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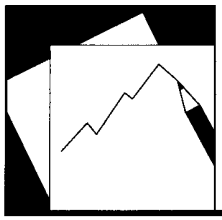

IMF Working Paper

The Effectiveness of Central Bank Interventions During the First Phase of the Subprime Crisis

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The Effectiveness of Central Bank Interventions During the First Phase of the Subprime Crisis

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Abstract

This paper provides evidence that central bank interventions had a statistically significant impact on easing stress in unsecured interbank markets during the first phase of the subprime crisis which began in July 2007. Extraordinary liquidity provisions, such as the Term Auction Facility by the Federal Reserve, are analyzed. First a decomposition of the Libor-OIS spread indicates that credit premia increased in importance as the crisis deepened. Second, using Markov switching models, central bank operations are then graphically associated with reductions in term funding stress. Finally, bivariate VAR and GARCH models are adopted to econometrically quantified these impacts. While helpful in compressing Libor spreads, the economic magnitudes of central interventions have overall not been very large.

JEL Classification Numbers: E43, E44, E52, G01

Keywords: Interbank markets, Financial Crisis, Markov-Switching, GARCH

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[1] Nathaniel Frank is with the Oxford–Man Institute of Quantitative Finance and Nuffield College, University of Oxford, and Heiko Hesse with the IMF. We thank Ulrich Klüh for input on the Libor spread decomposition and detailed discussion of the policy implications. In addition, thanks are due to Domenico Fanizza, Brenda Gonzalez- Hermosillo, John Kiff, Laura Kodres, Paul Mills and seminar participants at the Deutsche Bundesbank, European Central Bank, IMF and University of Oxford for comments. Oksana Khadarina provided excellent research assistance. Nathaniel Frank gratefully acknowledges financial support from the Economic and Social Research Council and the Oxford-Man Institute of Quantitative Finance.

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I. INTRODUCTION

Following the onset of the subprime crisis in July 2007, central banks have been at the center of the subsequent policy response to alleviate market dislocations due to the financial turbulence. Whilst the origins of the crisis can be traced back to a combination of imbalances in the global economy, structural weaknesses in the financial system and a severe relaxation of lending standards in the presence of over-abundant macro-liquidity, one of its main manifestations has been the partial dysfunction of the interbank money markets (see Frank and others (2008) for further discussion). Due to this unprecedented period of stress central banks have engaged in equally unprecedented liquidity providing operations, the nature and effectiveness of which are the focus of this paper. Within this framework of liquidity management one of the most important indicators of funding pressures has been the spread between lending in unsecured interbank markets over expected overnight rates.

In some recent work, Taylor and Williams (2008) propose a model for interest rate determination, and they hypothesize that central bank policies such as the Term Auction Facility (TAF) by the Federal Reserve will not materially reduce stress levels as measured through Libor spreads, as only a net injection of liquidity in the form of total supply of central bank reserves could potentially have an effect. Furthermore, they conduct a series of econometric tests and find that the TAF has indeed been largely ineffective in reducing term funding pressures. In contrast, Michaud and Upper (2008) reach different conclusions. Based on a comparison of the timing of central bank actions and major market moves, they show that extraordinary liquidity operations have contributed to a substantial compression of Libor spreads, whilst credit default swap (CDS) premia for banks did not appear to react in systematic ways. In addition, Aït-Sahalia and others (2009) find for a number of advanced economies and using an event study methodology that government interventions had a significant impact on the Libor spreads but this effect become smaller the more prolonged the crisis became.[2]

This paper builds on our initial work in IMF (2008) and extends it and the existing literature along several dimensions. *Firstly,* we decompose the Libor-Overnight Index Swap (OIS) spread into a liquidity component and into one reflecting credit or counterparty risks.[3] This is of importance as we believe that central bank interventions are more effective in addressing the former rather than the latter, a distinction which is not made by Taylor and Williams (2008). *Secondly,* we adopt a Markov switching framework in order to identify periods of differing levels of stress in the interbank money markets. Subsequently, the corresponding dates of regime transitions are related to major central bank announcements and policy

[2] Further discussion and findings in this area are provided by IMF (2008), where the underlying dynamics of the volatility of Euro and U.S. term spreads are modeled by employing univariate GARCH specifications. Focus is placed on intervention instruments already at the disposal to central banks during the onset of the crisis, whereby liquidity injections over and above the neutral level needed to just fulfill reserve requirements are analyzed.

[3] The Libor-OIS spread is used as a proxy for the interbanking money market stress during the crisis. For more details, see Section 2.

implementation. *Thirdly*, we improve the univariate analysis by Taylor and Williams (2008) by explicitly taking into account the partial co-movement between rates in different currencies. A bivariate VAR econometric model of the Euro and U.S. dollar Libor-OIS spreads is specified in order to test whether central bank operations have lowered stress in term funding markets. *Finally,* we adopt bivariate GARCH models in order to examine the impact of central banks' interventions on the volatility of the Libor spreads besides the level-effect.

The motivation for including the bivariate analysis is due to the fact that Libor fixings in Euros and U.S. dollars display substantial interdependence, as funding conditions are increasingly of a global nature, in particular during periods of crisis. Similarly, extraordinary changes to central bank liquidity operations in one currency have the potential to change funding conditions in another, as they are transmitted through the default probability of counterparties, conditions in foreign exchange markets and changes in overall risk aversion. Finally, some central bank measures put in place during the recent turmoil have explicitly targeted frictions in global liquidity allocation, most notably the extension of the TAF by the Federal Reserve through swap arrangements with the European Central Bank (ECB) and the Swiss National Bank (SNB).

In the empirical analysis of this paper much focus is placed on the effectiveness of two specific policy tools. Firstly, liquidity injections by the ECB through supplementary 90-day long term refinancing operations (LTROs) in excess of the benchmark allotments are used.[4] Secondly, the impact of both the introduction of the Term Auction Facility and the effect of cuts in the Federal funds and the discount rates by the Fed are quantified. In our study, we only examine the first phase of the subprime crisis from the summer of 2007 to April 2008 and do not include the Lehman Brothers collapse as well as the various new interventions tools by the Fed and the ECB.

What are our results? We find that for the early phases of the subprime crisis which began in July 2007, the rise in the Libor-OIS spread is initially attributed to funding illiquidity, whereas the credit risk component becomes increasingly important up until the rescue of Bear Stearns in March 2008. Furthermore, by employing Markov switching models it is graphically shown that relaxation of money market stress can be related to selected central bank interventions, whereby the announcement of the LTROs and the TAF seem most effective in reducing the overall Libor-OIS spreads. Finally, both the bivariate VAR and GARCH models confirm that the announcements of the TAF and LTROs have a statistically significant impact on both the level and volatility changes of the Libor spreads. But the economic magnitudes are not very large, which is supported by the fact that central banks' actions during the first phase of the subprime crisis, while successful in helping to bring down Libor spreads, have not led to an end of the liquidity crisis and a containment of the solvency concerns looming at the time.

[4] The benchmark allotment is the ECB's projection of the liquidity provision needed to fulfill its reserve requirements.

This paper is organized as follows. In Section 2, major developments in unsecured term funding markets during the crisis and subsequent central bank interventions to ease liquidity shortfalls are reviewed. In Section 3, estimation results are presented for the Markov-Switching and VAR models, while Section 4 discusses the GARCH framework. Finally, the conclusion and policy implications follow in Section 5.

II. Review of Developments and Policy Interventions

Background on term funding markets and Libor fixing

In our empirical analysis below, we focus on the impact of central bank intervention on the spread between the 3-month London Interbank Offer Rate, or Libor, and the OIS rate. In essence, the Libor-OIS spread is a measure of the premium that banks pay when borrowing funds for a pre-determined period relative to the expected interest cost from repeatedly rolling over funding in the overnight market. In times of sufficient liquidity and in the absence of market dislocations, these two measures should be close substitutes, as implied by the expectations hypothesis, such that the interest rate paid on term bank deposits ought to bear a close relationship with the expectation of the compounded overnight rates over the same horizon. During periods of crisis, the widening Libor-OIS spread provides an appropriate proxy for interbank money market stress in the form of liquidity and credit premia, quantifying the unwillingness of banks to extend unsecured loans. This is because the OIS is tied to the Federal funds rate and exhibits only limited credit risk as, like in the case of most interest rate swaps, no principal is exchanged.

Further motivation for analyzing the effect of central bank intervention on the Libor-OIS spread in this paper draws on the importance of the Libor instrument, both in terms of the functioning of securities markets and concerning its macrofinancial implications. With regard to the former, Libor is a measure of the cost at which banks may borrow unsecured funds, which over the past decade has become of increasing significance in the light of greater reliance on the wholesale interbank money markets, as discussed in IMF (2008). Furthermore, it is used as a risk free rate in discounting and thus pricing derivative contracts such as forward rate agreements, interest rate swaps and swaptions. Hull (2005) points out that Libor is the preferred reference rate rather than the yield implied by government securities as for tax and institutional reasons demand for Treasuries is increased, in turn implying an interest rate which is too low. As a result, Libor is important in ensuring market efficiency through accurate pricing of assets and in determining the funding costs of major financial institutions. In addition, there are also macroeconomic considerations, as the interbank money markets constitute an important channel for monetary policy transmission.

