the option price with respect to the spot exchange rate gives the option delta. An at-the-money call with exercise price at the current forward exchange rate has a call delta of about a half, that is, the option price reaction is only half of the change in the underlying exchange rate. The 25-delta refers to how far out of the money the options are, namely the strike of the call is at a call delta of 0.25, and the strike of the put is at a call delta of 0.75.

[7] The Augmented Dickey-Fuller test suggests that most of the variables are non-stationary in level but stationary in their first-differences form.

estimated by maximum likelihood estimation.

As a positive value of risk reversal (i.e. positive skewness) indicates an expected depreciation of the foreign currency, the expected sign for β_2 is therefore positive. Regarding the carry-to-risk ratio, when $(r_{FC} - r_{USD}) < 0$ so that the US dollar is the investment currency, the increase in ctr_t implies a decline of carry-trade incentives which leads to the depreciation of the US dollar. When $(r_{FC} - r_{USD}) > 0$ so that the US dollar is the funding currency, the increase in ctr_t implies an increase in carry-trade incentives. This also leads to the depreciation of the US dollar. Therefore, the effect of the carry-to-risk ratio is negative to the currency return R_t, i.e. β_3 is negative.[8]

Adrian et al. (2009) propose that growth of intermediary balance sheets will be associated with innovations in risk appetite. When balance sheets expand, there is an increase in risk appetite and risky asset prices are driven up. This drives down the market price of risk on risky assets in foreign currencies that decrease their expected returns, implying a future depreciation of such risky currencies (i.e. a dollar appreciation against such risky currencies). If this theory is correct, one would expect to see the reduced appetite for risk to be associated with deleveraging of US financial intermediary balance sheets in the crisis during 2007 - 2009 followed by subsequent dollar depreciations. In this context and assuming financial intermediaries in an economy are the main source of funding of its currency, an increase in the USD LIBOR-OIS spread reflects the reduced risk appetite of financial intermediaries in the US, which implies a future appreciation of the foreign currency because of the increased equilibrium risk premium on foreign assets. Therefore, the impact of the change in USD LIBOR-OIS spread (LSS_t^{USD}) is negative on the currency return (i.e. depreciation of USD and β_4 is negative), while that of the change in FC LIBOR-OIS spread (LSS_t^{FC}) is expected to be positive (i.e. appreciation of USD and β_5 is positive).

IV. Estimation Results

The estimation results are reported in Tables 2a-f. Due to the increasing volatility and the wide-range of unprecedented policy measures after the default of the Lehman Brothers, we split the sample period into sub-periods with the first period from 9 August 2007 to 12 September 2008 (upper panel) and the second period from 15 September 2008 to 31 March 2009 (lower panel). The estimated coefficients (in bold)

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8 Against the US dollar, the investment currency (e.g., AUD and NZD) which has a relatively high nominal interest rate has a positive carry-to-risk ratio, while the currency (e.g. JPY and CHF) with a low nominal interest rate exhibits a negative ratio.

for the mean equation and the corresponding p-values are reported underneath.[9] To identify the relative importance of the market-wide liquidity measures (the LIBOR-OIS spreads) and the carry-trade incentives (the carry-to-risk ratio), we explore different restricted specifications of Equation (1).[10] Using the log-likelihoods of these alternative specifications, we can identify whether the inclusion of new variables significantly improves the explanatory power of the model based upon the log-likelihood ratio (LR) test.[11] In particular, the LR-test statistics for the restricted specification which excludes the liquidity measures (i.e. impose $\beta_3 = \beta_4 = 0$) over the unrestricted specification in Equation (1) are reported.

Among the six currencies, the estimated coefficients for the risk reversal are all significant with the expected positive sign, indicating market expectation is an important determinant of exchange rate movements. This also verifies its role as an appropriate control variable. The carry-to-risk ratio shows the expected impact on the exchange-rate movements and is statistically significant under most circumstances. As expected, the carry-trade incentive is an important factor related to the exchange rate movements of JPY, AUD and NZD, which are commonly regarded as major carry-trade currency pairs.[12] However, the carry-trade incentive is not significant for EUR in the second part of the sample.

Tables 2a - c show that the effect of the market-wide liquidity risk measured by the LIBOR-OIS spreads on the three major European currencies (EUR, GBP and CHF) is significant (except the CHF LIBOR-OIS spread in the period before the Lehman default). The estimated coefficients for the USD LIBOR-OIS spread are negative, while the coefficients for the FC LIBOR-OIS spreads are positive. The result is consistent with the expected signs based on the theory proposed by Adrian et al. (2009) in the previous section. For the first period, the inclusion of market-wide liquidity

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[9] The estimations results for the variance equations are available upon request. As reported in Table 2, the Ljung-Box Q statistics for the autocorrelation of the standardized and squared standardised residuals are found to be insignificant, suggesting that the residuals of the estimation are adequately fitted and potential bias in the standard errors are removed.

[10] These alternative specifications also allow us to detect the potential multi-collinearity of the explanatory variables.

[11] The LR test makes a decision between two hypotheses (H_0 versus H_1) based on the likelihood ratios of the maximum probabilities under these two hypotheses. The LR-test statistic is denoted by: $LR = -2\,[\log(L_R) - \log(L_U)]$, where L_R and L_U are the likelihood for the restricted and unrestricted specification. The LR statistic has an asymptotic chi-square distribution with degrees of freedom equal to the number of restrictions (the number of added variables). The 5% confidence interval for the chi-square distribution with degree of freedom 1 and 2 are 3.84 and 5.99 respectively.

