North American Journal of Economics and Finance 28 (2014) 242–264

Contents lists available at ScienceDirect

North American Journal of Economics and Finance

Interest rate risk propagation: Evidence from the credit crunch

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ARTICLE INFO

JEL classification:
G01
G15
G21

Keywords:
Risk contagion
CoVaR
Liquidity risk
Credit risk
Financial crisis

ABSTRACT

During the 2007–2009 financial crisis, US subprime mortgage risk exposures led to severe liquidity problems in several other foreign markets. Such risk contagion was caused by enormous changes in interest rates. Although risk contagion has been investigated by several literatures, the magnitude of propagated interest rate risk around global financial markets remains unexplored. Therefore, this study quantifies the degree to which the increased credit risk within the US financial system propagated to the European markets' liquidity risks. Specifically, using a conditional value-at-risk (CoVaR) model, we quantitatively measure interest rate risk of a European country, by looking at the upside risk in distribution of changes in interest rate. And such propagation risk measure considers additional value-at-risk conditional on the interest rate movements in the US. The results show significantly positive differences between European country's value-at-risk conditional on the US financial markets being in a normal or distressed state. This propagating effect increased from 2007, and was particularly pronounced in the 2008–2009. In addition, the interest rate risk contagion is especially severe for some countries in the Euro regions with greater sovereign debt problems. Hence our result foretells the deterioration of the European sovereign debt crisis which started

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http://dx.doi.org/10.1016/j.najef.2014.03.010
1062-9408/

to unfold in 2010. Our work supplements the literature by successfully quantifying the magnitude of additional interest rate risk conditional on risk exposure from external sectors.

1. Introduction

In this paper, we posit that the interest rate risk contagion is the channel through which the credit risk in the US caused the European country illiquidity problems during the 2007–2009 credit crunch. The more illiquid financial institutions in the banking industry are, the larger the impact will be on risk contagion from an increase in interest rate, and such close linkages caused interest rate risk contagion (e.g., Brunnermeier & Pedersen, 2009). Therefore, banks suffering interbank credit risk threats are exposed to illiquidity, and such a contagion of systemic risk leads to subsequent bankruptcies (see e.g., Billio, Gatemansky, Lo, & Pelizzon, 2010; Diamond & Rajan, 2005; Enenajor, Sebastian, & Witmer, 2012; McAndrews, Sarkar, & Wang, 2009; Pais & Stork, 2011; Sarkar, 2009). Besides the risk contagion among institutions, the increased interest rate can also exacerbate international liquidity shortages, and the vicious circle makes interest rate risk more severe around different countries. Thus, from the risk contagion in country level, we quantify the degree to which the credit risk in one country spread to other countries by an increase in interest rate and result in liquidity problems.

The risk exposures from US credit losses quickly spread and exacerbated to the global financial market during the 2007–2009 credit crunch, and banks' insolvencies also spread rapidly to other countries by way of an increase in interest rates. The domino effect of interest rate risk propagation in the interbank market led to bank insolvency and liquidity risks in many European markets (e.g., Reinhart & Rogoff, 2009; Upper & Worms, 2004) and the 2007–2009 credit crunch (e.g., Melvin & Taylor, 2009; Longstaff, 2010). The facts of interest rate risk contagion are consistent with Diamond and Rajan (2005) that the contagion of interest rate risk problems occurs all the time, even when sectors share no explicit connection.

Although prior literature has investigated risk contagion across stock markets, carry-trade markets, real estate sectors, or foreign exchange markets. Similarly, risk contagion due to counterparty relationships, macroeconomic risk, or financial linkages has been fully investigated (e.g., Changa, McAleerc, & Tansuchat, 2013; Forbes & Rigobon, 2002; Mandilaras & Bird, 2007; Pais & Stork, 2011; Pritsker, 2001). However, less attention has been paid to interest rate risk and bank liquidity, and the magnitude of propagated interest rate risk around global financial markets remains unexplored.

During the 2007–2009 credit crunch, idiosyncratic credit problems originating from the US subprime mortgage market spread rapidly to other countries through the channels of changes in interest rate (e.g., Reinhart & Rogoff, 2009; Tang & Yan, 2010) because liquidity problems correspond to counterparty risk (e.g., Brunnermeier & Pedersen, 2009; Melvin & Taylor, 2009). Interest rate spread—that is, the difference between lending and riskless rates—therefore provides a key transmission channel for interest rate risk propagation, particularly for economic shocks (e.g., Edwards, 1998) and can be taken as a leading indicator of default risk (e.g., Bernanke, 1990; Friedman & Kuttner, 1993; Gertler, Hubbard, & Kashyap, 1991; Tang and Yan, 2010). In this study, we use a modified CoVaR measure to explore the degree to which the increased credit risk within the US financial system during the 2007–2009 credit crunch propagated the European markets' liquidity risks, which were caused by an increase in interest rates. We expect to see that the interest rate risk contagion is particularly severe in several specific illiquid Euro regions and during the financial crisis.

Conventional value-at-risk (VaR) models are incapable of effectively addressing the contagion effect because they do not reveal how the risk faced by one country influences the one faced in other countries. Therefore, we look at the upside risk in distribution of changes in interest rate and convert the unconditional VaR model to a CoVaR model, which allows us to capture the additional contagion interest rate risk by setting reasonable conditional factors (e.g., Adrian & Brunnermeier, 2011; Cakici & Foster, 2003). Specifically, we link the interest rate risk contagion to both the liquidity risk in Europe and the credit risk of the US financial system by modeling the CoVaR.

The benefit of CoVaR model is that it can estimate not only the sector's own risk but also risk propagation beyond the interdependence (e.g., Adrian & Brunnermeier, 2011). In addition, the CoVaR model uses a quantile regression without distributional assumption and allows for a large range of possible quantiles for risk preferences. We, therefore, explore country-level interest rate risk contagion by measuring the magnitude of the additional liquidity risk burden to European countries that spread from the US credit market during both a noncrisis (2003–2006) and crisis (2007–2009) periods. The changes in the interbank offered rate (IBOR) are used to proxy the liquidity risk in Europe, and the difference between Treasury Eurodollar (TED) spread—the difference between interest rates on interbank loans and short-term US government debt—is used to proxy the credit risk of the US financial system.

After controlling potential problems of heteroskedasticity and endogeneity by using fitted European liquidity risks, the results show significantly positive differences between European country's VaR conditional on the US financial markets being in a normal or distressed state. The interest rate risk propagating effect increases since 2007 and is particularly significant in 2008 and 2009 when liquidity problems are most severe. Our evidence reveals that the CoVaR model can successfully capture European markets' liquidity risk conditional on the credit risk of US financial system, particularly during the crisis. We also find that liquidity risks are particularly larger in several Euro regions with smaller economic scale (Switzerland, Austria, Belgium, Finland, and Netherlands) or sever sovereign debt problems (Portugal, Ireland, and Greece).

The empirical results suggest that when calculating interest rate VaR, financial sectors should focus not only on their own liquidity problems but also on the additional risk propagated from the US. Our application of the CoVaR model for measuring interest rate risk contagion contributes to the literature in the following ways. First, we show that the magnitude of interest rate risk contagion can be quantitatively measured. Although past studies use different methods to examine whether the propagation relationship between different sectors is significant, they do not measure the actual magnitude of risk contagion. Our study, in contrast, resolves the research question of quantification of the magnitude of interest rate risk propagation.

Second, we complement the literature by providing empirical evidence to support prior theoretical views that credit insolvency in one country exacerbates other countries' liquidity risks (e.g., Diamond & Rajan, 2005; Pais & Stork, 2011; Zheng & Zuo, 2013). Application of CoVaR in interest rate risk propagation provides persuasive evidence that financial institutions should evaluate not only their own liquidity risk but also the credit spillover from other sectors. Finally, our study uses all available global data to identify the current contagion risk. Most prior empirical studies address only the existence of the risk contagion phenomenon, while our results measure the severity of risk contagion. Therefore, financial institutions can adopt our model and use all available data for ex ante analysis to evaluate current interest rate risk contagion to understand whether their capital and financial status can prevent any further crisis threats.

The remainder of the study is organized as follows. Section 2 develops the CoVaR model to capture the contagion of interest rate risk and introduces the data. Section 3 provides our empirical results, and Section 4 offers our concluding remarks.