The Libor rate, the cost of unsecured lending between banks, is set on a daily basis and is published at 11 a.m. by the British Bankers Association. It is constructed using a survey from banks that comprise the Libor panel, composition of which is subject to change over time and which may include foreign banks operating in London. The calculation of the reference rate is based on the average of quotes rather than that of actual trades, whereby the upper and lower quartiles are omitted in order to avoid manipulation. As part of this process Libor is set for 15 maturities ranging from overnight to 12 months in ten different currencies.

It should be noted though that the Libor fixing mechanism exhibits limitations and that the reference rate is merely a proxy for the interest charged by banks amongst each other. Quantification of the actual interest rate is difficult as such trades are bilateral and are not centrally recorded, thus providing no readily available data. Importantly, any quotes are non-binding and may differ from the subsequent interest rates which are agreed upon. Furthermore, concerns have been voiced as to whether the banks in the Libor panel have incentives to make quotes in an accurate fashion, especially during times of financial stress. Downward biases may be present due to signaling effects, whereby a high offer incurs reputational damage as it indicates the need to attract significant interest payments. Finally, there are incentives for banks to influence the Libor fixing process in order to affect the pricing of securities and thus their respective book values. In response to these issues, the tails of the quote distribution are discarded, implying that manipulation of the Libor rate would only be possible through widespread collusion amongst reporting banks. In addition, transparency has been improved as part of new guidelines set by the British Bankers Association (see BBA (2008) for further details) by requiring individual financial institutions to publish their offers.

Review of developments since July 2007

This subsection briefly reviews some of the major developments of the crisis since July 2007, which are of importance with regard to the interbank money markets. As outlined in more detail by Frank and others (2008), this period of financial turbulence was triggered by a credit event, namely the bursting of the subprime mortgage bubble due to falling house prices and the reversal of interest rates which had been previously at historical lows. Many financial institutions exhibited exposures to mortgage-backed securities, often in the form of off-balance sheet entities such as structured investment vehicles (SIVs). These SIVs or conduits were funded through the issuance of short term asset-backed commercial paper (ABCP) in order to take advantage of higher yields resulting from longer term investments, and thus exhibited an inherent maturity mismatch. Due to the increasing uncertainty with regard to their exposure to and the value of the underlying mortgage-backed assets, investors became unwilling to roll over the corresponding ABCP. As the problems with the SIVs and conduit facilities deepened, banks came under increasing pressure to rescue those that they had sponsored by providing liquidity and by taking their respective assets onto their own balance sheets.

Following this reabsorbtion of the SIVs, lending within the interbank money markets was curtailed for reasons of liquidity and credit risk. With regard to the former, increases in the Libor-OIS spreads, especially at longer dated maturities, are explained by the hoarding of funding in order to cover further contingent liabilities following asset price declines, subsequent marking-to-market of securities and forced liquidations. Concerning the latter, rising credit concerns were priced into the Libor spread as interbank lending is unsecured and whereby this counterparty risk arises due to the uncertainty of the banks' exposure to troubled assets. An alternative explanation for the widening of the Libor spreads has been proposed by Giavazzi (2008) who has put forward the notion of predatory banks. In a model of strategic behavior amongst financial institutions there are two reasons why excess cash is not lent. Firstly, if another bank was to fail, its assets could be bought at a depressed price

following it being placed into administration. Secondly, the probability of such an event occurring is endogenously determined by the amount of liquidity available in the interbank money markets, such that the optimal strategy may be to hoard any funds.

During the crisis the Libor fixing process itself was also affected. At times of the most serious market dislocations and heightened risk aversion, term funding at longer dated maturities was entirely unavailable. In addition to an increase in the level of Libor quotes, the variance of the individual fixings made by banks also rose significantly. In this context it has been argued that this was in part due to heterogeneity with regard to credit risk. Financial institutions exhibited differing exposures to asset-backed securities and to contingent credit lines in the form of implicit guarantees for SIVs, whereby high liabilities towards these entities induced increased upward pressure on the respective quotes.

Finally, due to the shortage of U.S. dollar liquidity following the reabsorbtion of conduits and SIVs, European banks became increasingly engaged in FX swaps, whereby especially Euro and Sterling were used as the funding currencies in such deals, as discussed by Baba and others (2008). The spillovers from the interbank to the FX swap market led to a situation whereby FX swap prices temporarily deviated from their covered interest parity condition, which further highlighted the international interconnectedness of funding requirements by banks. These linkages are of importance in the context of our paper as central banks responded on December 12, 2007 by extending the Term Auction Facility by the Fed through swap arrangements with the ECB and the Swiss National Bank in order to address these foreign currency shortages.

Monetary policy implications

Whilst motivating this paper, it was previously argued that the dislocations in the interbank money markets also have macroeconomic effects such as impairing the transmission mechanism of monetary policy.

During tranquil times this process operates in that policy rates affect money markets, which in turn determine the cost of lending to households and companies, and thus the level of economic activity and price stability. The banking sector is of importance in the transmission mechanism as it transforms the maturity of loans. Over the past two decades the financial industry has undergone structural changes, whereby banks have become increasingly reliant on wholesale funding as compared to retail deposits, in addition to the more recent emergence of a shadow banking sector. This is comprised of the aforementioned specialized investment vehicles (SIVs) and other off-balance sheet entities which were devised in order to circumvent the Basel II capital requirements for risky assets. The funding of long term investments held by banks and their respective SIVs has occurred increasingly through issuance of short-term commercial paper and overnight repo agreements, such that a yield differential is exploited, whilst also creating a maturity mismatch.

During the most recent period of financial stress, the effectiveness of the monetary policy transmission mechanism has been directly diminished. This is because changes in the policy rates have only had limited impact on the interbank money markets, such that in effect the

central banks have lost control over the short end of the yield curve. More specifically, financial institutions have not passed on the cuts in rates to lower the cost of unsecured borrowing, but rather Libor fixings have remained elevated due to the increase in the previously discussed liquidity and credit related premia over and above the risk free rate. Furthermore, these conditions of market dislocations have been amplified due to the recent structural changes in financial markets, in turn increasing systemic risks. Banks have exhibited ever greater reliance on wholesale money markets with the respective funding share of deposits declining from over 50 percent in 1980 to under 20 percent in 2008 (IMF (2008)). At the same time the conditions in the interbank money markets have been significantly more volatile during the crisis period as compared to the interest rate payments made to retail customers. As pointed out in Figure 1, widening of Libor spreads and thus increased funding costs were not geographically confined such that diversification of liquidity access was curtailed. Combined with the increased mismatch between funding and investment maturities, a system reliant on market confidence as in the classic bank-run literature following Diamond and Dybvig (1983) emerged, potentially leading to self-fulfilling equilibria of investment withdrawals.

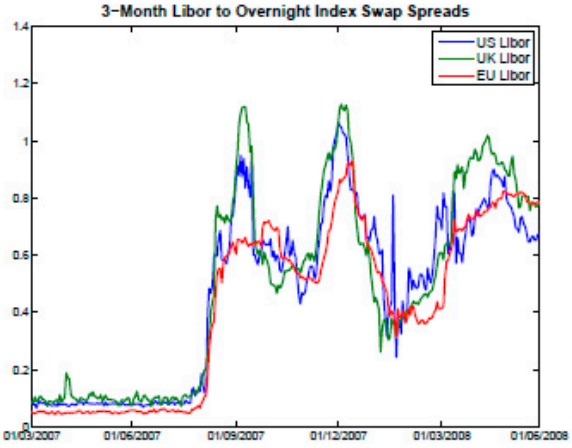

Figure 1: U.S., U.K. and Euro area Libor-OIS Spreads. Interbank money market pressures were not limited to any geographical region. Spread levels reached over 100 basis points during times of most severe market dislocations, compared to a range of 5 to 10 basis points before the onset of the subprime crisis.

Policy tools

In the empirical analysis in the following section, much focus is placed on the effectiveness of two main policy tools, namely the supplementary 90-day long-term refinancing operations (LTROs) by the ECB and on the Term Auction Facility (TAF) by the Fed. These intervention instruments were devised in order to provide additional liquidity following the impairment of the interbank money markets, the increased demand for central bank liquidity and to address the widening spread between secured and unsecured lending.