[12] Brunnermeier et al. (2008) argue that the risk reversals may contain information about carry-trade activities as out-of-the-money currency options are often used to hedge the downside risk of the carry trades. However, it is difficult to separate the contributions of pure market expectation from the effect of carry-trade activity on traditional carry-trade currencies such as JPY, AUD and NZD. For these currencies, the estimation results suggest potential collinearity between the risk reversal and carry-to-risk ratio. As a robustness check, we have dropped out risk reversal to study the direct impact of the carry trade incentives. The results suggest that the carry-trade factor alone explains roughly 15% to 20% of the currency returns. The estimation results are reported in Table 4a.

measures provides additional explanatory power of 2.0% for EUR, 4.7% for GBP and 5.4% for CHF. After the Lehman default, the additional explanatory power for EUR and CHF has reduced slightly to 0.5% and 4.6% respectively, while that for GBP increased marginally to 5.2. The reduced impact is possibly due to the unprecedented policy measures introduced by central banks around the world to provide funding and enhance market liquidity. Nevertheless, the LR test suggests that the LIBOR-OIS spreads are statistically significant factors to explain the daily returns of the three currencies, both before and after the Lehman default.

For JPY, AUD and NZD, the LIBOR-OIS spreads show mixed impacts on the exchange rate movements in Tables 2d-f. The effect of the LIBOR-OIS spreads on the exchange-rate movements of AUD and NZD is in general insignificant. After the Lehman default, the impact of the liquidity became relatively more significant for AUD. However, the effect is marginal in comparison with the carry-trade factor and the LR tests suggest that these liquidity variables do not parsimoniously improve the explanatory power. For JPY, the major determinant of the exchange-rate movement is the carry-trade factor. Before the Lehman default, while the LR test suggests that the LIBOR-OIS spreads has statistically significant contribution, the increase in the explanatory power is only marginal (increased by 2.4% from 44.1% to 46.5%). After that, the contribution of the market-wide liquidity virtually disappeared as the unwinding of carry trades dominated the foreign exchange movements.

The estimation results suggest that the market-wide liquidity risk has a significant impact on the exchange-rate movements of EUR, GBP and CHF during the financial crisis. To better understand the relative economic importance of the LIBOR-OIS spreads and the carry-trade incentives, we use the estimated coefficients in Table 2 (the unrestricted specification (i)) to measure the exchange-rate movement in response to a one standard-deviation change in the LIBOR-OIS spreads and the carry-to-risk ratio respectively.[13] As shown in Table 3, the economic significance of the USD LIBOR-OIS spread is slightly higher than the carry-trade incentives for EUR and CHF, while the impact of the FC LIBOR-OIS spread is the smallest among the three for the three currencies. During this crisis period, banks reportedly faced severe liquidity problems in particular the US-dollar funding shortages due to financial-sector deleveraging. This explains why the USD LIBOR-OIS spread has a larger impact on the swings of the exchange rates. It is noted that the economic significance of all the three variables rose sharply after the Lehman default, suggesting that the exchange rates were more sensitive to the liquidity problem and risk appetite when the crisis deepened.

As a robustness check, we use different proxies for the interbank rates,

[13] It should be noted that this exercise has not taken into account the interaction between the explanatory variables. Therefore, it only provides indicative information about the true economic significance of these variables.

including the TIBOR for JPY and the bank-bill rates for AUD and NZD. The onshore nature of these interbank rates suggests that these variables may contain more relevant information on the country-specific liquidity conditions.[14] The estimation results in Table 4b show that the onshore interbank-rate proxies are better able to explain the exchange-rate movements as reflected by the improvement in the significance of estimated coefficients and explanatory powers (by 3.2% for AUD and 1.2% for JPY for the first period). Nevertheless, the overall results are qualitatively the same as those reported in Tables 2d-f. Estimations based on data at the one-month and six-month tenors for LIBOR-OIS spreads, carry-to-risk ratios and risk reversals are conducted for the robustness tests. The results are similar to those based on the data at the 3-month tenor.[15]

V. CONCLUSION

Given the deleveraging process in the banking sector, banks were reluctant to lend funds in the interbank market because of uncertainty about their own future need for funds during the financial crisis of 2007 - 2009. The aggregate liquidity then declined. This paper investigates the impact of the market-wide liquidity risk and carry-trade incentives on exchange-rate movements. The estimation results suggest that the liquidity risk measured by the LIBOR-OIS spread was a significant factor affecting the exchange-rate movements of the euro, British pound and Swiss franc, while carry trades were important for the Japanese yen, Australian dollar and New Zealand dollar. The economic significance of the market-wide liquidity and carry trades surged after the Lehman default. This reflects that the exchange rates were more sensitive to the liquidity problem and risk appetite when the crisis deepened.

The results show that the market-wide liquidity problem in the US dollar due to the financial-sector deleveraging associated with the increase in the US-dollar LIBOR-OIS spread put pressure on the US dollar to depreciate. Conversely, the liquidity problem in other currencies will push the US dollar up against those currencies. This finding is consistent with the theory proposed in Adrian et al. (2009) that contraction of the US intermediary balance sheets will be associated with a drop in risk appetite. This drives up the equilibrium risk premium on risky assets in foreign currencies, implying a future appreciation of risky currencies (i.e. a dollar depreciation against such risky currencies).