2. Risk contagion modeling

2.1. Interest rate risk contagion

The important role of banking liquidity and its determinants had been raised from the credit crunch. Exposure to market uncertainties and economic shocks within financial institutions are main causes to disrupt the balance between liquidity supply and demand in the banking system and exacerbates funding problems. As some financial institutions increasingly finance their asset holdings and investments with shorter maturity instruments, liquidity problems become more severe in the whole financial system (e.g., Brunnermeier & Pedersen, 2009; Pais & Stork, 2011; Upper & Worms, 2004). Moreover, during the 2007–2009 credit crunch, US subprime mortgage risk exposures led to severe liquidity problems in several other foreign markets, caused by the enormous change in interbank interest rates (e.g., Melvin & Taylor, 2009). In addition, Diamond and Rajan (2005) and Brunnermeier and Pedersen

(2009) indicate that because financial institutions have very large amounts of trades across various counterparties, credit risk spreads to other financial sectors and causes severe liquidity problems. Therefore, the liquidity problem is caused not only by the local interbank funding problems, but also by the credit risk propagated from external sectors.

The liquidity problems caused from external credit risk contagion are through the interbank linkages and changes in interest rate. Firstly, regarding to the interbank linkages, Longstaff (2010) suggests that an economic shock and the subsequent crisis leads financial assets to be transferred to other sectors, which is consistent with Diamond and Rajan (2005), Brunnermeier, Nagel, and Pedersen (2008), and Pais and Stork (2011) that banks' liquidity problems are closely linked with systemic risk. Also, Diamond and Rajan (2005) address that when one sector's assets become illiquid; its corresponding counterparties also face similar liquidity problems. Thus, the interbank linkages cause banking illiquidity and can trigger a global financial crisis.

Secondly, the interest rate risk propagates rapidly from one country to another even if the two are not explicated connected (e.g., Diamond & Rajan, 2005; Longstaff, 2010). Literatures suggest that the main reason for risk contagion is excessive risk exposures and interbank linkages (e.g., Elsinger, Lehar, & Summer, 2006; Furfine, 2003; Johansson, 2009; Pais & Stork, 2011; Upper & Worms, 2004). In addition to the direct linkages, other mechanisms also allow risk to transfer to different counterparties. For example, Smith (1991) and Allen and Gale (2000) find that interest-rate risk propagation is more severe in banks with higher interbank loans. Although price comovement and cross-market interdependence have been fully explored (e.g., Dungey & Martin, 2007; Forbes & Rigobon, 2002; Pais & Stork, 2011; Pritsker, 2001), studies on interest-rate risk propagation in financial markets are rare. In this paper, we posit that the change in interest rate use the propagation mechanisms through which the credit risk in one country spreads efficiently to other financial market liquidity.

Since the spillover relation between the credit market and liquidity is through a channel of changes in interest rate, the interest rate spread can be used to capture this contagion phenomenon (e.g., Adrian & Shin, 2010; Borio & Zhu, 2012; Brunnermeier & Pedersen, 2009; Fong, Valente, & Fung, 2010; Gorton & Metrick, 2012). The Treasury Eurodollar (TED) spread is a measure of credit risk caused by enterprise distresses in financial market (e.g., Chan-Lau, 2010). When credit risk is more severe in the US, the TED spread increases, and bank runs cause financial institutions to turn from risky portfolios toward less risky investments (e.g., Brunnermeier et al., 2008). Therefore, for measuring the US credit market in this research, we adopt the changes in the TED spread, the difference between the yield of the three-month IBOR and the three-month Treasury bill rate, as the credit risk. As ΔTED_t, the difference in TED spread between time t and time $t-1$, increases, the cost of capital risk also increases (e.g., Billio et al., 2010; Diamond & Rajan, 2005; Sarkar, 2009).

Because the changes in the interbank offered rate (IBOR) can be regarded as the upside of risk exposure to liquidity risk (e.g., Melvin & Taylor, 2009; Chan-Lau, 2010; Delis & Kouretas, 2011; Wong & Fong, 2011), the IBOR is taken as opportunity cost of capital transfer between financial institutions and investors (e.g., Hull, 2009). Because a bank needs to satisfy certain creditworthiness criteria to quote an IBOR, such a rate is regarded as an index for illiquid funding market. We, therefore, take the change in the IBOR at time t ($\Delta IBOR_t$), the difference in one-month IBOR between time t and time $t-1$, as each European country's liquidity risk. A higher $\Delta IBOR_t$ is an indication of a decreased willingness to lend by major banks, while a lower $\Delta IBOR_t$ means higher liquidity in the market. As such, by using ΔTED_t as an indication of the banks' creditworthiness of financial market and $\Delta IBOR_t$ as a general availability of liquid funds for banking lending activities, larger interest rate spreads indicate an increase in interbank illiquidity and interest rate risk contagion.

2.2. CoVaR model

The extant literature proposes various measuring approaches for studying the channels and causes of risk contagion, but distribution assumptions and modeling limitations constrain some of the traditional approaches. VaR models, for example, only provide their own minimum loss if a tail event takes place. Such models do not reveal the potential loss caused by risk propagated from other sectors. The error terms of the dynamic correlation or autoregressive conditional heteroscedasticity models need to be assumed to have a specific distribution, which leads to a bias toward the coefficients' estimations. Also, the logit and probit models only fit discrete or limited dependent variables. Besides, the extreme value methodology may ignore the information content of a large portion of a data sample, and the risk measure could be underestimated (e.g., Wong & Fong, 2011). In addition to the distribution presumptions and modeling limitations, another concern is time lag.

Different from prior approaches for estimating risk contagion effects in financial markets, some studies examined the contagion effect by measuring the distance to default and then comparing the default rate among different banks. However, the expected default frequency model needs to be assumed a static debt structure, although the value of a firm's assets changed (e.g., Saunders & Allen, 2002). Therefore, these default-based models cannot capture the ex-ante risk contagion effect. Thus, we propose an alternative approach without limitations to measure the contagion risk.

To construct a contagion risk model in which ex-ante risk propagation can be quantitatively measured without distribution limitations, we modify the CoVaR model proposed by Adrian and Brunnermeier (2011). Specifically, we emphasize the additional liquidity risks caused by risk propagated from external credit market. Such interest rate risk contagion effect conditional on external sectors' risk can be estimated by using quantile regression of changes in IBOR on the changes in TED spread. This approach is particularly useful for considering different risk preference and varied percentiles free from distribution assumptions.

For measuring systemic risk, the $\Delta CoVaR$ measurement proposed by Adrian and Brunnermeier (2011) is defined as the difference between VaR conditional on the institution being in a normal state and VaR conditional on the institution being in distress. During the 2007–2009 global financial crisis, the US economy faced severe credit risk, causing US financial sectors to come under stress; in contrast, during a normal time period, the US financial system is liquid, and changes in interbank interest rate reflect normal variation of credit risk. It is expected to see that during crisis periods, the value of $\Delta CoVaR$ is higher compared to the one in normal time period. Therefore, the $\Delta CoVaR$ value can be used to identify the risk spillover effects and additional risks faced by an institution caused by interconnected and systemically significant institutions. In addition, it can be specifically taken as an index to capture the too-interconnected-to-fail phenomenon. In the following, the modeling for the $\Delta CoVaR$ value will be specifically introduced.

For downside risk, unconditional VaR of institution i at the q percentile is defined as

$$Pr(X^i \leq VaR_q^i) = q. \tag{1}$$

The VaR of institution, ${VaR^i}_q$, typically a negative number, is determined by the asset return value of institution i (X^i) and quantile q. Beyond conventional unconditional VaR, we extend to a conditional VaR, which is the VaR of institution j conditional on institution i's event $\mathbb{C}(X^i)$, say distress or illiquidity. When institution i's asset—return attains its VaR value $\{X^i = {VaR_q}^i\}$:

$$Pr(X^j \leq CoVaR_q^{j|\mathbb{C}(X^i)} | \mathbb{C}(X^i)) = q. \tag{2}$$

Furthermore, institution i's contribution to the risk of institution j can be defined as

$$\Delta CoVaR_q^{j|i} = CoVaR_q^{j|X^i=VaR_q^i} - CoVaR_q^{j|X^i=Median^i}, \tag{3}$$

where $CoVaR_q^{j|X^i=Median^i}$ denotes the VaR of institution j's asset returns when institution i's returns are at its normal state of their distribution (e.g. 50% percentile), and $CoVaR_q^{j|X^i=VaR_q^i}$ is institution j's VaR when institution i's returns are at a distressed or extremely poor state such as during a crisis period. Moreover, $\Delta CoVaR_q^{j|i}$ indicates the difference between VaR of institution j conditional on the distress of another institution i and VaR of institution j conditional on the normal state of institution i. Such CoVaR quantifies how much an institution adds to another institution's risk.