During periods of tranquility the ECB provides liquidity to market participants through short term operations (MROs) over 4–5 week reserve maintenance periods (RMPs). In this context,

the projected benchmark allotment is defined as the amount of funding required to allow all counterparties to fulfill their respective commitments. Following the onset of the subprime crisis the ECB began injecting additional liquidity into interbank money markets, whereby a series of fine-tuning operations totaling more than $200 billion were carried out between August 9 and August 14, 2007 following the emergence of liquidity shortages. Furthermore, a supplementary LTRO was announced on August 22. Within these interventions additional liquidity was provided at the beginning of the RMP over and above that required by the benchmark allotment in order to account for increased uncertainty with regard to liquidity demands. Emphasis was especially placed on liquidity shortages at longer dated maturities as this financing was harder to obtain for banks during the crisis due to higher associated risk premia. By simultaneously withdrawing short term funding the maturity composition rather than the aggregate amount of reserves was changed, such that monetary policy and interest rate targets could be achieved throughout.

With end-of-year funding pressures increasing, the Fed on December 12, 2007 announced a temporary Term Auction Facility such that banks could borrow loans for up to 28 days maturity, secured against permissible collateral. There were two main reasons for its introduction. Firstly, liquidity in U.S. markets is normally provided by the Fed through a few select brokers which limits the number of eligible counterparties for receipt of central bank funding. During times of severe market stress and funding illiquidity, these intermediaries hoarded funds, thus impairing their distribution. Secondly, the introduction of the TAF was intended to overcome the stigma attached to accessing the discount window due to negative signaling effects in the presence of asymmetric information and limited confidence by market participants with regard to the health of financial institutions.

The TAF was also linked through a foreign currency swap operation with the ECB and the Swiss National Bank, allowing them to provide U.S. dollars to their much wider set of recipient institutions. Other policy tools included the New Primary Dealer Credit Facility which was introduced by the Fed in March 2008, whilst the Bank of England on April 21, 2008 launched a special liquidity scheme whereby banks were able to exchange mortgage-backed securities against UK Gilts for a period of up to three years.

III. EMPIRICAL ANALYSIS

Decomposition of the Libor-OIS spread into liquidity and credit components

In this first part of the empirical section the Libor-OIS spread is decomposed into two components which are associated with liquidity and credit risk premia using the methodology proposed by the Bank of England (2007). This is related to less formal work by Michaud and Upper (2008). As previously argued, a no arbitrage condition dictates theoretical equality between Libor and the correspondingly dated overnight index swap rate. The subsequent spread between these two measures is mostly explained by liquidity and credit premia, whereby the latter arises due to the fact that Libor is an interest rate associated with unsecured lending. The main reason for this decomposition is that it allows us to quantify changes in the make-up of the Libor-OIS spreads as crisis events unfolded. Furthermore,

it is of interest with regard to motivating future research as it would be possible to distinguish between the impact of central bank intervention on these two differing constituents, thus extending the analysis by Taylor and Williams (2008) which does not disentangle these effects. In this context it is to be expected that the liquidity providing operations such as the LTROs and the TAF would affect the observable total spread level whilst being unable to reduce interbank money market stress emanating from counterparty risk.

We make the simplifying assumption that the Libor spread is fully explained by a liquidity and by a credit component, such that volatility effects of the future expected overnight rates and market liquidity in general are ignored. The credit premium is derived by employing credit default swap (CDS) spreads for banks in the Libor panel, whereby it is furthermore assumed that liquidity and solvency risks are independent and that CDS spreads provide a fair probability of default.[5] In the first stage of the decomposition a no arbitrage argument under risk neutrality is employed to infer the implied probability of default of Libor panel banks, by combining the observed market prices of their CDS contracts with a recovery rate of 40 percent.[6] Next, this probability is used to derive the premium above the risk free OIS rate which is required for investors to be indifferent to accepting the credit risk within the interbank money market. Finally, these spreads are averaged across the banks in the Libor panel in order to quantify the credit component of the Libor-OIS spread, whereby the residual is attributed to a liquidity premium.

In our analysis we extend the sample used by the Bank of England by six months until April 2008 so that the rescue of Bear Stearns is included. As it can be seen from Figure 2, during the onset of the subprime crisis the increase in the Libor-OIS spread was mainly driven by liquidity risks. As discussed in the previous section, funds were extended to off-balance sheet investment vehicles and liquidity was hoarded by banks, thus reducing the interbank lending in both the U.S. and Euro area money markets. Liquidity pressures subsequently declined during the autumn of 2007 but end-of-year effects, driven by window dressing of balance sheets by financial institutions, raised demand for interbank money market funds. Interestingly, credit concerns rose continuously until the rescue of Bear Stearns in mid-March 2008 due to increasing write downs of structured securities, uncertainty with regard to the value of their underlying assets and heightened risk aversion in general. Subsequently this trend is reversed, whereby capital markets seemingly re-priced the probability of the survival of financial institutions conditional on implicit guarantees provided by the U.S. government, causing the corresponding CDS spreads to decline dramatically.

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[5] Clearly, this is not always the case, especially during times of financial turbulence, such as in Iceland where in 2008 hedge funds speculated on sovereign and corporate default. Furthermore, the effects of government bailouts and nationalization of financial institutions are ignored. This is of importance as such events may affect CDS spreads by causing convergence between those of banks and those corresponding to government debt.

[6] Clearly, this is a further simplifying assumption as the recovery rate following default will vary across individual banks depending on their respective financial health, and may also decline as the extent of market dislocations deepens over the sample period. Also, it is not clear in how far government guarantees affect the recovery rate as compared to the probability of default itself.

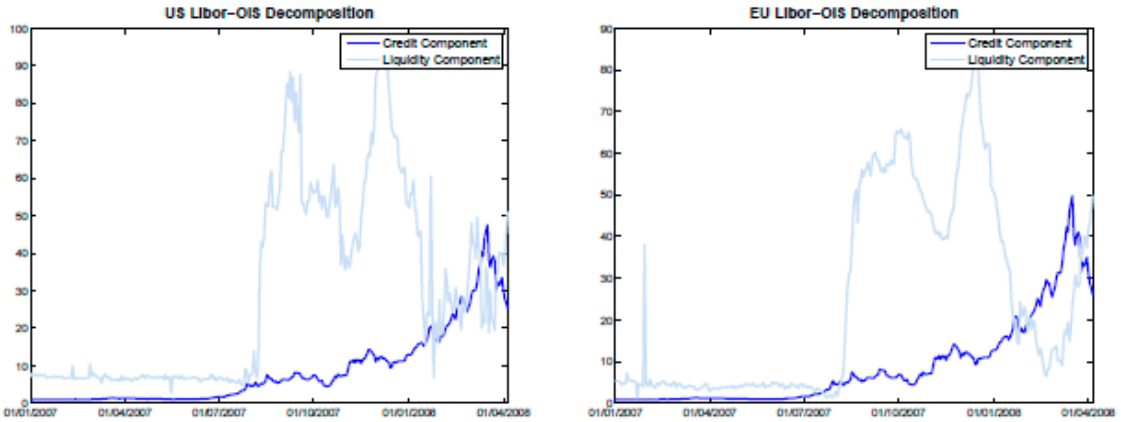

Figure 2: Decomposition of U.S. and Euro area Libor-OIS spreads. In the early stages of the crisis most of the widening of the spread can be explained by funding illiquidty. As events further unfolded, the credit component became of increasing importance up until the rescue of Bear Stearns in March 2008.

In addition to analyzing the changing composition of the Libor-OIS spread in levels during the early phases of the subprime crisis, in Figure 3 the liquidity and credit risk premia for the Euro area and U.S. Libor spreads are presented in first differences around the time of the introduction of the first TAF.[7] Interestingly, as can be seen from the top panel, before the implementation of the auction on December 17, 2007 changes in the Euro area spread associated with liquidity risks were positive on 19 out of 20 trading days, indicating that money market stress emanating from this risk premium increased systematically before this event. Subsequently, on 21 out of 24 days following this intervention the changes in the liquidity component were negative, whereas no such systematic impact is observed for the corresponding credit component. With regard to the first differences of the decomposed Libor-OIS spread for the U.S., similar results are found, but where the sign change occurs following the announcement of the TAF on December 12, rather than on its implementation date. As previously mentioned, we believe that these results motivate further research in order to explicitly quantify the effectiveness of central bank intervention on both components. Especially as the percentage of the Libor-OIS spread which is attributed to credit risk is increasing throughout the crisis, findings in Figure 3 would suggest that the impact of liquidity providing instruments has declined.

[7] This analysis is related to similar findings in Michaud and Upper (2008) which were written simultaneously to the publication of IMF (2008) and during the conceptualization of this paper.