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[14] TIBOR is the Tokyo Interbank Offered Rate set at 11:00 am Tokyo time. The bank bill-rates for AUD and NZD are the interest rate swap reference rates.

[15] The results are available upon request.

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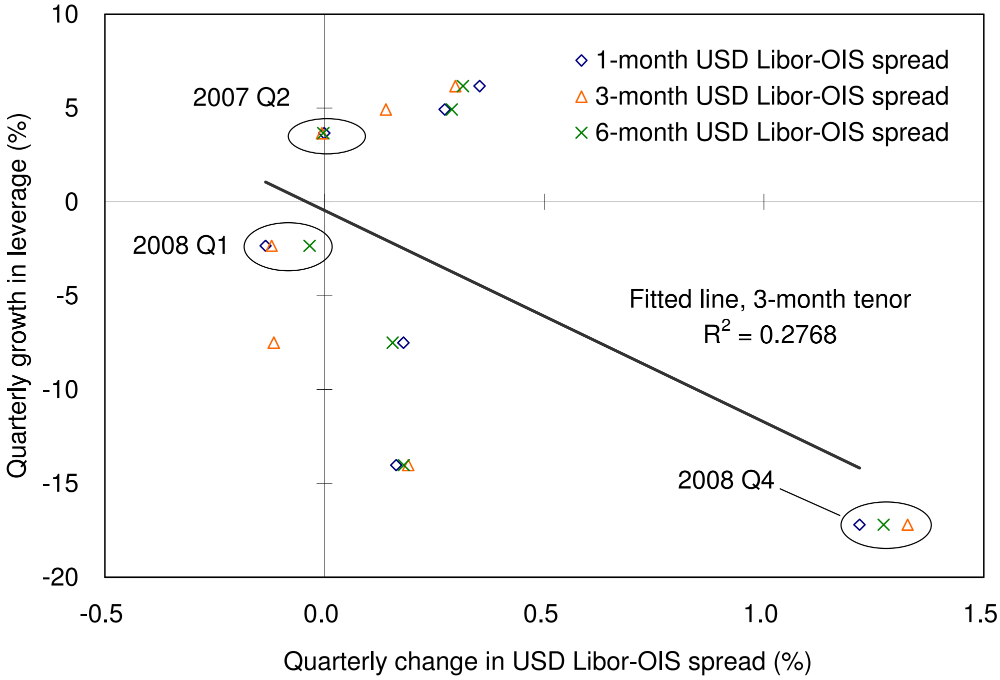
Figure 1: Relationship between the leverage of US banks and US dollar LIBOR-OIS spread during 2007 Q2 - 2008 Q4



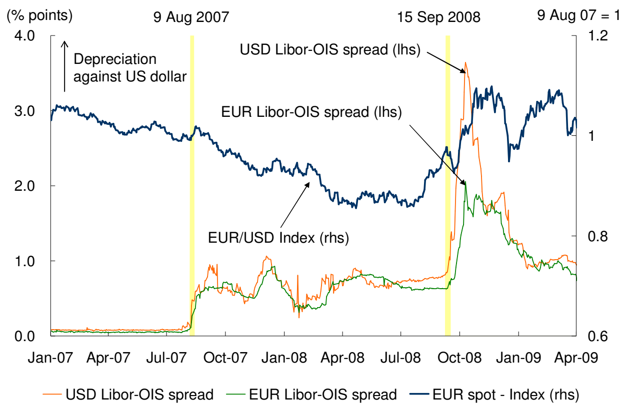
Notes:

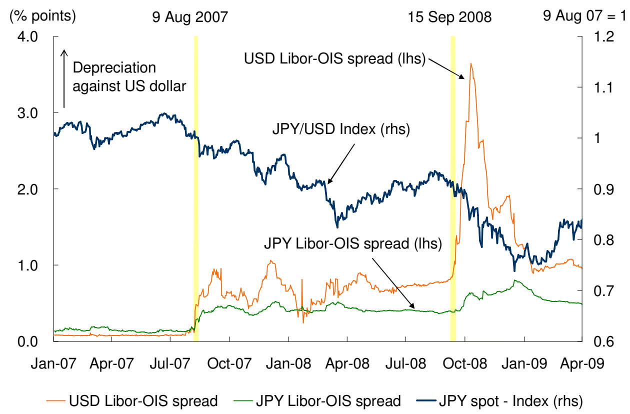
1. The leverage is measured as the average asset-to-equity (book value) ratio of the following institutions: Goldman Sachs, Morgan Stanley, Citigroup, Merrill Lynch, Bear Sterns (until 2008 Q1) and Lehman Brothers (until 2008 Q2). The sample of institutions is the same as in Adrian and Shin (2008). The data are from Bloomberg.