The variation in asset return value of institution i (X^i) is estimated as a function of state variables:

$$X_t^i = \alpha^i + \mathbf{M}_{t-1}^i \gamma^i + \varepsilon_t^i \tag{4}$$

where **M** denotes a vector of state variables. Also, to capture VaR of institution j conditional on another institution i, the variation in asset return X^j can also be estimated by including the institution i's asset return variation (X^i):

$$X_t^j = \alpha^{j|i} + \beta^{j|i} X_t^i + \mathbf{M}_{t-1}\gamma^{j|i} + \varepsilon_t^{j|i}, \tag{5}$$

The estimation runs the quantile regression by optimizing a modified function:

$$\min_{\alpha_q,\beta_q,\gamma_q} \sum_t \begin{cases} q|X_t^j - \alpha_q^{j|i} - \beta_q^{j|i} X_t^i - \mathbf{M}_{t-1}\gamma_q^{j|i}| & \text{if } (X_t^j - \alpha_q^{j|i} - \beta_q^{j|i} X_t^i - \mathbf{M}_{t-1}\gamma_q^{j|i}) \geq 0 \\ (1-q)|X_t^j - \alpha_q^{j|i} - \beta_q^{j|i} X_t^i - \mathbf{M}_{t-1}\gamma_q^{j|i}| & \text{if } (X_t^j - \alpha_q^{j|i} - \beta_q^{j|i} X_t^i - \mathbf{M}_{t-1}\gamma_q^{j|i}) < 0 \end{cases} \tag{6}$$

Throughout the study, we estimate the percentiles $q = 99\%$ and 95% cases as most of the literatures suggest. With the estimated quantile regression parameters, predicted values of CoVaR are

$$CoVaR_t^{j|i}(q) = CoVaR_q^{j|X^i = VaR_q^i} = \hat{\alpha}^{j|i} + \hat{\beta}^{j|i} VaR_t^i(q) + \mathbf{M}_{t-1}\hat{\gamma}^{j|i}. \tag{7}$$

Such predicted CoVaR value indicates underlying company j's value of risk propagated from institution i. Finally, the $\Delta CoVaR$ for each institution can be further calculated:

$$\Delta CoVaR_t^{j|i}(q) = CoVaR_t^{j|i}(q) - CoVaR_t^{j|i}(50\%) = \hat{\beta}^{j|i}[VaR_t^i(q) - VaR_t^i(50\%)]. \tag{8}$$

$\Delta CoVaR$ value can be taken as the difference between VaR, conditional on the institution being in a normal state, $CoVaR_t^j(50\%)$ and VaR conditional on the institution being in distress, $CoVaR_t^j(q)$. It can also be taken as the additional VaR caused from outside influences, which is above the ordinary interdependences.

Different from past literatures focusing on institution or company levels, we focus on cases in which i and j are at the level of different countries to measure the quantity of interest rate risk contagions among countries because during a financial crisis, portfolio returns of all financial institutions are at their VaR level. We next address the modified CoVaR model to measure the interest rate risk contagion. Because the credit risk faced by financial institutions is more severe when the interest rate increases, the interest rate risk concerns the increase of interest rate changes. Therefore, the VaR of interest rate focuses on the upside risk of the distribution of changes in interest rate. Following Cakici and Foster (2003), we consider the upside risk of changes in country i's interest rate by modifying the conventional VaR model as

$$Pr(IR^i \geq VaR_q^i) = q, \tag{9}$$

where IR^i is the changes in interest rate of country i, and VaR_q^i is its VaR at the qth percentile, indicating the market has qth percentage of confidence that the changes in interest rate will not exceed IR^i.

We further modify the CoVaR model of Adrian and Brunnermeier, (2011) to denote European country j's interest rate VaR conditional on the risk spillover from the US credit market in distress. The quantile regression is adopted by which the unconditional VaR can be efficiently transformed as conditional VaR under any prespecified preferred percentile:

$$Pr(IR^j \geq CoVaR_q^{j|\text{US}} | IR^{\text{US}} = VaR_q^{\text{US}}) = q. \tag{10}$$

The predicted value from the quantile regression can be taken as the VaR of European country j conditional on the VaR of the US. Within the quantile regression framework, our CoVaR can be now formally specified as

$$CoVaR_t^{j|\text{US}}(q) = VaR_{q,t}^j | VaR_{q,t}^{\text{US}} = \hat{\alpha}^{j|\text{US}} + \hat{\beta}^{j|\text{US}} VaR_t^{\text{US}}(q) + \mathbf{M}_{t-1}\hat{\gamma}^{j|\text{US}}, \tag{11}$$

where $\mathbf{M}_{t-1}$ is a vector of state variables made up of global risk instruments at time $t-1$. In this study, we include several country level state variables for controlling other potential determinants in the US, such as changes in European country j's interbank offered rate at time $t-1$ ($\Delta IBOR_{t-1}$), returns of West Texas Intermediate crude oil at time $t-1$ (Oil_{t-1}), and returns of Chicago Board Options Exchange gold price index at time $t-1$ ($Gold_{t-1}$).

Because the interest rate risk contagion explored in our study is the spillover from the US to European countries, we estimate $\hat{\alpha}$, $\hat{\beta}$, and $\hat{\gamma}$ in Model (11) in a quantile regression by replacing interest rate in country *i* (IR^{US}) with changes in the TED spread (ΔTED). Also, the interest rate in country *j* (IR^{j}) in Model (11) is replaced with changes in the European country *j*'s interest rate spread measured by their interbank offered rate ($\Delta IBOR$).

Because endogeneity can potentially result in inconsistent results (e.g., Forbes & Rigobon, 2002), we include instruments to fit the changes in interest rates. Firstly, we use the returns of the underlying country's stock index and its implied volatility index as instruments to determine the changes in interest rate because the 2007–2009 credit crunch was accompanied by significant increases in the implied volatility index. In addition, foreign exchange exposures were one of the factors burdening banks during the 2007–2009 shock (e.g., Elsinger et al., 2006; Melvin & Taylor, 2009). We, therefore, include the underlying country's foreign exchange rate (taken as US dollars to the country *i*'s currency) as another instrument. Following Tang and Yan (2010), we reduce potential endogeneity problem by using the above instruments to measure the fitted the changes in interest rates, ΔTED and $\Delta IBOR$.

Using the daily data, the conditional event where an increase in ΔTED spread attains the VaR value $\{\Delta IBOR^{j} \geq CoVaR_q^{j|US} | \Delta TED^{US} = VaR_q^{US}\}$ can be further specified by

$$CoVaR_t^{j|US}(q) = VaR_{q,t}^{j} | VaR_{q,t}^{US} = \hat{\alpha}^{j|US} + \hat{\beta}^{j|US} VaR_t^{US}(q) + \mathbf{M}_{t-1}\hat{\gamma}^{j|US} \quad (12)$$

where the coefficients are estimated by all of the daily data in sample periods (2003–2009). After estimating the coefficients of Model (12), the variable $VaR_t^{US}(q)$ is then replaced with ΔTED_t^{US} to have fitted $CoVaR_t^{j|US}(q)$ in Model (11). The $\Delta CoVaR$ value can be further measured by the difference between an underlying European country *j*'s interest rate upside VaR conditional on the US credit market being in a normal state, $CoVaR_t^{j|US}(50\%)$, and VaR conditional on the US credit market being in distress, $CoVaR_t^{j|US}(q)$, $q = 99\%$ or 95%.

$$\Delta CoVaR = CoVaR_t^{j|US}(q) - CoVaR_t^{j|US}(50\%). \quad (13)$$

This $\Delta CoVaR$ measure can therefore successfully addresses the magnitude of additional European country *j*'s liquidity risk conditional on credit risk exposure from the US.