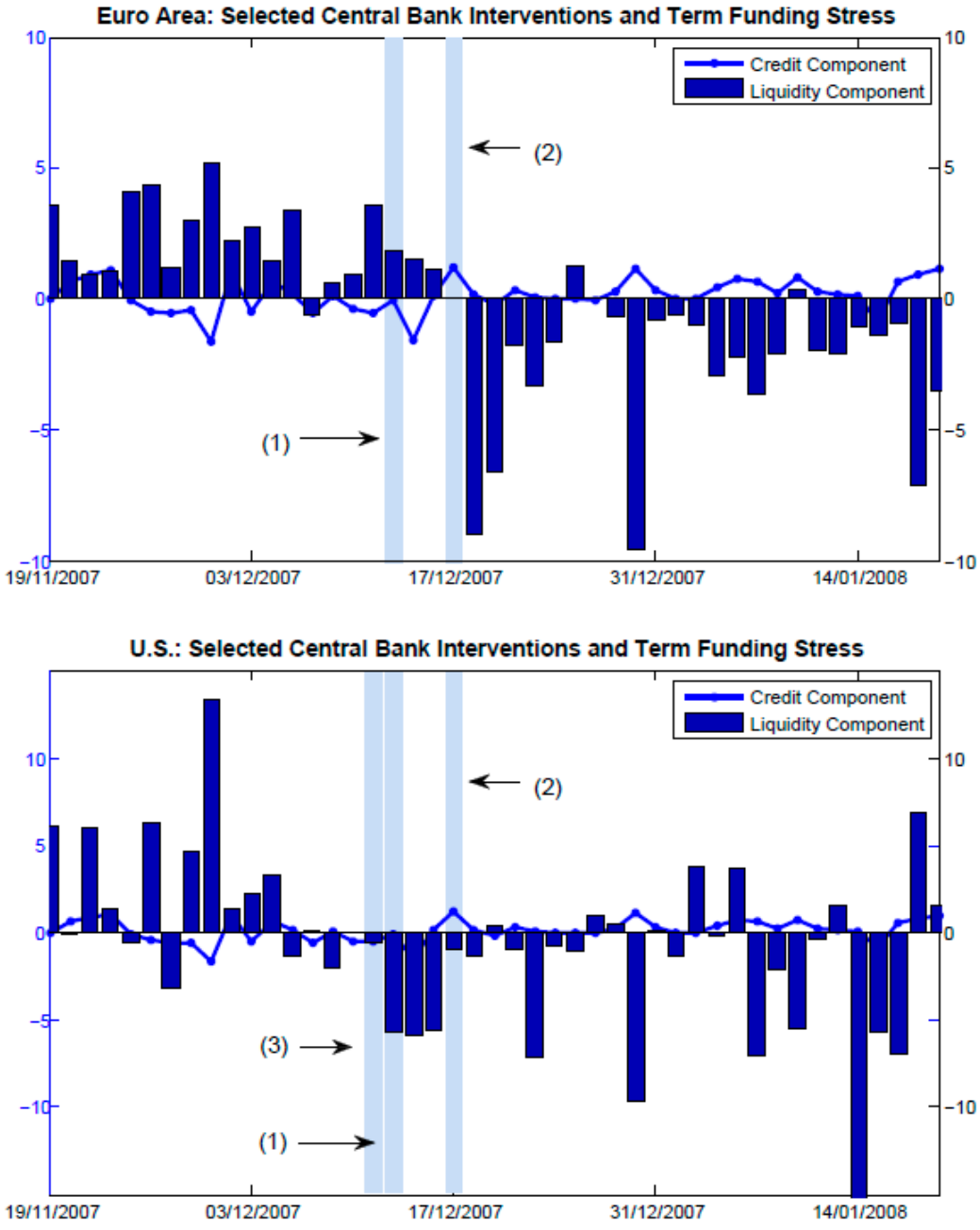

Figure 3: Decomposition of Libor-OIS spreads. Changes in the credit and liquidity components are measured in basis points on both axes. The central bank interventions are labeled as follows: (1) = joint announcement by major central banks with regard to the introduction of the TAF, (2) = first TAF auction, (3) = Federal funds target and discount rates lowered by 25 basis points.

Graphical analysis using a Markov-Switching Approach

To assess the effectiveness of central bank intervention in reducing the stress in interbank money markets, we first employ a graphical analysis that compares the timing of distinct policy events with changes in the levels and the volatility of Euro area and U.S. Libor spreads. To this end it is hypothesized that the respective data generating processes are subject to regime changes. Markov switching models in the first two moments of the Libor spreads are estimated, such that probabilities of being in certain states of the world can be derived. These findings build upon work published in IMF (2008). In the Markov Switching analysis, we focus on the behavior of the overall Libor-OIS spreads rather than the liquidity and credit component.

A Markov-switching model differs from a standard econometric regression in that the coefficients and the variance terms may be dependent on an unobserved state variable St, which is assumed to follow a Markov chain. These models allow for detection of unobserved structural breaks in the data and subsequent transitions between differing states of the world. As part of the estimation, inference with regard to smoothed probabilities $Pr\{S_t|r_t, r_{t-1}, ...\}$ is made, which denote the probability of a respective regime occurring, conditioned ex post on the entire past realizations of rt.

In this paper, the Markov switching framework is used in order to analyze the effect of central bank intervention on the regime transitions of the first two moments of the Libor spreads. In both cases, the existence of three states of the world is assumed.[8] The corresponding model for the first differences of the spread levels is based on the univariate mean-variance specification by Hamilton (1989)

$$r_t = \beta_{S_t} + \epsilon_t \qquad \epsilon_t|S_t \sim N(0, \Omega_{S_t}), \qquad (1)$$

where $S_t \in \{1, 2, 3\}$ are the three states of the world. Here, first differences of the Libor spreads rt are a function of a state dependent constant β_{S_t} , whereas the variance of the subsequent residuals also exhibits respective regime shifts.

The volatility of the first differences of the spreads is captured using the Markov switching ARCH (SWARCH, hereafter) model proposed by Hamilton and Susmel (1994). The mean equation is specified as an AR(1) process $r_t = \alpha + \phi r_{t-1} + \epsilon_t$,

[8] This selection is motivated by the constancy of the Libor-OIS spread before the onset of the subprime crisis, which is not well captured by a 2 regime specification which would only model increases and decreases in the spread.

where the conditional variance is parameterized as

$$\epsilon_t = \sqrt{\gamma_{S_t}} \cdot \tilde{\epsilon}_t \qquad \tilde{\epsilon}_t = h_t \cdot \nu_t \tag{2}$$

$$h_t^2 = a_0 + a_1 \tilde{\epsilon}_{t-1}^2 + a_2 \tilde{\epsilon}_{t-2}^2 + ... + a_q \tilde{\epsilon}_{t-q}^2,$$

where $\nu_t \sim N(0,1)$ and $S_t \in \{1,2,3\}$. Thus the ARCH(q) process in (2) is state dependent due to multiplication with a scaling factor St which is normalized to unity for the low volatility regime.[9] [10]

In Table 1 the results for the Markov switching estimation are presented based on a sample ranging from February 1, 2007 until April 4, 2008.[11] The mean-variance model in (1) implies that for the Euro area the average changes in the level of the Libor spreads in the low, medium and high intercept states of the world are approximately -1, 0 and 1.6 basis points per day, respectively. This compares to daily changes for the U.S. of -0.8, 0 and 3.4 basis points such that the coefficient quantifying the upward pressure in the interbank money markets is twice as high as compared to that for Europe. Before the onset of the crisis the model indicates for both markets that the data generating process is best characterized by the middle regime, which is consistent with the observation that during this period Libor spreads showed very little change and remained approximately constant.

	EU Levels Model			U.S. Levels Model		
	State 1	State 2	State 3	State 1	State 2	State 3
Beta	-1.0266	-0.0140	1.6483	-0.8485	0.0094	3.3974
	EU Volatility Model			US Volatility Model		
	State 1	State 2	State 3	State 1	State 2	State 3
Gamma	1	17.3629	29.334	1	34.2072	249.455

Table 1: Markov switching parameters for levels and volatility models.

[9] In this analysis an ARCH specification is estimated, as the GARCH(p,q) is not nested within the SWARCH framework, due to its implicit infinite lag representation.

[10] In this paper we acknowledge that the model selection can be further refined. Firstly, the mean-variance specification in (1) could be augmented using an autoregressive parameterization or through the inclusion of further exogenous regressors explaining the Libor-OIS spread. Secondly, it would be possible to make the mean equation for the SWARCH model state dependent. Finally, in future research we aim to make the smoothed probabilities of being in specific regimes a direct function of central bank interventions. Due to the restrictive modeling tools within the Markov switching framework, this has so far not been possible.

[11] The statistical significance of the scaling parameter ɣ indicates the existence of switches in the data generating process. Inference with respect to gamma is complicated by the fact that corresponding significance tests exhibit non-standard distributions. Following argumentation by Hamilton and Susmel (1994) it is concluded that as the associated test statistics are of such great magnitude, the null hypotheses of no regime changes are rejected for both volatility models, regardless of whether the skew in the distribution is accounted for or not.