2. The LIBOR-OIS spread in the chart is the quarterly average figure.

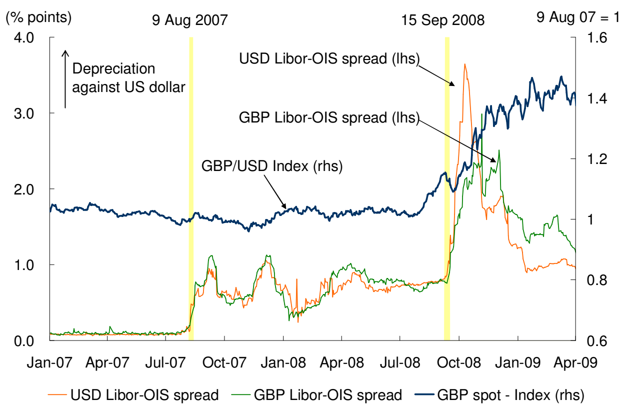
Figure 2: LIBOR-OIS spreads and exchange rate (foreign currency/USD) index

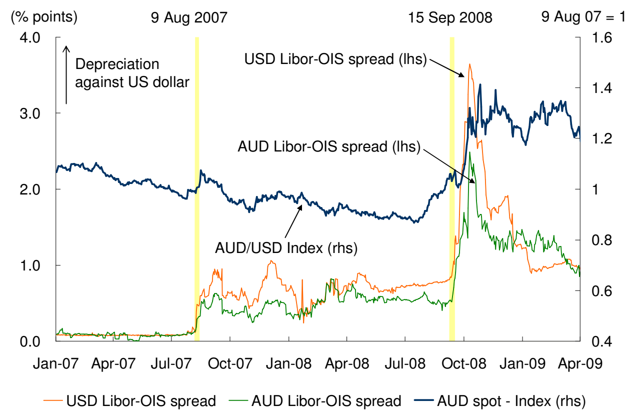
EUR	JPY



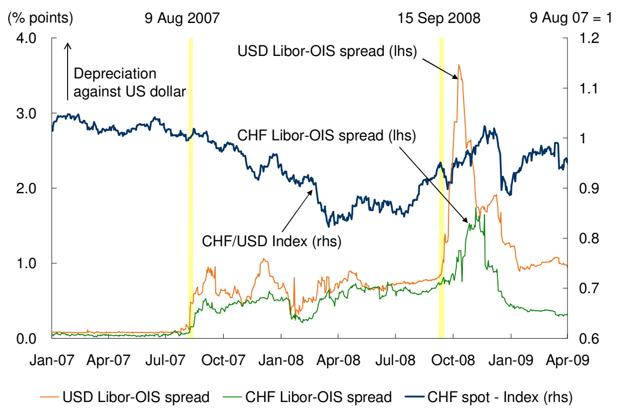


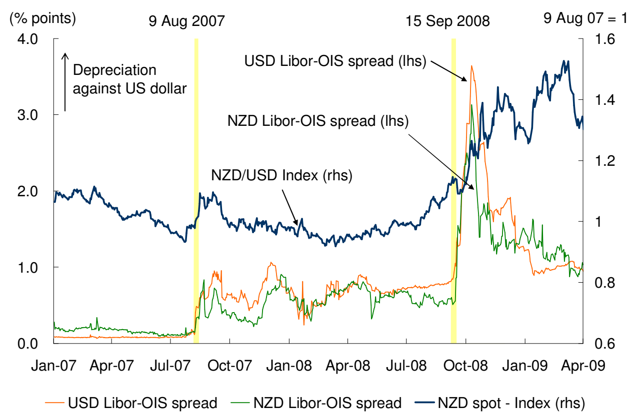
GBP	AUD





CHF	NZD





Note: The exchange rate (foreign currency/USD) index is the normalised exchange rate based on the spot rate on 9 August 2007.

Table 1: Selected summary statistics of variables in Equation (1)

	Before the Lehman default		After the Lehman default	
	Mean (level)	Standard deviation (daily change)	Mean (level)	Standard deviation (daily change)
EUR				
Exchange rate	0.67	0.574	0.76	1.229
Risk reversal	0.36	0.083	0.49	0.206
Carry-to-risk ratio	0.09	0.007	0.06	0.006
FC LIBOR-OIS spread	0.63	0.026	1.23	0.067
GBP				
Exchange rate	0.50	0.552	0.66	1.370
Risk reversal	0.80	0.068	2.32	0.226
Carry-to-risk ratio	0.26	0.009	0.08	0.008
FC LIBOR-OIS spread	0.71	0.041	1.70	0.125
CHF				
Exchange rate	1.09	0.688	1.15	1.176
Risk reversal	-0.62	0.089	-0.89	0.191
Carry-to-risk ratio	-0.12	0.008	-0.05	0.007
FC LIBOR-OIS spread	0.52	0.030	0.72	0.090
JPY				
Exchange rate	108.77	0.746	95.95	1.380
Risk reversal	-3.45	0.278	-6.37	0.365
Carry-to-risk ratio	-0.27	0.018	-0.07	0.011
FC LIBOR-OIS spread	0.42	0.013	0.59	0.016
AUD				
Exchange rate	1.11	0.879	1.47	2.415
Risk reversal	1.38	0.189	4.19	0.416
Carry-to-risk ratio	0.31	0.010	0.13	0.010
FC LIBOR-OIS spread	0.50	0.040	1.33	0.101
NZD				
Exchange rate	1.32	0.937	1.78	1.920
Risk reversal	1.80	0.193	4.25	0.413
Carry-to-risk ratio	0.37	0.012	0.17	0.011
FC LIBOR-OIS spread	0.67	0.053	1.49	0.137
USD				
USD LIBOR-OIS spread	0.69	0.065	1.57	0.103

Note: The daily change of exchange rate is computed as log-return, while first-differencing is used for other variables.