Besides the fact that interest rate risk contagions are prevalent among global money markets, the contagion risks vary daily, and such variations are dependent on the credit quality of risk propagation sources. The US credit risk affects European country's liquidity risk, and the changes in this European country's risk vary with the state of the US economy. Although the financial markets may consider their own everyday interest rate risk, the capital reserves for the contagion risk may not be sufficient to satisfy the needs for the variation in risk contagion. Therefore, risk management should reflect any changes in states from the interest rate risk sources. The economic inference of the $\Delta CoVaR$ value indicates the percentage change in interest rate risk conditional on another financial market, which is the additional interest rate risk change that the European money markets face when credit risks in the US shift from a normal state toward a more severely risky state. Therefore, increases in $\Delta CoVaR$ can be taken as additional liquidity risk incurred by the money market when it faces another institution's credit problem.

The explanation of the $\Delta CoVaR$ value is that many countries are burdened with additional VaR propagated from external financial markets, and the value of $\Delta CoVaR$ here is the difference between VaR conditional on the US financial markets being in a normal state and VaR conditional on the US system being in distress. If the US financial market is under stress, credit risks in the US financial system are severe and systemic risks are propagated to international money markets. Such a phenomenon causes European money markets to face higher liquidity risk, leading to further severe changes in interest rates. As such, the risk contagion makes the $\Delta CoVaR$ higher because the difference between VaR conditional on the US in a normal state and VaR conditional on the US in distress becomes larger.

2.3. Preliminary analyses

To capture the interest rate risk contagion, the European country's liquidity risk should reflect the variation in US credit risk. Fig. 1 shows the trends of the London IBOR (LIBOR), US Treasury bill rate

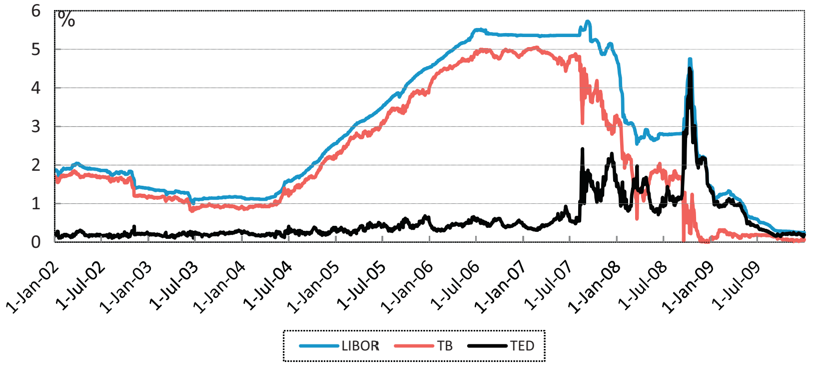

Fig. 1. The London interbank offered rate (LIBOR), Treasury bill rate (TB), and the US Treasury Eurodollar (TED) spread.

(TBR), and the TED spread in which the differences between the LIBOR and the TBR are larger when the TED spread increases. The TED spread increased dramatically after August 2007, and the LIBOR-TBR difference becomes larger. The credit crunch started at that time, causing further risk contagion around the world. The crisis was most severe in September 2008 when the TED spread reached its highest and the LIBOR-TBR difference was the largest. These relations suggest that the interest rate spread can reflect the change in credit risk of the US financial market. Therefore, the European country's $\Delta IBOR$ and the US ΔTED could be further taken as proxy of liquidity risk and credit risk, respectively.

The $\Delta CoVaR$ model is particularly useful for capturing the contagion risk among different financial sectors (e.g., Adrian & Brunnermeier, 2011). During the 2007–2009 credit crunch, systemic risk caused many US financial institutions to go bankrupt. The US financial markets were faced with larger credit risks that were propagated to other countries. The most significant occurrence of liquidity problems was the risk contagion from the US to European money markets. We therefore adopt the $\Delta CoVaR$ model to measure such interest rate risk contagion. When the US financial markets came into distress, European country j's $CoVaR$ during the financial crisis, $CoVaR_t^j(q)$, is larger than during ordinary times, $CoVaR_t^j(50\%)$, and the $\Delta CoVaR$ value is significantly larger than zero. Thus, we expect that the $\Delta CoVaR$ value during the 2007–2009 financial crisis will be significantly larger than the $\Delta CoVaR$ before the credit crunch. Table 1 provides the variable summaries and correlation coefficients.

Table 1, Panel B shows that the Pearson coefficients of correlation between European IBOR and US TED are positive and larger from 2003–2006 to 2007–2009, suggesting that the linkages between US credit market and European money market are increasingly crucial during the crisis periods. In addition, the higher the correlation coefficients are, the more often that European country's interest rate risk is affected by the US credit market. However, because the correlation coefficients are incapable of describing the exact contagion phenomenon, we use the IBOR and TED data and the CoVaR model to measure the risk contagion, the results of which are described in the following discussion.

3. Empirical analyses

3.1. Main findings

We explore the degree to which Europe's liquidity risks were caused by propagation of the credit risk in US financial system during the 2007–2009 credit crunch using a CoVaR model in which credit risk and liquidity risk are estimated by the difference in TED spread and the difference between the IBOR, respectively. Fig. 2A shows the US TED and the interbank offer rates in the largest European countries (the United Kingdom, Germany, and France). Fig. 2B, in contrast, indicates the same for European countries with most severe liquidity problems (Portugal, Ireland, Italy, Greece, and Spain). Fig. 2C shows the changes in IBOR of other European countries. The three panels show that the trends of European IBORs are similar.

Table 1
Summary statistics.

	European interbank offered rate (IBOR)													US Treasury Eurodollar (TED)
	UK	Germany	France	Swiss	Austria	Belgium	Finland	Netherlands	Portugal	Ireland	Italy	Greece	Spain	
Panel A: Descriptive summaries														
Mean	4.210	2.614	2.765	1.147	2.764	2.803	2.803	2.773	2.765	2.636	2.615	2.776	2.757	0.575
Median	4.594	2.580	2.630	0.750	2.633	2.670	2.670	2.630	2.633	2.580	2.579	2.640	2.630	0.360
Max	6.750	4.450	5.200	4.620	5.197	5.269	5.270	5.190	5.197	4.421	4.363	5.200	5.250	4.510
Min	0.500	0.240	0.420	0.156	0.422	0.428	0.430	0.320	0.422	0.299	0.250	0.420	0.370	0.103
Std. Dev.	1.479	1.070	1.109	0.851	1.109	1.124	1.125	1.106	1.110	1.056	1.070	1.109	1.088	0.576
Skewness	−1.225	−0.438	−0.120	0.665	−0.121	−0.121	−0.120	−0.150	−0.122	−0.386	−0.449	−0.140	−0.082	2.557
Kurtosis	3.974	2.656	2.467	2.251	2.467	2.467	2.465	2.509	2.463	2.577	2.650	2.462	2.558	11.517
Obs.	1724	1724	1724	1724	1724	1724	1724	1724	1724	1724	1724	1724	1724	1724
Panel B: Correlation coefficients between IBOR and TED														
2003–2006	0.628	0.421	0.478	0.784	0.478	0.478	0.478	0.484	0.478	0.431	0.424	0.458	0.448	
2007–2009	0.465	0.452	0.564	0.520	0.564	0.564	0.564	0.569	0.564	0.465	0.452	0.564	0.600	
2003–2009	0.304	0.392	0.534	0.642	0.534	0.534	0.534	0.538	0.533	0.413	0.393	0.527	0.555	