In the lower half of the Table 1, the scaling parameter γ_{S_t}, as described above, is presented for the Markov switching ARCH models for both Libor spreads. During the financial crisis and the corresponding occurrence of the medium and the highest volatility regimes, the conditional variance in the European money markets is 17 and 29 times greater relative to that in the pre-crisis period which is characterized by the normalization of γ_{S_t}= 1. In the U.S., this multiplication factor is even more pronounced, standing at 34 and 249, reflecting the fact that the conditional variance is driven by the large outliers in the changes of the Libor spread during the period of market turbulence.

Mean-Variance Model

In Figure 4 a graphical representation of findings for the mean-variance models is reported for both the European and U.S. Libor-OIS spreads. Here, the blue line represents the smoothed probability of being in the highest intercept state as measured on the right axes, whereas the shaded bars denote major central bank interventions. Throughout, focus is placed on the aforementioned LTROs by the ECB, in addition to cuts in both the Federal funds and discount rates, and the introduction of the Term Auction Facility by the Fed.

The top panel in this figure indicates that stress in the Euro area money markets began to rise substantially around August 9, 2007, illustrated by multiple upward movements in the Libor spread of approximately 8 basis points per day. Apart from a shock on September 27, the magnitude of these pressures decreased, followed by a reduction in the spread during October until mid-November 2007. On November 19, end-of-year pressures in the interbank money markets become apparent, as banks hoarded liquidity in order to support their respective balance sheets during the financial reporting season, in addition to suffering further write downs and credit related losses. A sign change in the first difference of the spread occurs on December 18, 2007, after which the Libor rate decreased systematically at an average rate of about three basis points per trading day.

Corresponding to these data, the Markov switching model implies two main periods during which a unit probability of being in the highest intercept state is assigned. The first corresponds to the beginning of the interbank money market stress during August, and the second to the-end-of-year pressures in November and December. The brief transition around September 27, 2007 is attributed solely to the corresponding outlier mentioned above.

Regarding the effectiveness of the central bank interventions, the ECB announced and carried out its first supplementary LTRO on August 22 and 23. As is evident from the upper panel in Figure 4, the magnitude of the changes in the Libor rates decreases from approximately 8 basis points, and apart from two exceptions on September 5 and 27, does not exceed 2 basis points until mid-November.

Thus, the supply of this additional long-term liquidity coincides with a fall in the rate at which the Libor spread increased.

Following the end-of-year pressures in the money markets, the ECB conducted a further supplementary LTRO on November 22, but which largely remained ineffective in encouraging banks to lend to their respective counterparties. Finally, on December 12, the Fed announced the introduction of the TAF and the implementation of the first auction on December 17, which is associated with a clear sign change in the first difference of the Euro area Libor spread. While it increased on average at approximately two basis points per day before the TAF implementation, decreases of about three daily basis points are observed afterwards.

In the lower panel of Figure 4, the results of the mean-variance specification for the U.S. are presented. In comparison to the European Libor, the changes in the spreads are of greater magnitude, but at the same time are less persistent.

Again, money market stress starts building significantly on August 9, after which the Libor spread stabilizes and subsequently declines between October 22nd and November 1st. As in the case above, end-of-year pressures are also present in the U.S. interbank money market.

These periods of market dislocations are captured by increases in the smoothed probability of being in the highest intercept state in the Markov switching model. As implied by Table 1, during late August and early September, the average increase in the U.S. Libor spread is approximately 3.4 basis points per trading day.

This period is followed by a regime switch into the lowest state of the world, implying that money market stress is reduced by 0.85 basis points per day until approximately November 16, when end-of-year pressures cause the model to switch back. A further regime change to the lowest intercept occurs on December 7, 2007.

Following a cut of 50 basis points in the Federal funds target and the discount rates on September 18, the U.S. Libor spread exhibited its steepest decline over the entire sample period by falling 35 basis points, as illustrated in the lower panel of Figure 4. Subsequently, the interbank money market entered a period of relative calm until mid November. In response to increasing pressures during the end of the year, both rates were cut again by 25 basis points on December 11, which was followed by the TAF announcement and implementation. As in the case of the Euro area Libor, these events are associated with a sign change in the movements of the U.S. spread.

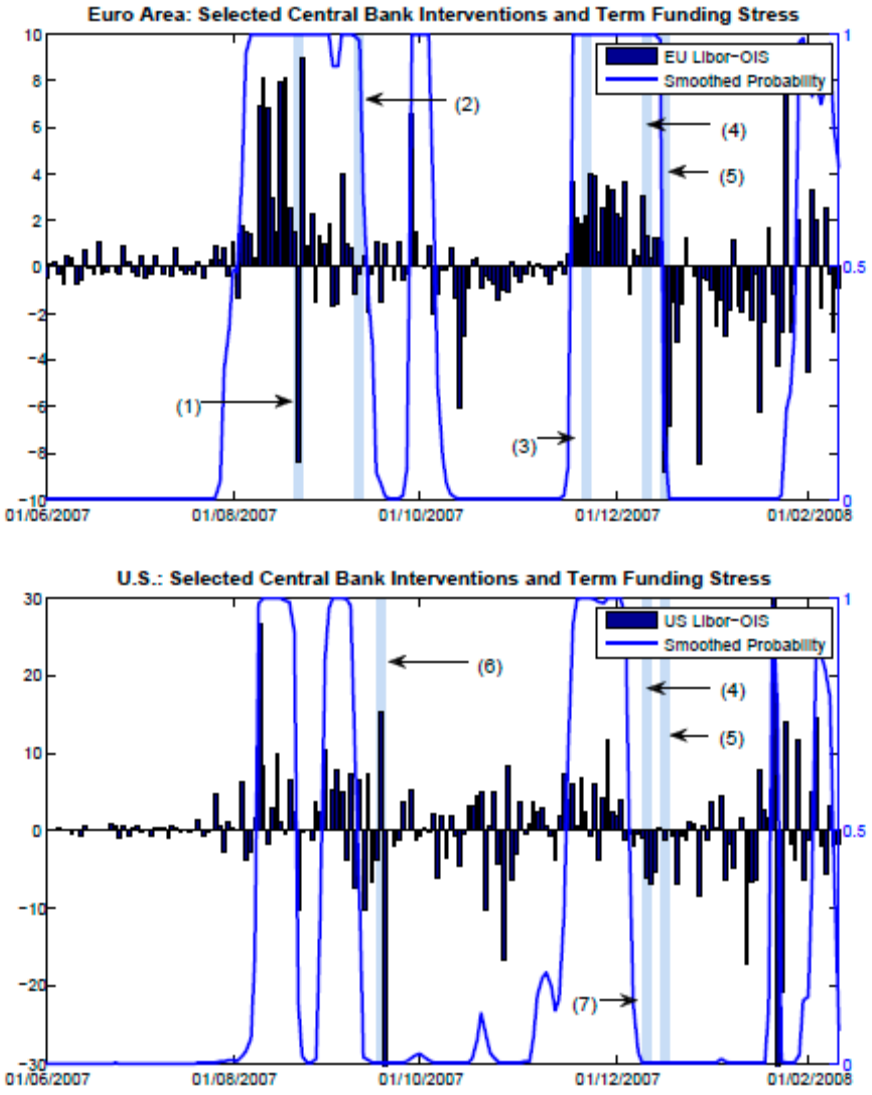

Figure 4: Markov switching mean-variance model for Euro area and U.S. Libor-OIS spreads. Changes in the spreads are measured in basis points on the left axes. The blue line denotes the smoothed probability of being in the highest intercept regime implied by the Markov switching model. The central bank interventions are labeled as follows: (1) = ECB announcement and implementation of first LTRO, (2), (3) = supplementary LTROs, (4) = joint announcement by central banks on introduction of the TAF, (5) = first TAF auction, (6) Fed funds target and discount rates lowered by 50 basis points, (7) = Fed funds target and discount rates lowered by 25 basis points

Conditional Variance Model

The graphical representation of the results from the Markov switching ARCH model is presented in Figure 5 in which the effects of the same central bank interventions, as discussed above, on the conditional variance of the spreads are analyzed.

Two distinct periods of highest volatility are observed in the case of the Euro area Libor-OIS spread. The first is driven primarily by the increases in the spreads at the beginning of the crisis in August 2007, during which time a switch from the lowest to the highest volatility regime occurs. The econometric model implies that this elevated level of interbank money market stress subsequently begins to retreat in the beginning of September. The period of market calm lasts until November 19, 2007, after which the second period of heightened volatility is observed. This is caused by the previously mentioned end-of-year effects, which led the Libor spread to increase on average by 2 basis points per trading day. No further regime switches are recorded during the sample period. Despite the sign change around the time of the TAF introduction, the absolute value of the changes of the spread does not decline.

With regard to the effectiveness of central bank intervention, we find some tentative evidence that the announcement and implementation of the ECB's LTROs had a volatility reducing effect. As previously described, following the liquidity injection on August 22/23, the magnitude of the changes in Euro area Libor declined significantly. Due to the autoregressive parameterization of the Markov switching ARCH model a lag arises though when quantifying this effect by assigning the corresponding smoothed probabilities of being in the respective volatility states.