Table 2a: Estimation result for EUR

I. Sample period: 9 August 2007 to 12 September 2008

	(i)	(ii)	(iii)	(iv)	(v)
Constant	**-0.009**	**-0.010**	**-0.017**	**-0.016**	**-0.030**
	0.76	0.74	0.59	0.60	0.33
Log return in spot (lag)	**-0.15****	**-0.16****	**-0.16****	**-0.16****	**-0.16****
	0.02	0.01	0.02	0.02	0.02
Risk reversal	**3.49****	**3.60****	**3.39****	**3.44****	**3.47****
	0.00	0.00	0.00	0.00	0.00
Carry-to-risk ratio	**-15.69****	**-13.06****	**-8.60***	**-7.91***	
	0.00	0.01	0.08	0.10	
FC LIBOR-OIS spread	**2.27***		**1.04**		
	0.10		0.41		
USD LIBOR-OIS spread	**-1.86****	**-1.55****			
	0.00	0.00			
Adjusted R-squared	21.2%	20.4%	19.1%	19.2%	18.9%
F-statistic	9.03	9.61	8.92	10.11	11.48
Log likelihood	-192.98	-194.67	-198.48	-198.83	-200.00
LR test	11.69**				
Ljung-Box test up to lag 8					
Std. residuals (p-value)	0.769	0.783	0.714	0.740	0.605
Sq. std. residuals (p-value)	0.841	0.879	0.816	0.848	0.819

II. Sample period: 15 September 2008 to 31 March 2009

	(i)	(ii)	(iii)	(iv)	(v)
Constant	**0.035**	**0.047**	**0.082**	**0.082**	**0.090**
	0.68	0.59	0.34	0.35	0.28
Log return in spot (lag)	**-0.21****	**-0.24****	**-0.23****	**-0.23****	**-0.23****
	0.00	0.00	0.00	0.00	0.00
Risk reversal	**3.54****	**3.75****	**3.82****	**3.92****	**3.97****
	0.00	0.00	0.00	0.00	0.00
Carry-to-risk ratio	**-27.57**	**-31.73**	**2.76**	**-4.40**	
	0.16	0.11	0.88	0.79	
FC LIBOR-OIS spread	**2.38****		**1.73**		
	0.04		0.15		
USD LIBOR-OIS spread	**-2.70****	**-2.09***			
	0.02	0.05			
Adjusted R-squared	34.4%	34.0%	33.7%	33.9%	34.4%
F-statistic	8.75	9.57	9.45	10.74	12.61
Log likelihood	-182.32	-183.50	-184.44	-185.01	-185.07
LR test	5.37*				
Ljung-Box test up to lag 8					
Std. residuals (p-value)	0.886	0.764	0.754	0.677	0.663
Sq. std. residuals (p-value)	0.271	0.249	0.823	0.776	0.785

Notes:

1. The p-value is computed from the t-statistics using the Bollerslev-Wooldrige robust standard errors.
2. * and ** indicate significant at 10% and 5% levels respectively.

Table 2b: Estimation result for GBP

I. Sample period: 9 August 2007 to 12 September 2008

	(i)	(ii)	(iii)	(iv)	(v)
Constant	**0.057****	**0.061****	**0.050***	**0.054***	**0.006**
	0.05	0.04	0.10	0.07	0.84
Log return in spot (lag)	**-0.15****	**-0.17****	**-0.14****	**-0.16****	**-0.13**
	0.01	0.00	0.02	0.01	0.01
Risk reversal	**2.62****	**2.90****	**2.59****	**2.79****	**2.74****
	0.00	0.00	0.00	0.00	0.00
Carry-to-risk ratio	**-22.55****	**-19.10****	**-17.38****	**-15.89****	
	0.00	0.00	0.00	0.00	
FC LIBOR-OIS spread	**2.18****		**1.18**		
	0.01		0.14		
USD LIBOR-OIS spread	**-2.11****	**-1.66****			
	0.00	0.00			
Adjusted R-squared	22.7%	21.2%	18.0%	18.0%	12.1%
F-statistic	9.79	10.07	8.36	9.42	7.15
Log likelihood	-181.12	-184.79	-189.49	-190.59	-196.53
LR test	18.95**				
Ljung-Box test up to lag 8					
Std. residuals (p-value)	0.597	0.749	0.453	0.599	0.873
Sq. std. residuals (p-value)	0.284	0.586	0.515	0.573	0.150

II. Sample period: 15 September 2008 to 31 March 2009

	(i)	(ii)	(iii)	(iv)	(v)
Constant	**0.016**	**0.120**	**0.127**	**0.142**	**0.185****
	0.86	0.19	0.18	0.14	0.05
Log return in spot (lag)	**-0.13****	**-0.14****	**-0.12**	**-0.13***	**-0.13***
	0.05	0.04	0.13	0.08	0.09
Risk reversal	**3.07****	**3.61****	**3.59****	**3.77****	**3.99****
	0.00	0.00	0.00	0.00	0.00
Carry-to-risk ratio	**-54.26****	**-40.16****	**-25.53****	**-21.43****	
	0.00	0.01	0.01	0.03	
FC LIBOR-OIS spread	**1.83****		**1.12****		
	0.00		0.01		
USD LIBOR-OIS spread	**-3.88****	**-2.94****			
	0.00	0.01			
Adjusted R-squared	37.1%	35.3%	32.4%	31.9%	31.4%
F-statistic	9.72	10.09	8.96	9.92	11.16
Log likelihood	-191.55	-197.87	-200.17	-201.27	-202.72
LR test	19.46**				
Ljung-Box test up to lag 8					
Std. residuals (p-value)	0.561	0.305	0.506	0.458	0.500
Sq. std. residuals (p-value)	0.562	0.184	0.425	0.544	0.613

Notes:
1. The p-value is computed from the t-statistics using the Bollerslev-Wooldrige robust standard errors.
2. * and ** indicate significant at 10% and 5% levels respectively.