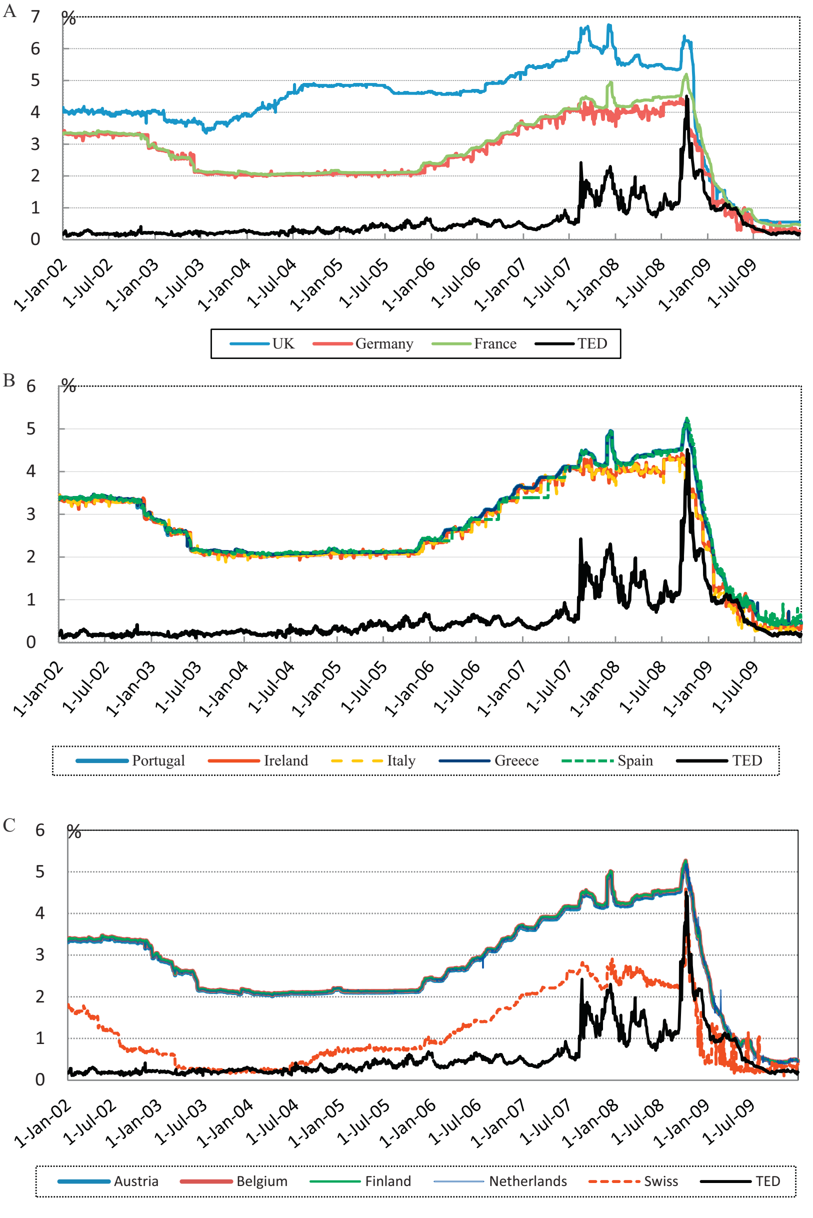

Fig. 2. (A) The US Treasury Eurodollar (TED) spread and the interbank offered rate (IBOR) for the largest European countries (United Kingdom, Germany, and France). (B) US TED spread and the IBOR for the European countries with most severe liquidity problems (Portugal, Ireland, Italy, Greece, and Spain). (C) US TED Spread and IBOR for the other European countries (Austria, Belgium, Finland, the Netherlands, and Switzerland).

During the years of financial crisis, interest rate changes peak several times. The first peak is in August 2007. The American Home Mortgage Investment Corporation filed Chapter 11 bankruptcy on August 6. In addition, the Mortgage Guaranty Insurance Corporation announced discontinuation of cooperation with the Radian Group on August 8, and the next day, August 9, the French investment bank BNP Paribas stop trading in subprime mortgage debt funds due to liquidity problems. Therefore, we suggest that the interest rate risk contagion effect of the subprime crisis propagated rapidly from the United States to European countries in August 2007.

The second peak of interest rate changes is at the end of 2007. On November 1, the Federal Reserve provided more than US$41 billion for financial institutions, indicating that the US financial system at that time faced severe liquidity problems. However, outside investors and international institutions cannot identify whether the counterparties with whom they were dealing were in distress. If the financial institutions are under stress, their investors and loan borrowers would run on their banks. Therefore, the Financial Accounting Standards Board's standards on Fair Value Measurements required financial sectors to provide greater transparency of information, further protecting the investors' rights.

The third peak is not seriously significant in European countries compared to the first two peaks as the individual company event was reflected in stock and money markets. Although Bear Sterns was provided with funding by the Federal Reserve on March 14, 2008, it was acquired by JP Morgan Chase for $2 a share on March 16, with the Federal Reserve backing the acquisition. One month later, Bear Sterns announced the reduction of operating cost by laying off more than 5000 employees.

The forth peak was the worst: On September 7, 2008, the US federal government took over Fannie Mae and Freddie Mac, and the US house mortgage market collapsed. The takeover caused severe panic, and the liquidity pressure rapidly spread to other countries. In addition, the risk contagion caused increased pressure and mistrust among financial institutions, further increasing IBORs. The Bank of America acquired Merrill Lynch on September 14, and the next day Lehman Brothers filed bankruptcy. The crunch was not over until the US Federal Reserve provided more than US$85 billion funding to the American International Group on September 17. The subsequent bankruptcies and bank runs caused significant liquidity problems, and the credit crunch further exacerbated interest rate risk contagion. During the week of October 6–10, 2008, the US stock market faced severe losses. The representatives of central bank and finance ministers of the G7 agreed to cooperate in dealing with the liquidity problems. However, the details of the financial supports were not specifically provided at that time, causing further money market uncertainties.

The four peaks of interest rate in the European countries' IBOR and the US TED spread are due to the same source of risk: the US financial market credit risk. Therefore, we expect to find a positive relation between the interest rate risk contagions from the US to these European countries. We first adopt percentile $q = 99\%$ quantile regressions to estimate the coefficients of changes in a European country's IBOR on the changes in the US TED spread. Table 2 shows that the relations between European IBOR changes and the US TED spread differences are positive. This result indicates that the credit risk of the US financial system determine the liquidity risks in Europe and suggest that the interest rate risk contagion from the US to the European markets is crucially significant. After examining the interest rate contagion effect, we next use the estimates to measure the European money market liquidity risk conditional on the credit risk of the US financial system.

After estimating the coefficients from the quantile regression, we take the realized value of the changes in European country *j*'s ΔIBOR and the US TED spread to fit the dependent variables. The resulting fitted value can be taken as the interest rate VaR of a European country *j* conditional on the credit risk at US financial system (CoVaR). This CoVaR value captures not only the interest rate risk in the European country *j* but also the additional risk propagated from the US credit market.

Although the systemic beta $\beta^{j|US}$ in Model (12) can be taken as the degree to which European country *j*'s liquidity risk is affected by the US credit risk, such coefficient only provides the overall sensitivity of the two interest rate changes, and the quantified magnitude of the risk contagion can only be specifically addressed by the $\Delta CoVaR$ value. The higher the value of the systemic beta $\beta^{j|US}$, the greater the $\Delta CoVaR$ is, meaning that the risk contagion becomes more severe. The main differences between systemic beta and $\Delta CoVaR$ values are as follows. First, the systemic beta measures the sensitivity of risk contagion, while $\Delta CoVaR$ gives the quantified value of risk contagion. $\Delta CoVaR$ is calculated by multiplying the changes in interest rate risks with the systemic beta. Therefore, the conditional value of risk can only be achieved by the $\Delta CoVaR$ value. Second, the measures differ in comparability. $\Delta CoVaR$ is the value of contagion risk, and the values are changes in percentages. In contrast, the systemic betas are estimation coefficients, not contagion risk values. Therefore, only $\Delta CoVaR$ values

Table 2
CoVaR and $\Delta CoVaR$ for each European Country with contemporaneous ΔTED and 99% quantile.