The second panel of Figure 5 contains the findings for the U.S. Libor spread. During the beginning of the interbank money market stress the data generating process is in the highest volatility state with approximately unit probability. A shift into the medium regime occurs on September 28. Unlike in the case of Euro Libor, this period of market calm does not extend into October, as large negative changes in the spread induce an increase in the volatility, which is eventually also driven by end-of-year effects. These findings are also consistent with central bank intervention having reduced stress in the U.S. interbank money markets when measured in terms of Libor spread volatility. As previously mentioned, the lowering of the Federal funds target and discount rates on September 18 led to a decline in the spread of 35 basis points, after which the magnitude of Libor changes falls in absolute value. The Markov switching ARCH model is influenced by this large negative shock, but picks up the volatility reducing effects by September 27. As in the case of the Euro area Libor, the effect of the TAF on volatility is limited as despite the induced sign change, the absolute value of the spread movements does not decline.

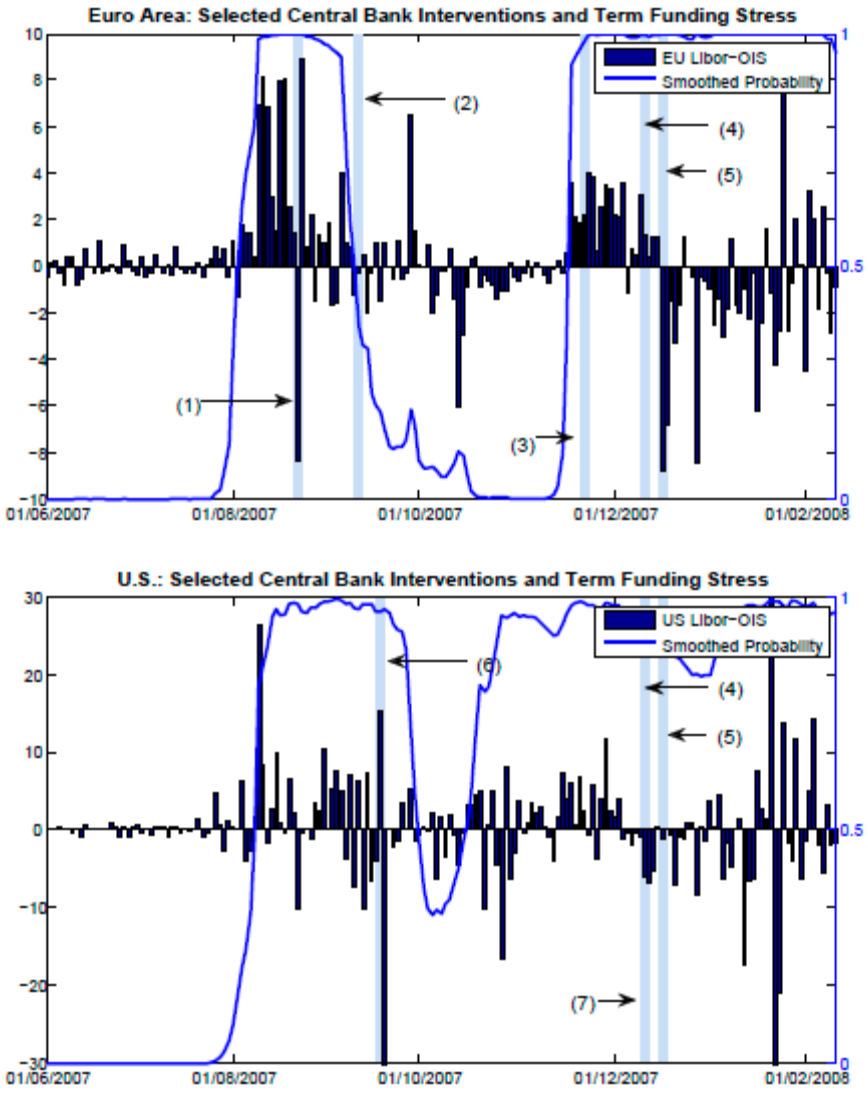

Figure 5: Markov switching ARCH model for Euro area and US Libor-OIS spreads. Changes in the spreads are are measured in basis points on the left axes. The blue line denotes the smoothed probability of being in the highest volatility regime implied by the Markov switching model. The central bank interventions are labeled as follows: (1) = ECB announcement and implementation of first LTRO, (2), (3) = supplementary LTROs, (4) = joint announcement by central banks on introduction of the TAF, (5) = first TAF auction, (6) Fed funds target and discount rates lowered by 50 basis points, (7) = Fed funds target and discount rates lowered by 25 basis points

In summary, Markov switching models for both changes in the levels and the volatilities of the Euro area and U.S. Libor-OIS spreads are employed in order to assess the effectiveness of central bank intervention on money market pressures. Graphical evidence is provided that the LTROs by the ECB, and the interest rate cuts and the introduction of the TAF by the Fed were able to reduce term funding stress.

Bivariate VAR Model

In addition to the descriptive and graphical analysis of the previous subsection, we specify a bivariate model in which the behavior of the overall Libor-OIS spreads is explained as a function of a series of variables capturing extraordinary central bank operations. Whilst approaches such as the Markov switching framework or the univariate specification by Taylor and Williams (2008) provide first useful insights towards understanding the effect of central bank policies, they ignore a series of important aspects of the recent crisis. As previously argued, Libor fixings in Euros and U.S. dollars are likely to display substantial interdependencies, as funding conditions are increasingly of a global nature, in particular during periods of crisis.

Similarly, liquidity provisions by central banks in one currency potentially alter funding conditions in another, as they are transmitted through changes in the default probability of counterparties, conditions in foreign exchange markets and by affecting overall risk aversion. Finally, central bank measures were put in place during the recent turmoil which has explicitly targeted frictions in global liquidity allocation, most notably the extension of the TAF through swap arrangements with the ECB and the Swiss National Bank.

In order to account for these interdependencies between funding markets a bivariate Vector Autoregression (VAR) is estimated which quantifies the impact of emergency response to liquidity stress by jointly modeling changes in the U.S. and Euro area Libor-OIS spreads.[12] As before, the LTROs by the ECB and the TAF by the Fed are used as explanatory variables, whereby differentiation is also made between the announcement and the actual implementation dates. In addition to these extraordinary liquidity operations by central banks, the Fed reduced its policy rates during the financial turmoil, which is also included in the model in order to gauge any possible impact of these more conventional policy tools. The VAR specification in (3) is estimated for the crisis period spanning from July 1, 2007 until April 3, 2008, where rt is defined as the first difference of the spread between the three-month Libor and OIS.[13] I_{t-j} for $j = 1, 2$ denotes central bank intervention with this instrument being in the form of a dummy variable which takes on the value of 1 during the occurrence of the intervention and 0 otherwise. In this context, all policy events in our sample are 1 day long, whereby in addition to the announcement and implementation of the first TAF there are 5 LTROs, 6 cuts in the Federal funds and 8 reductions in the discount rates.

[12] Similarly to the Markov switching approach, we focus on the overall Libor-OIS spreads rather than the liquidity and credit components.

[13] With regard to model selection, standard techniques such as information criteria and residual analysis are employed. Here it is found that the VAR(1) specification in (3) is sufficient due to limited auto- and cross correlations in the changes of the spreads.

$$\begin{bmatrix} r_t^{EU} \\ r_t^{US} \end{bmatrix} = \begin{bmatrix} \mu_1 \\ \mu_2 \end{bmatrix} + \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} r_{t-1}^{EU} \\ r_{t-1}^{US} \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} \begin{bmatrix} I_{t-1} \\ I_{t-2} \end{bmatrix} + \begin{bmatrix} \epsilon_t^{EU} \\ \epsilon_t^{US} \end{bmatrix} \quad (3)$$

In Table 2 we present the corresponding results for the effectiveness of differing policy measures on the Libor-OIS spreads of the 6 individual VAR(1) specifications that each capture a separate type of intervention. With regard to the announcement of the TAF, it is shown that a compression of the U.S. spread by approximately 9 and 7 basis points at one and two lags, respectively, is achieved whereas the effect in the Euro area is negligible. Interestingly, the subsequent introduction of the TAF itself is ineffective with regard to reducing interbank money market stress, which indicates efficiency in that this new information has already been priced in.