Table 2c: Estimation result for CHF

I. Sample period: 9 August 2007 to 12 September 2008

	(i)	(ii)	(iii)	(iv)	(v)
Constant	**-0.033**	**-0.033**	**-0.038**	**-0.034**	**-0.054**
	0.34	0.33	0.27	0.33	0.12
Log return in spot (lag)	**-0.19****	**-0.19****	**-0.18****	**-0.19****	**-0.18****
	0.00	0.00	0.00	0.00	0.00
Risk reversal	**3.10****	**3.15****	**2.78****	**2.80****	**2.72****
	0.00	0.00	0.00	0.00	0.00
Carry-to-risk ratio	**-10.03****	**-10.02****	**-7.12***	**-7.09***	
	0.03	0.02	0.07	0.08	
FC LIBOR-OIS spread	**1.23**		**-0.31**		
	0.38		0.80		
USD LIBOR-OIS spread	**-1.94****	**-1.87****			
	0.00	0.00			
Adjusted R-squared	20.3%	20.0%	14.4%	14.9%	13.6%
F-statistic	8.62	9.40	6.67	7.75	8.07
Log likelihood	-236.19	-234.54	-242.91	-242.40	-245.16
LR test	12.43**				
Ljung-Box test up to lag 8					
Std. residuals (p-value)	0.601	0.722	0.644	0.633	0.449
Sq. std. residuals (p-value)	0.664	0.568	0.894	0.899	0.927

II. Sample period: 15 September 2008 to 31 March 2009

	(i)	(ii)	(iii)	(iv)	(v)
Constant	**0.034**	**-0.021**	**0.014**	**0.067**	**0.050**
	0.62	0.72	0.86	0.29	0.46
Log return in spot (lag)	**-0.15****	**-0.12****	**-0.13****	**-0.13****	**-0.14****
	0.00	0.00	0.01	0.00	0.00
Risk reversal	**3.10****	**3.13****	**3.06****	**3.06****	**3.32****
	0.00	0.00	0.00	0.00	0.00
Carry-to-risk ratio	**-24.84****	**0.15**	**3.80**	**11.05****	
	0.04	0.99	0.70	0.03	
FC LIBOR-OIS spread	**2.06****		**0.33**		
	0.00		0.58		
USD LIBOR-OIS spread	**-2.02****	**-1.03****			
	0.00	0.01			
Adjusted R-squared	24.0%	20.9%	19.9%	19.4%	21.0%
F-statistic	5.66	5.40	5.14	5.56	6.89
Log likelihood	-175.21	-175.03	-178.94	-178.04	-175.50
LR test	5.66*				
Ljung-Box test up to lag 8					
Std. residuals (p-value)	0.786	0.804	0.856	0.812	0.862
Sq. std. residuals (p-value)	0.838	0.757	0.866	0.868	0.610

Notes:

1. The p-value is computed from the t-statistics using the Bollerslev-Wooldrige robust standard errors.
2. * and ** indicate significant at 10% and 5% levels respectively.

Table 2d: Estimation result for JPY

I. Sample period: 9 August 2007 to 12 September 2008

	(i)	(ii)	(iii)	(iv)	(v)
Constant	**-0.040**	**-0.035**	**-0.044**	**-0.039**	**-0.043**
	0.21	0.28	0.17	0.22	0.18
Log return in spot (lag)	**-0.26****	**-0.28****	**-0.32****	**-0.32****	**-0.33****
	0.00	0.00	0.00	0.00	0.00
Risk reversal	**1.44****	**1.44****	**1.59****	**1.57****	**1.82****
	0.00	0.00	0.00	0.00	0.00
Carry-to-risk ratio	**-5.72***	**-5.09**	**-4.47**	**-4.44**	
	0.05	0.10	0.17	0.17	
FC LIBOR-OIS spread	**4.63***		**1.36**		
	0.07		0.59		
USD LIBOR-OIS spread	**-2.05****	**-1.74****			
	0.00	0.00			
Adjusted R-squared	46.5%	46.6%	43.8%	44.1%	43.9%
F-statistic	26.97	30.35	27.21	31.34	36.08
Log likelihood	-209.32	-210.92	-216.29	-216.35	-217.74
LR test	14.06**				
Ljung-Box test up to lag 8					
Std. residuals (p-value)	0.574	0.642	0.702	0.712	0.579
Sq. std. residuals (p-value)	0.519	0.183	0.514	0.434	0.660