Country j	UK	Germany	France	Swiss	Austria	Belgium	Finland	Netherlands	Portugal	Ireland	Italy	Greece	Spain
Quantile estimation: $\Delta IBOR_t^j = \alpha^{j\mid US} + \beta^{j\mid US}\Delta TED_t^{US} + \mathbf{M}_{t-1}\hat{\gamma}^{j\mid US} + \varepsilon_t^{j\mid US}$													
Intercept	0.0048***	0.0046***	0.0053***	0.0048***	0.0041***	0.0047***	0.0032***	0.0033***	0.0049***	0.0036***	0.0046***	0.0036***	0.0017***
ΔTED_t^{US}	0.2401***	0.0815***	0.3465***	0.2566***	0.3636***	0.2678***	0.2268***	0.2527***	0.4969***	0.3495***	0.3453***	0.4361***	0.1795***
$\Delta IBOR_{t-1}^j$	−0.0046	−0.0102***	−0.0093***	−0.0037***	−0.0033*	−0.0006	−0.0001	0.0080**	−0.0088	0.0150***	−0.0029	0.0008	−0.0032***
Oil_{t-1}	0.0001	−0.0001***	−0.0001***	−0.0001**	0.0001	−0.0001*	−0.0001***	−0.0002***	0.0001	0.0000	−0.0000	−0.0002***	0.0001***
$Gold_t-1$	0.0002	0.0002***	0.0003***	−0.0001***	−0.0000	−0.0001**	0.0001	0.0000	−0.0000	0.0000***	−0.0002***	−0.0001	0.0000
99% $\Delta CoVaR$ values by individual year and averages over 2003–2006 and 2007–2009													
$\Delta CoVaR = CoVaR_t^{j\mid US}(99\%) - CoVaR_t^{j\mid US}(50\%)$; $CoVaR_t^{j\mid US}(q) = VaR_{q,t}^j \mid VaR_{q,t}^{US} = \hat{\alpha}^{j\mid US} + \hat{\beta}^{j\mid US}\Delta TED_t^{US} + \mathbf{M}_{t-1}\hat{\gamma}^{j\mid US}$													
2003	8.20	2.80	11.80	8.70	12.40	9.10	7.70	8.60	16.90	11.90	6.00	14.90	6.10
	(16.03)	(5.56)	(17.25)	(23.49)	(62.07)	(24.79)	(33.36)	(20.24)	(57.81)	(40.95)	(58.33)	(30.58)	(23.91)
2004	6.40	2.20	9.30	6.90	9.80	7.20	6.10	6.80	13.30	9.40	4.70	11.70	4.80
	(12.22)	(5.62)	(16.34)	(21.29)	(62.00)	(21.49)	(32.81)	(20.69)	(60.68)	(62.23)	(67.90)	(27.86)	(21.73)
2005	6.10	2.20	8.80	6.40	9.20	6.80	5.80	6.40	12.60	8.90	4.50	11.10	4.60
	(14.24)	(5.80)	(16.85)	(20.12)	(49.88)	(20.96)	(31.98)	(18.97)	(48.51)	(49.08)	(54.68)	(26.70)	(21.48)
2006	6.40	2.20	9.30	7.00	9.80	7.20	6.10	6.80	13.30	9.40	4.70	11.70	4.80
	(9.28)	(5.70)	(13.60)	(15.85)	(58.08)	(17.29)	(35.76)	(23.17)	(58.52)	(41.80)	(57.33)	(25.73)	(20.45)
2007	8.00	2.70	11.50	8.50	12.00	8.90	7.50	8.40	16.50	11.60	5.80	14.40	5.90
	(14.36)	(5.43)	(15.92)	(22.50)	(53.00)	(25.95)	(44.45)	(19.63)	(35.88)	(16.87)	(35.44)	(35.12)	(13.30)
2008	13.40	4.50	19.40	14.20	20.10	14.90	12.50	14.00	27.50	19.30	9.80	24.10	9.90
	(9.81)	(5.65)	(12.41)	(11.55)	(24.49)	(15.06)	(21.02)	(18.65)	(23.02)	(26.82)	(21.49)	(18.36)	(16.98)
2009	28.20	8.90	40.80	28.10	39.70	31.50	24.80	27.60	54.30	38.20	19.30	47.70	19.60
	(27.41)	(14.70)	(35.51)	(29.22)	(79.53)	(44.14)	(65.28)	(41.65)	(76.53)	(82.63)	(79.20)	(58.18)	(40.46)
2003–2006	6.80	2.30	9.80	7.30	10.30	7.60	6.40	7.20	14.10	9.90	5.00	12.30	5.10
	(24.61)	(11.15)	(31.13)	(38.87)	(100.34)	(41.04)	(62.92)	(40.35)	(96.33)	(85.80)	(98.60)	(53.61)	(42.76)
2007–2009	14.90	5.40	21.50	17.00	24.00	16.60	15.00	16.70	32.80	23.10	11.70	28.80	11.90
	(21.32)	(13.78)	(25.03)	(27.49)	(43.21)	(29.70)	(40.98)	(36.09)	(41.63)	(42.47)	(41.16)	(38.66)	(31.88)

Notes: The yearly $\Delta CoVaR$ measures in this table are the average of daily $\Delta CoVaR$ values per year. The parentheses are the corresponding t-statistics. $\Delta IBOR_t^j$ is the changes in European country j's IBOR at time t, and ΔTED_t^{US} is the change in US Treasury Eurodollar spread at time t. The state variables of global risk factors at time $t-1$, $\mathbf{M}_{t-1}$, includes the changes in European interbank offered rates at time $t-1$ ($\Delta IBOR_{t-1}^j$), the return of West Texas Intermediate crude oil prices at time $t-1$ (Oil_{t-1}), and returns of Chicago Broad Options Exchange gold price index at time $t-1$ ($Gold_{t-1}$).
***, **, and * indicate statistical significance at 1%, 5%, and 10% levels, respectively.

can be compared and evaluated alongside each other. We therefore calculate the difference between VaR conditional on US distress and VaR under normal state to address the role of contagion risk.

Because the fitted VaR conditional on the US in distress is larger than the VaR conditional on the US in a normal state, particularly during the beginning of the credit crisis, we expect to see significantly positive differences between them. In addition, the trading days in which the CoVaR differences are positive are prevalent in our data settings, the reasonableness of using CoVaR as the measure of interest rate risk contagion can be supported. We therefore take $\Delta CoVaR$ as the difference between European country *j*'s VaR conditional on the US in distress and its VaR conditional on the US in the normal state, and average the daily $\Delta CoVaR$ values to acquire the yearly measures of interest rate risk contagion from 2003 to 2009. Table 2 provides the $\Delta CoVaR$ results. The positive values of the difference suggest that the European markets need to address not only their own liquidity problems caused by the increase in their interest rate risks but also the risk propagated from the US credit market.

The economic implication for the $\Delta CoVaR$ values can be explained based on its measurement. The UK's $\Delta CoVaR$ value in 2003 is 8.20 (see Table 2). This positive value suggests that the UK liquidity market not only faces interest rate risk contagion from the US in a normal state but also faces another positive increment of risk contagion from the US under weak credit market conditions. Therefore, the quantified risk value of 8.20 indicates that besides the value of risk caused by the United Kingdom itself, an additional 8.2% of interest rate spreads exists above the ordinary UK–US interdependence that should be considered when measuring the value of interest rate risk. This additional increment is caused by the differences in the US credit market between its normal and distress states.

Using *t*-test statistics, we further examine whether CoVaR differences are significant. Table 2 shows that CoVaR differences by year and by noncrisis and crisis periods are significantly positive. It is expected to see that the additional interest rate contagion risk increased significantly from 2007 to 2009 when systemic risk and credit problems became more severe. Based on the *t*-statistics, the rejection power increase from 2007 and is highest in 2009, the end of the credit crisis, suggesting that interest rate risk contagion was most prevalent in these years and such ex-ante interest rate risk contagion measurement provides evidence of effectiveness of prediction of the credit crisis in 2007–2009.

Besides the changes along the time horizon of crisis and noncrisis periods, the $\Delta CoVaR$ values vary across different cross-sectional countries. Table 2 shows that the magnitudes of $\Delta CoVaR$ value in the largest European nations (UK, German and France) are lower during the noncrisis periods. However, the $\Delta CoVaR$ values are larger in France in the crisis period as it faced a larger potential problem of sovereign debt compared to the United Kingdom and German. In addition, the $\Delta CoVaR$ values in the five highly debt-ridden Eurozone nations—Portugal, Ireland, Italy, Greece, and Spain—are relatively larger because of their liquidity problems. Among these five nations, the risk contagion effects in the two bigger countries, Italy and Spain, are lower as their sovereign debt problems are not significantly severe before 2009.

Although the results of interest rate risk contagion are from the same CoVaR model, the $\Delta CoVaR$ values are quite different in various quantiles. The $\Delta CoVaR$ values from $q = 95\%$ should be lower than the values from $q = 99\%$. In Model (9), the differences in European country *j*'s $\Delta CoVaR$ values between the conditions of US financial markets being in a normal state or in distress should be lower for $q = 95\%$, thereby having lower contagion risk values. In contrast, the $\Delta CoVaR$ values from $q = 99\%$ is particularly high due to the risk of more extreme changes in interest rates.