	Euro Libor-OIS	U.S. Libor-OIS
Announcement of TAF (-1)	-0.7853 (0.0136)	-9.0718 (0.0000)
Announcement of TAF (-2)	1.2092 (0.0000)	-7.4878 (0.0000)
Date of TAF Auction (-1)	-2.5280 (0.160)	-2.9021 (0.375)
Date of TAF Auction (-2)	-1.7941 (0.1002)	0.1012 (0.9555)
Announcement of LTRO (-1)	-2.3818 (0.0076)	-6.5587 (0.0010)
Announcement of LTRO (-2)	1.9560 (0.000)	-1.0082 (0.2734)
Date of LTRO (-1)	0.8352 (0.2294)	-0.1321 (0.9398)
Date of LTRO (-2)	0.1080 (0.8877)	-1.5595 (0.2643)
Cut in Federal Funds Rate (-1)	-0.4549 (0.0669)	-7.5477 (0.0024)
Cut in Federal Funds Rate (-2)	-0.8624 (0.1265)	-4.4956 (0.0569)
Cut in Discount Rate (-1)	-1.1531 (0.3912)	-7.8338 (0.0035)
Cut in Discount Rate (-2)	-0.2328 (0.7522)	-3.5638 (0.0857)

Table 2: Bivariate VAR Model. Here TAF denotes Term Auction Facility by the Fed and LTRO the 90-day long term refinancing operation by the ECB. *P*-values are reported in parentheses. The announcement of the TAF and the LTRO are effective in the U.S. and to a limited extent in the Euro area. Their actual implementation has no impact on the reduction of interbank money market stress, indicating possible market efficiency. Cuts in both the Federal funds and the discount rates led to significant spread compression in the U.S. markets.

The announcement of the LTROs by the ECB has a statistically significant spread reducing effect in both markets at one lag, albeit only a small impact of 2 basis points in the Euro area compared to a 7 point reduction in the U.S.. As in the case of the TAF, the actual implementation is insignificant, further highlighting possible market efficiencies with regard to information arrival and processing. Finally, the impact of cuts in both the Federal funds and the discount rates are quantified. In this case the degree of spread compression in the U.S. money markets exceeds that in Europe substantially for both policy tools. Overall, while the announcement of the TAF by the Fed and the LTROs by the ECB have a statistically significant effects, the economic magnitudes are not very large compared to the sharp increase of the Libor spreads since the beginning of the subprime crisis. While central bank interventions have been helpful in bringing down the spreads, they have not been successful in arresting the still very high levels of Libor spreads, compared to the pre-crisis period, as well as the continuous hoarding of liquidity by financial institutions due to counterparty concerns.

Finally, we quantify the cumulative effect of central bank intervention on the interbank money markets. We use parameter estimates from Table 2 to construct impulse response functions for the change in the spreads following a shock to the binary intervention variable. More specifically, the forward iteration of (3) is constructed with and without interventions, whereby the difference in these measures is presented in Figure 6 for selected policies. The reported 95 percent confidence intervals are obtained using Monte Carlo simulations based on the asymptotic joint normality of the parameters of the VAR.

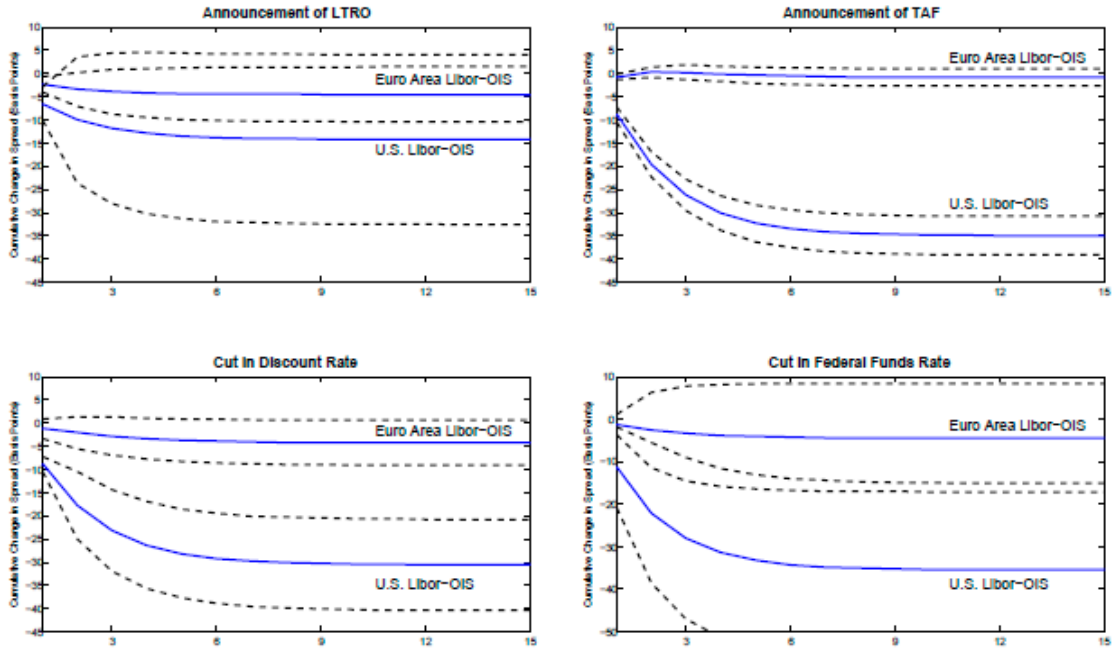

Figure 6: Impulse response functions, measured in changes in basis points on the left axis, quantify the cumulative effect of central bank intervention on the U.S. and Euro area Libor-OIS spreads. 95% confidence intervals are constructed using Monte Carlo simulations based on the asymptotic joint normality of the parameters of the VAR.

Following from a reparametrization of the results, provided in Table 2, we find that the dynamic impact of central bank intervention, as measured by the impulse response functions, is greater in the U.S. money market as compared to that in Europe. The forward iteration of (3) indicates that the announcement of the LTROs by the ECB caused a cumulative effect of a 15 basis point reduction in the former market in addition to a 5 basis point compression in the latter.

With regard to the announcement of the TAF, these quantities are 35 basis points and 1 basis point, respectively. The impulse response for the Euro area exhibits a slight hump whereby it is initially negative before turning positive and subsequently declining again. This shape can be explained by the sign change of the corresponding parameters in Table 2. Interestingly, the final decline arises due to the positive cross-correlation in the A matrix in (3) indicating that interdependency between money markets is important, which is an effect not modeled by Taylor and Williams (2008). Finally, as expected, cuts in the interest rates by the Fed have a greater effect in the U.S. than in Europe.

Concerning the interpretation of these results it should be noted though that despite the fact that in absolute value the reduction in the Euro area Libor-OIS spread is small, the policy interventions by the ECB can be seen as having been helpful in bringing down the spreads. During the crisis period used in this analysis, the mean spread level has been approximately 55 basis points such that the announcement of the LTRO facility reduced the money market stress by approximately 10 percent.

In this section it is shown that liquidity providing interventions by central banks achieved a compression of the Libor-OIS spreads. Alternatively, it can be argued that the volatility of such spreads is a further adequate proxy for interbank money markets stress as it captures the uncertainty with regard to future write downs, credit conditions and economic activity in general.

IV. BIVARIATE GARCH FRAMEWORK

To complement the descriptive and VAR analysis of the previous section, we estimate a series of GARCH models in which we explain the conditional variance of Libor-OIS spreads as a function of their own past realizations and a series of variables capturing extraordinary central bank operations.[14] To get a sense of the underlying dynamics, we first modeled the volatility of Euro and U.S. dollar term spreads using a univariate GARCH specifications focusing on intervention variables that were available to central banks when the crisis started (IMF, 2008). While these GARCH results for most of the ECB intervention variables were inconclusive, there appeared to be a statistically robust and significant volatility-reducing effect in the case of the ECB's supplementary LTRO. The Fed's interventions via additional repurchase agreements, in turn, appeared to have had a significantly negative

[14] Again, we focus on the overall Libor-OIS spreads rather than its liquidity and credit components.

contemporaneous effect on U.S. dollar spread levels and volatilities. The former, however, is largely offset by a rebound on the next day, and both effects are sensitive to the chosen lag structure.

As previously argued, while a univariate GARCH model provides a first useful step towards understanding the effect of central bank policies on conditional means and variances, it ignores the dynamic interaction between Libor fixings in Euros and U.S. dollars. To account for this, we estimate a bivariate GARCH model which evaluates the impact of the central banks' emergency response to liquidity stress by jointly modeling U.S. and Euro Libor spreads. As before, the ECB's LTRO and the Fed's TAF are included as explanatory variables and we also differentiate between the possible effect of the intervention announcement and the actual intervention date. The estimation is conducted for a sample spanning from July 1, 2007 to April 3, 2008.