II. Sample period: 15 September 2008 to 31 March 2009

	(i)	(ii)	(iii)	(iv)	(v)
Constant	**-0.105**	**-0.095**	**-0.112**	**-0.083**	**-0.113**
	0.20	0.26	0.18	0.32	0.22
Log return in spot (lag)	**-0.24****	**-0.25****	**-0.24****	**-0.24****	**-0.29****
	0.00	0.00	0.00	0.00	0.00
Risk reversal	**1.76****	**1.81****	**1.81****	**1.97****	**2.42****
	0.00	0.00	0.00	0.00	0.00
Carry-to-risk ratio	**-25.63****	**-26.03****	**-24.36****	**-22.76****	
	0.01	0.01	0.01	0.02	
FC LIBOR-OIS spread	**-5.04**		**-6.29**		
	0.37		0.25		
USD LIBOR-OIS spread	**-0.37**	**-0.56**			
	0.62	0.45			
Adjusted R-squared	37.8%	38.1%	38.1%	38.4%	36.5%
F-statistic	9.76	11.02	10.99	12.57	13.45
Log likelihood	-185.03	-185.30	-185.11	-185.58	-189.40
LR test	1.11				
Ljung-Box test up to lag 8					
Std. residuals (p-value)	0.979	0.960	0.978	0.922	0.996
Sq. std. residuals (p-value)	0.651	0.640	0.588	0.493	0.886

Notes:

1. The p-value is computed from the t-statistics using the Bollerslev-Wooldrige robust standard errors.
2. * and ** indicate significant at 10% and 5% levels respectively.

Table 2e: Estimation result for AUD

I. Sample period: 9 August 2007 to 12 September 2008

	(i)	(ii)	(iii)	(iv)	(v)
Constant	**-0.019**	**-0.021**	**-0.016**	**-0.021**	**-0.035**
	0.63	0.59	0.68	0.58	0.37
Log return in spot (lag)	**-0.19****	**-0.19****	**-0.19****	**-0.19****	**-0.21****
	0.00	0.00	0.00	0.00	0.00
Risk reversal	**2.80****	**2.74****	**2.78****	**2.75****	**3.03****
	0.00	0.00	0.00	0.00	0.00
Carry-to-risk ratio	**-10.21****	**-11.09****	**-10.66****	**-11.25****	
	0.02	0.01	0.01	0.01	
FC LIBOR-OIS spread	**-1.07**		**-0.69**		
	0.33		0.49		
USD LIBOR-OIS spread	**0.56**	**0.35**			
	0.38	0.56			
Adjusted R-squared	35.9%	36.1%	35.8%	36.1%	33.6%
F-statistic	17.72	19.96	19.76	22.67	23.68
Log likelihood	-277.15	-277.51	-277.50	-277.71	-281.82
LR test	1.11				
Ljung-Box test up to lag 8					
Std. residuals (p-value)	0.149	0.156	0.138	0.148	0.056
Sq. std. residuals (p-value)	0.505	0.450	0.513	0.465	0.594

II. Sample period: 15 September 2008 to 31 March 2009

	(i)	(ii)	(iii)	(iv)	(v)
Constant	**0.246****	**0.314****	**0.408****	**0.078**	**0.273***
	0.04	0.00	0.00	0.59	0.07
Log return in spot (lag)	**-0.51****	**-0.41****	**-0.49****	**-0.38****	**-0.25****
	0.00	0.00	0.00	0.00	0.00
Risk reversal	**2.44****	**2.63****	**2.36****	**2.62****	**2.52****
	0.00	0.00	0.00	0.00	0.00
Carry-to-risk ratio	**-82.97****	**-50.19****	**-70.40****	**-76.02****	
	0.00	0.00	0.00	0.00	
FC LIBOR-OIS spread	**4.97****		**3.83****		
	0.00		0.00		
USD LIBOR-OIS spread	**-0.99**	**1.63**			
	0.37	0.04			
Adjusted R-squared	38.8%	37.4%	38.1%	39.6%	28.3%
F-statistic	10.31	10.88	11.14	13.35	9.69
Log likelihood	-260.02	-260.96	-256.03	-264.01	-270.49
LR test	7.99**				
Ljung-Box test up to lag 8					
Std. residuals (p-value)	0.057	0.542	0.114	0.469	0.474
Sq. std. residuals (p-value)	0.172	0.397	0.323	0.870	0.450

Notes:

1. The p-value is computed from the t-statistics using the Bollerslev-Wooldrige robust standard errors.
2. * and ** indicate significant at 10% and 5% levels respectively.

Table 2f: Estimation result for NZD

I. Sample period: 9 August 2007 to 12 September 2008

	(i)	(ii)	(iii)	(iv)	(v)
Constant	**0.056**	**0.051**	**0.065**	**0.062**	**0.053**
	0.19	0.23	0.13	0.14	0.23
Log return in spot (lag)	**-0.17****	**-0.16****	**-0.17****	**-0.17****	**-0.16****
	0.00	0.00	0.00	0.00	0.00
Risk reversal	**2.43****	**2.42****	**2.43****	**2.48****	**3.03****
	0.00	0.00	0.00	0.00	0.00
Carry-to-risk ratio	**-15.08****	**-14.70****	**-16.25****	**-15.71****	
	0.00	0.00	0.00	0.00	
FC LIBOR-OIS spread	**0.03**		**0.27**		
	0.98		0.79		
USD LIBOR-OIS spread	**0.95**	**0.98**			
	0.22	0.22			
Adjusted R-squared	31.1%	31.4%	30.7%	30.7%	26.8%
F-statistic	14.52	16.41	15.87	17.99	17.39
Log likelihood	-298.56	-298.80	-298.52	-298.69	-306.43
LR test	0.26				
Ljung-Box test up to lag 8					
Std. residuals (p-value)	0.997	0.994	0.992	0.994	0.984
Sq. std. residuals (p-value)	0.114	0.284	0.250	0.209	0.464