Table 3 shows the robustness of the CoVaR model with $q = 95\%$ quantile regression. Compared to the results in Table 2, the yearly averages of the daily interest rate risk contagion are lower because the $q = 95\%$ quantile encompasses events not only from the extreme distress cases (as under $q = 99\%$ quantile) but also from other minor uncertainties that can cause increases in interest rate spread. Therefore, the $\Delta CoVaR$ values from 95% quantile could underestimate risk contagion, and such evidence of $\Delta CoVaR$ highlights the crucial role of interest rate risk contagion in extreme distress cases. As a result, we suggest that selecting the appropriate upside risk confidence level (99% vs. 95%) should be dependent on the risk preference and is crucially important to prevent the underestimation of interest rate risk. The larger $\Delta CoVaR$ values from $q = 99\%$ (see Table 2) suggest that when considering risk contagion under more extreme cases, the financial institutions in European countries would have higher

Table 3
CoVaR and $\Delta CoVaR$ for each European Country with contemporaneous ΔTED and 95% quantile.

Country *j*	UK	Germany	France	Swiss	Austria	Belgium	Finland	Netherlands	Portugal	Ireland	Italy	Greece	Spain
Quantile estimation: $\Delta IBOR_t^j = \alpha^{j\|US} + \beta^{j\|US}\Delta TED_t^{US} + \mathbf{M}_{t-1}\hat{\gamma}^{j\|US} + \varepsilon_t^{j\|US}$													
Intercept	0.0018***	0.0019***	0.0019***	0.0032***	0.0021***	0.0031***	0.0014***	0.0016***	0.0024***	0.0013***	0.0026***	0.0016***	0.0001
ΔTED_t^{US}	0.1716***	0.1356***	0.2446***	0.2452***	0.3320***	0.2581***	0.2771***	0.2605***	0.4458***	0.3592***	0.2962***	0.3353***	0.1548***
$\Delta IBOR_{t-1}^j$	0.0010	−0.0061***	−0.0045***	−0.0010	−0.0049***	−0.0046***	0.0022	−0.0031*	−0.0051	−0.0029	−0.0052***	0.0017	0.0011
Oil_{t-1}	0.0001	−0.0000	0.0001**	0.0000	0.0001**	0.0000	−0.0000	−0.0000	0.0000	−0.0000	0.0000	−0.0000	−0.0000
$Gold_{t-1}$	0.0003***	0.0001	0.0001	−0.0001***	−0.0001***	−0.0002***	−0.0001*	−0.0000	−0.0000*	0.0000***	−0.0002***	−0.0001***	−0.0001***
95% $\Delta CoVaR$ values by individual year and averages over 2003–2006 and 2007–2009													
$\Delta CoVaR = CoVaR_t^{j\|US}(95\%) - CoVaR_t^{j\|US}(50\%)$; $CoVaR_t^{j\|US}(q) = VaR_{q,t}^j \| VaR_{q,t}^{US} = \hat{\alpha}^{j\|US} + \hat{\beta}^{j\|US}\Delta TED_t^{US} + \mathrm{M}_{t-1}\hat{\gamma}^{j\|US}$													
2003	4.50	3.60	6.40	6.40	8.70	6.80	7.30	6.90	11.70	9.50	5.50	8.80	4.10
	(7.23)	(19.37)	(20.63)	(22.96)	(35.79)	(18.86)	(40.05)	(44.73)	(60.06)	(82.67)	(43.73)	(29.36)	(15.99)
2004	3.00	2.30	4.20	4.20	5.70	4.50	4.80	4.50	7.70	6.20	3.60	5.80	2.70
	(5.05)	(16.62)	(15.31)	(18.03)	(32.38)	(14.54)	(32.13)	(39.92)	(69.69)	(168.44)	(38.68)	(22.32)	(11.43)
2005	2.70	2.30	3.80	3.80	5.20	4.00	4.30	4.10	7.00	5.60	3.30	5.20	2.40
	(4.92)	(16.52)	(14.88)	(17.54)	(30.91)	(14.17)	(30.97)	(38.51)	(64.73)	(150.52)	(36.90)	(21.57)	(11.52)
2006	3.10	2.40	4.40	4.40	5.90	4.60	4.90	4.60	7.90	6.40	3.70	6.00	2.80
	(3.98)	(12.92)	(14.04)	(14.04)	(31.33)	(11.66)	(24.02)	(31.49)	(64.10)	(94.59)	(29.54)	(17.17)	(9.15)
2007	3.60	2.80	5.10	5.10	6.90	5.40	5.70	5.40	9.20	7.40	4.30	6.90	3.20
	(5.68)	(9.86)	(15.20)	(20.62)	(26.72)	(15.08)	(28.91)	(32.47)	(36.79)	(48.50)	(32.73)	(23.51)	(11.81)
2008	5.60	4.40	8.00	8.00	10.80	8.50	9.00	8.50	14.50	11.70	6.80	10.90	5.00
	(3.80)	(10.70)	(12.15)	(13.02)	(24.29)	(11.20)	(21.43)	(22.99)	(31.79)	(33.33)	(22.69)	(15.74)	(8.99)
2009	12.60	9.10	18.00	16.40	22.20	19.00	18.50	17.40	29.80	24.00	13.90	22.40	10.40
	(10.42)	(34.06)	(29.31)	(36.97)	(54.21)	(30.94)	(54.89)	(57.39)	(65.80)	(70.13)	(58.25)	(44.82)	(27.02)
2003–2006	3.30	2.60	4.70	4.70	6.40	5.00	5.30	5.00	8.60	6.90	4.00	6.50	3.00
	(10.35)	(30.45)	(31.25)	(34.39)	(56.58)	(28.44)	(56.03)	(63.50)	(84.07)	(98.81)	(61.93)	(41.95)	(23.26)
2007–2009	6.50	5.40	9.30	9.90	13.30	9.80	11.10	10.40	17.90	14.40	8.30	13.40	6.20
	(9.39)	(24.59)	(23.80)	(30.58)	(39.31)	(23.43)	(39.85)	(39.80)	(43.14)	(44.40)	(40.09)	(34.62)	(23.19)

Notes: The yearly $\Delta CoVaR$ measures in this table are the average of daily $\Delta CoVaR$ values per year. The parentheses are the corresponding *t*-statistics. $\Delta IBOR_t^j$ is the changes in European country *j*'s IBOR at time *t*, and ΔTED_t^{US} is the change in US Treasury Eurodollar spread at time *t*. The state variables of global risk factors at time $t-1$, $\mathbf{M}_{t-1}$, includes the changes in European interbank offered rates at time $t-1$ ($\Delta IBOR_{t-1}^j$), the return of West Texas Intermediate crude oil prices at time $t-1$ (Oil_{t-1}), and returns of Chicago Broad Options Exchange gold price index at time $t-1$ ($Gold_{t-1}$).
***, **, and * indicate statistical significance at 1%, 5%, and 10% levels, respectively.

$\Delta CoVaR$ values. They may have more critical risk burdens if they tend to soundly protect themselves from being exposed to more severe interest rate risk contagion.

3.2. Robustness

Credit conditions may not efficiently influence current default spread and bond yields (e.g., Hull, Predescu, & White, 2004; Norden & Weber, 2004.). For reducing potential problem that the information on US credit risk cannot be fully reflected on current European liquidity, we explore the causal effect by adapting the model with $\Delta TED_{t-1}^{\text{US}}$ as regressors. Tables 4 and 5 provide the evidence on the lead-lag relation with 99% and 95% quantile regression estimates. The empirical results are similar to Table 2, namely, that the US credit market is positively related to the liquidity of countries within Europe. Regarding to the changes in interest rate risk contagion, the $\Delta CoVaR$ measures increase from 2007 to 2009, it consistent with the notion that the $\Delta CoVaR$ measures reflect the phenomenon that liquidity problems propagated from the US credit market are more severe during the credit crunch.