More specifically, the bivariate BEKK GARCH (1,1) model, developed by Engle and Kroner (1995), is modified in order to include the intervention variables as exogenous regressors. This model thus allows us to capture the dynamic interactions between both the U.S. and Euro Libor spreads explicitly, as well as to quantify the effect of any particular intervention on the first two moments of the Libor spreads. Furthermore, by construction, the conditional covariance matrix is always positive definite, which overall makes the BEKK GARCH (1,1) model very tractable for our purposes. The mean equations are specified as

$$\begin{aligned} \Delta y_t^{EU} &= a_1 + b_1 \Delta y_{t-1}^{EU} + b_2 \Delta y_{t-1}^{US} + c_1 I_{t-1} + \varepsilon_{1,t} \\ \Delta y_t^{US} &= a_2 + b_3 \Delta y_{t-1}^{EU} + b_4 \Delta y_{t-1}^{US} + c_2 I_{t-1} + \varepsilon_{2,t} \end{aligned} \qquad (4)$$

where $\Delta y_t = (\Delta y_t^{EU}, \Delta y_t^{US})$ captures changes in the US and Euro 3-month Libor spreads, I_{t-1} denotes the intervention of the ECB or Fed (e.g. TAF or LTRO) and $\varepsilon_t = (\varepsilon_{1,t}, \varepsilon_{2,t})$ are the residuals with $\varepsilon_t | \Omega_{t-1} \sim N(0, H_t)$. The conditional covariance matrix H_t is given by

$$H_t = M + A\varepsilon_{t-1}\varepsilon_{t-1}' A' + BH_{t-1}B' + EI_{t-1} \qquad (5)$$

where M is a scalar and A, B as well as E are diagonal 2×2 matrices. In addition, the model is estimated with Bollerslev-Wooldridge robust standard errors.

Table 3 provides the findings for the effectiveness of central bank intervention on the conditional variance of the 3-months Euro and U.S. Libor-OIS spreads. Both the announcement and the implementation date of the TAF auction have some volatility reducing impact on the U.S. Libor at 2 lags. Furthermore, the volatility of the Euro Libor spread significantly declines following the announcement and implementation of the LTRO. The date of the TAF auction has also a significant impact on the conditional variance of the Euro

Libor spread but, as expected, magnitudes are lower than in the case of the U.S. Libor spread. Finally, the mean equations of the BEKK models show the same results as in the VAR specifications.

Overall, the results of the BEKK model are consistent with the findings from the Markov-Switching approach and the bivariate VAR but should be seen as rather indicative given some caveats. Firstly, the BEKK model employed here is not a structural model. Secondly, it does not account for alternative explanatory variables of the Libor-OIS spreads. Thirdly, some of the findings are not robust across different lags and the differing effects of policy announcement and its actual implementation are not as pronounced as in the VAR analysis.

Table 3. Impact of Central Bank Interventions on LIBOR-OIS Spreads

	Volatility of Euro Libor- OIS	Volatility of US Libor-OIS
Announcement of TAF (-1)	36.405	-18.572
	(0.317)	(0.551)
Announcement of TAF (-2)	33.889	-70.562
	(0.196)	(0.000)***
Date of TAF Auction (-1)	-5.632	-9.252
	(0.000)***	(0.709)
Date of TAF Auction (-2)	-1.566	-23.504
	(0.012)**	(0.000)***
Announcement of LTRO (-1)	-3.905	-2.791
	(0.000)***	(0.959)
Announcement of LTRO (-2)	-6.901	4.360
	(0.000)***	(0.417)
Date of LTRO (-1)	-1.440	12.107
	(0.501)	(0.418)
Date of LTRO (-2)	-10.800	-4.874
	(0.000)***	(0.348)

Source: Own calculations.

Note: The mode is computed using Bollershev- Wooldridge robust standard errors. *** indicates significance at the 1 percent level and **(*) indicates significance at the 5 (10) percent level. The sample is from July, 1, 2007 to April 3, 2008. OIS= overnight index swap; TAF= term auction facility; LTRO= long term refinancing operation.

V. Policy Implications and Conclusions

In summary this paper has provided some evidence that a range of central bank policies had an impact on the dynamics of stress in unsecured interbank markets during the subprime crisis, as measured by the spread between Libor and OIS rates. In this context, the supplementary long term refinancing operations by the ECB as well as the Term Auction Facility by the Fed have been helpful in compressing Libor spreads. But the economic magnitudes are not very large, which is supported by the fact that central banks' actions

during the first phase of the subprime crisis, while successful in helping to bring down Libor spreads, have not led to an end of the liquidity crisis and a containment of the solvency concerns looming at the time.

In addition to these extraordinary liquidity operations, policy rates have been reduced by central banks. Whilst these cuts have mainly been in response to changes in the macroeconomic outlook, financial stability considerations have also been taken into account. In the case of the Fed, the empirical results suggest that reductions in both the Federal funds and the discount rates appear to have had statistically significant effects on alleviating funding pressures.

Finally, further interventions were made by the Fed, such as the provision of guarantees during the rescue of Bear Stearns in March 2008 and the provision of discount window access to investment banks. Anecdotal evidence suggests that these policies directly affected the assessment by capital markets with regard to the probability of the failure of financial institutions. In the previous section this was discussed in the context of the decomposition of the Libor-OIS spreads into liquidity and credit related premia, whereby the latter substantially decreased following these events.

In quantifying the effectiveness of central bank intervention, we believe that there is scope for further research. More specifically, selection of the Markov switching models could be refined by making the transition probabilities a direct function of policy events. Furthermore, the decomposition would be improved by overcoming the restrictive assumptions used in this paper. Subsequently, it would also be of interest to conduct the inferential analysis separately on the liquidity and the credit component of the decomposed Libor-OIS spread. If, as hypothesized, it were the case that the credit premium is not influenced by these interventions, this would imply that the liquidity injections in the money markets have become less effective as the crisis unfolded, as the percentage of the Libor-OIS spread which is attributed to counterparty risk has increased.

In conclusion we discuss some policy implications, whereby focus is placed on the characteristics which the operational framework of these liquidity providing policies ought to exhibit, in addition to their potential limitations. In this context, the effectiveness of the LTROs and the TAF by the ECB and the Fed, respectively, is ensured by providing central bank funding against a broad pool of eligible collateral. This includes financial instruments which have either suffered declines in market prices due to illiquidity during the crisis period, or those which exhibit outright uncertainty with regard to their fundamental value. Accepting such collateral is and has always been a crucial feature of crisis management, and does not represent a fundamental departure from long-standing principles, such as those formulated by Bagehot (1873).

Furthermore, access to liquidity is provided to a broad range of potential counterparties. Examples of this are the increased eligibility of central bank facilities such as the refinancing operations by the ECB which allow access to over 500 financial institutions, as well as the TAF auction and the extension of the discount window facility in order to overcome the aforementioned distributional limitations due to the hoarding of funds by select brokers. In

response to increased demand for longer dated liquidity, central bank policies placed emphasis on providing funds at maturities ranging from one week to six months. Finally, differences between traditional liquidity provisions and arrangements such as the TAF and LTROs were made in that emergency funding was no longer provided on a discretional basis in the form of short term bridge financing, but rather within the scope of standard open market operations which were rolled over continuously.

It should be noted though that the design and implementation of these liquidity operations pose serious limitations and introduce the risk of commercial banks engaging in regulatory arbitrage. In this context the main issue is that of incentive compatibility and subsequent moral hazard. As noted by Goodhart (2007), financial institutions have taken out a protective put on central bank liquidity during the crisis period. The associated risks have been increasingly transferred to the public sector, whilst the upside in the form of the yield differential due to liquidity premia has been taken advantage of. This issue is of central importance as, due to externalities resulting from the fact that the banking system is a public good, ex post it is mostly optimal to rescue systemically important entities. In order to address these concerns it has been suggested that liquidity ought only be provided at a penal rate against good collateral. This latter consideration is essential in limiting the credit risk which is assumed by central banks, whilst also providing incentives for financial institutions to hold higher quality assets.

Furthermore, the construction of an optimal framework for liquidity management has to take recent structural changes within the banking sector explicitly into account. Whereas the Basel accords govern the adequacy of the capital holdings of financial institutions, no such arrangement exists for liquidity. Subsequently, the percentage of liquid assets held by British banks on their balance sheets has continuously declined from approximately 30 percent in 1950 to about 1 percent presently. This is of significance as the maturity mismatch inherent in the financial industry has simultaneously increased. Banks and their respective SIVs have become more reliant on wholesale money and the short term commercial paper markets in order to fund longer dated investments. This in turn has raised the risk of systemic funding illiquidity because, as seen in Figure 1, stress in these markets may become geographically correlated. As a response, policy makers have been challenged to determine the adequate degree of maturity mismatch and holding of liquid assets, such that banks have a reserve to meet their short-run funding commitments, whilst ensuring operational efficiency.

Finally, the optimal incidence of insuring against funding illiquidity between the public and private sectors is to be determined. Complete private coverage for such infrequent events may be inefficient as optimal risk sharing in the presence of incomplete markets is unobtainable, in addition to the costs associated with self insurance by holding large amounts of liquid assets being high. At the same time, incentives are to be provided such that the public sector acting as lender of last resort to the financial industry during periods of illiquidity does not make the occurrence of such events more likely. Exactly how these measures are to be combined within the operational framework by central banks and in the regulatory oversight of liquidity management is still a question for further research.

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