II. Sample period: 15 September 2008 to 31 March 2009

	(i)	(ii)	(iii)	(iv)	(v)
Constant	**0.073**	**0.075**	**0.082**	**0.078**	**0.139**
	0.57	0.56	0.52	0.54	0.31
Log return in spot (lag)	**-0.21****	**-0.21****	**-0.21****	**-0.21****	**-0.17****
	0.01	0.01	0.01	0.01	0.03
Risk reversal	**2.24****	**2.15****	**2.22****	**2.16****	**2.59****
	0.00	0.00	0.00	0.00	0.00
Carry-to-risk ratio	**-36.56****	**-36.91****	**-37.88****	**-37.59****	
	0.00	0.00	0.00	0.00	
FC LIBOR-OIS spread	**-0.85**		**-0.59**		
	0.33		0.47		
USD LIBOR-OIS spread	**0.64**	**0.29**			
	0.48	0.74			
Adjusted R-squared	24.8%	26.0%	25.6%	26.6%	23.3%
F-statistic	5.88	6.84	6.72	7.87	7.73
Log likelihood	-249.99	-250.23	-250.12	-250.26	-254.57
LR test	0.54				
Ljung-Box test up to lag 8					
Std. residuals (p-value)	0.821	0.782	0.812	0.780	0.600
Sq. std. residuals (p-value)	0.045	0.035	0.049	0.038	0.649

Notes:

1. The p-value is computed from the t-statistics using the Bollerslev-Wooldrige robust standard errors.
2. * and ** indicate significant at 10% and 5% levels respectively.

Table 3: Impact (in terms of magnitude) of a unit standard deviation shock on daily currency return (%)

	Before the Lehman default	After the Lehman default
EUR		
Carry-to-risk ratio	0.11	0.16
FC LIBOR-OIS spread	0.06	0.16
USD LIBOR-OIS spread	0.12	0.28
GBP		
Carry-to-risk ratio	0.20	0.46
FC LIBOR-OIS spread	0.09	0.23
USD LIBOR-OIS spread	0.14	0.40
CHF		
Carry-to-risk ratio	0.08	0.17
FC LIBOR-OIS spread	0.04	0.19
USD LIBOR-OIS spread	0.13	0.21

Table 4a: Robustness check: estimation results for JPY, AUD and NZD using carry-to-risk ratio

	JPY		AUD		NZD	
Sample period	1	2	1	2	1	2
Constant	**-0.031**	**-0.037**	**0.020**	**0.071**	**0.057**	**0.081**
	0.37	0.71	0.67	0.66	0.21	0.57
Log return in spot (lag)	**-0.20****	**-0.14****	**-0.02**	**-0.19****	**-0.09***	**-0.11**
	0.00	0.06	0.68	0.02	0.07	0.18
Carry-to-risk ratio	**-21.68****	**-64.19****	**-34.76****	**-86.85****	**-31.02****	**-63.82****
	0.00	0.00	0.00	0.00	0.00	0.00
Adjusted R-squared	29.5%	23.0%	13.8%	18.9%	16.6%	9.2%
F-statistic	19.80	7.49	8.20	6.14	9.92	3.25
Log likelihood	-241.60	-202.49	-317.95	-279.05	-322.38	-264.54
Ljung-Box test up to lag 8						
Std. residuals (p-value)	0.661	0.517	0.741	0.173	0.992	0.732
Sq. std. residuals (p-value)	0.993	0.842	0.476	0.796	0.611	0.094

Table 4b: Robustness check: estimation results for JPY, AUD and NZD using alternative interbank rate proxies

	JPY		AUD		NZD	
Sample period	1	2	1	2	1	2
Constant	**-0.046**	**-0.091**	**-0.018**	**-0.036**	**0.043**	**0.115**
	0.17	0.31	0.67	0.80	0.35	0.37
Log return in spot (lag)	**-0.22****	**-0.22****	**-0.15****	**-0.34****	**-0.20****	**-0.27****
	0.00	0.00	0.01	0.00	0.00	0.00
Risk reversal	**1.46****	**1.82****	**2.57****	**2.68****	**1.98****	**2.21****
	0.00	0.00	0.00	0.00	0.00	0.00
Carry-to-risk ratio	**-5.54***	**-19.64****	**-14.61****	**-89.43****	**-19.51****	**-35.81****
	0.08	0.05	0.00	0.00	0.00	0.02
Interbank rate-OIS spread	**9.75****		**2.56****	**2.26****	**1.17**	**-1.25**
	0.01		0.01	0.00	0.29	0.40
USD LIBOR-OIS spread	**-2.03****	**-0.17**	**0.82**	**2.28**	**1.08**	**0.11**
	0.01	0.82	0.20	0.24	0.29	0.90
Adjusted R-squared	47.7%	37.1%	39.1%	40.7%	31.2%	25.9%
F-statistic	26.91	10.09	19.52	10.85	14.28	6.04
Log likelihood	-209.04	-175.49	-270.92	-255.83	-302.26	-244.11
Ljung-Box test up to lag 8						
Std. residuals (p-value)	0.603	0.352	0.257	0.701	0.889	0.514
Sq. std. residuals (p-value)	0.638	0.748	0.491	0.970	0.966	0.035

Notes:

1. The p-value is computed from the t-statistics using the Bollerslev-Wooldrige robust standard errors.
2. * and ** indicate significant at 10% and 5% levels respectively.