Although the significant results in Tables 2–5 are similar, the $\Delta CoVaR$ values and the difference between 2003–2006 and 2007–2009 are lower for the lead–lag relation between $\Delta IBOR$ and ΔTED. These results suggest that although the information on US credit distress cannot be completely reflected on European liquidity market on a current day, most of the interest rate risk contagion effects can efficiently reflected. That is, the interest rate risk in European countries is propagated not only mainly from the current US credit market but also minored from yesterday's US credit condition. However, the effects of overnight spillover are lower compared to current-day risk contagion. Also, the changes in $\Delta CoVaR$ values between 2003–2006 and 2007–2009 are also lower for the lead–lag relation models. Therefore, we find that using the lead–lag relation models for estimating the interest rate contagion underestimate the risk contagion effects.

Another concern is that the magnitude of the effect on ΔIBOR is larger when the ΔTED increases as the conditional distress event would be more extreme, while and the magnitude is lower for reducing ΔTED. For considering the varied effects on ΔIBOR due to different direction of changes in ΔTED, we follow Lopez-Espinosa, Moreno, Rubia, and Valderrama (2012) to adopt the asymmetric CoVaR approach to re-estimate the CoVaR values.

$$\Delta IBOR_t^j = \alpha^{j|\text{US}} + \beta_1^{j|\text{US}} \Delta TED_t^{\text{US}} \mathbf{I}_{(\Delta TED_t^{\text{US}} \geq 0)} + \beta_2^{j|\text{US}} \Delta TED_t^{\text{US}} \mathbf{I}_{(\Delta TED_t^{\text{US}} < 0)} + \mathbf{M}_{t-1}\gamma^{j|\text{US}} + \varepsilon_t^{j|\text{US}} \tag{14}$$

$$\Delta IBOR_t^j = \alpha^{j|\text{US}} + \beta_1^{j|\text{US}} \Delta TED_{t-1}^{\text{US}} \mathbf{I}_{(\Delta TED_t^{\text{US}} \geq 0)} + \beta_2^{j|\text{US}} \Delta TED_{t-1}^{\text{US}} \mathbf{I}_{(\Delta TED_t^{\text{US}} < 0)} + \mathbf{M}_{t-1}\gamma^{j|\text{US}} + \varepsilon_t^{j|\text{US}} \tag{15}$$

where $\mathbf{I}_{(\Delta TED_t^{\text{US}} \geq 0)}$ is an indicator function that equals 1 if the changes in ΔTED is positive, that is the increase in TED spread, and zero otherwise, while $\mathbf{I}_{(\Delta TED_t^{\text{US}} < 0)}$ is, in contrast, is an indicator function that equals 1 if the changes in ΔTED is negative, that is the decrease in TED spread, and zero otherwise. We next to use the same approach to measure the $\Delta CoVaR$ values with different 99% or 95% quintiles. Tables 6 and 7 provide the results on Model (14) with 99% and 95% quintiles, and Tables 8 and 9 provide the evidence on the lead-lag relation from Model (15). Similarly, the evidence is consistent with prior regression results that interest rate risk propagations turned increasingly severe since 2007 and that the contagion was particularly severe during 2008 and 2009.

The CoVaR model provides a risk measure for evaluating interest rate risk not only from the sector itself but also from other external influences. Unlike traditional VaR models that underestimate risk from other sectors, the CoVaR model quantifies the magnitude of additional exposure to risk propagation. When a financial crisis is about to occur, the interest rate risk exposure is exacerbated because a financial sector must deal not only with its own liquidity risks but also with the risk propagated from other credit markets. Our evidence from the CoVaR measure is consistent with the fact that the interest rate risk propagations turned increasingly severe since 2007 and that the contagion was particularly severe during the crisis period of 2008–2009.

Our quantified measure can also be applied to firm-level interest rate risk contagion by providing the magnitude of liquidity risk conditional on external institutions subject to different risks. Because the CoVaR measure identifies the risk impact degree under exposure to risk from another outside sector, the quantified value can be used to compare the magnitude of risk propagated from other external

Table 4

CoVaR and $\Delta CoVaR$ for each European Country with lagged ΔTED and 99% quantile.

Country j	UK	Germany	France	Swiss	Austria	Belgium	Finland	Netherlands	Portugal	Ireland	Italy	Greece	Spain
Quantile estimation: $\Delta IBOR_t^j = \alpha^{j\mid US} + \beta^{j\mid US}\Delta TED_{t-1}^{US} + \mathbf{M}_{t-1}\hat{\gamma}^{j\mid US} + \varepsilon_t^{j\mid US}$													
Intercept	0.0037***	0.0048***	0.0044***	0.0039***	0.0044***	0.0044***	0.0042***	0.0049***	0.0051***	0.0045***	0.0051***	0.0043***	0.0052***
ΔTED_{t-1}^{US}	0.0572**	0.0576***	0.0424**	0.1337***	0.1241***	0.0943***	0.0653***	0.0670*	0.0755**	0.1315**	0.0501	0.1274***	0.0706***
$\Delta IBOR_{t-1}^j$	−0.0017	−0.0074***	−0.0067***	−0.0066***	−0.0087***	−0.0071***	−0.0067***	−0.0080***	−0.0114***	−0.0130***	−0.0086***	−0.0075***	−0.0082***
Oil_{t-1}	−0.0001***	−0.0001***	−0.0000*	0.0001***	0.0002*	−0.0001	−0.0001	−0.0001	0.0002*	0.0001	−0.0001**	−0.0001**	−0.0000
$Gold_{t-1}$	0.0002***	0.0001*	0.0001**	0.0001*	0.0002***	0.0001	−0.0000	0.0001	0.0002**	0.0000**	0.0000	0.0003***	0.0001
99% $\Delta CoVaR$ values by individual year and averages over 2003–2006 and 2007–2009													
$\Delta CoVaR = CoVaR_t^{j\mid US}(99\%) - CoVaR_t^{j\mid US}(50\%)$; $CoVaR_t^{j\mid US}(q) = VaR_{q,t}^j \mid VaR_{q,t}^{US} = \hat{\alpha}^{j\mid US} + \hat{\beta}^{j\mid US}\Delta TED_{t-1}^{US} + \mathbf{M}_{t-1}\hat{\gamma}^{j\mid US}$													
2003	4.50	4.50	3.30	10.50	9.70	7.40	5.10	5.30	5.90	10.30	1.70	10.00	5.50
	(10.36)	(9.83)	(10.22)	(25.78)	(15.12)	(21.72)	(20.71)	(13.66)	(8.29)	(28.39)	(6.53)	(15.92)	(16.42)
2004	3.50	3.50	2.60	8.20	7.60	5.70	4.00	4.10	4.60	8.00	1.30	7.80	4.30
	(9.07)	(9.66)	(9.65)	(21.13)	(12.83)	(22.84)	(22.22)	(14.63)	(7.18)	(28.76)	(7.71)	(15.28)	(15.13)
2005	3.30	3.50	2.40	7.60	7.10	5.40	3.80	3.90	4.30	7.60	1.30	7.30	4.10
	(9.80)	(9.90)	(9.91)	(20.80)	(12.89)	(22.60)	(21.24)	(14.39)	(7.22)	(26.40)	(7.55)	(15.54)	(14.84)
2006	3.50	3.50	2.60	8.20	7.50	5.70	4.00	4.10	4.60	8.00	1.30	7.70	4.30
	(8.19)	(10.11)	(7.62)	(23.43)	(10.32)	(22.75)	(22.90)	(14.58)	(6.24)	(29.73)	(8.49)	(13.20)	(9.66)
2007	4.20	4.30	3.10	9.90	9.20	7.00	4.80	5.00	5.60	9.70	1.70	9.40	5.20
	(11.99)	(10.70)	(7.59)	(22.44)	(12.44)	(17.35)	(14.37)	(12.32)	(6.77)	(15.23)	(4.12)	(15.21)	(4.77)
2008	7.20	7.20	5.30	16.60	15.40	11.80	8.10	8.30	9.40	16.30	2.80	15.80	8.80
	(8.62)	(9.38)	(7.50)	(11.31)	(9.60)	(15.40)	(14.03)	(11.52)	(5.96)	(16.86)	(5.92)	(11.88)	(9.83)
2009	15.50	14.50	11.50	33.70	31.20	25.50	16.40	16.90	19.00	33.10	5.50	32.00	17.80
	(20.54)	(25.13)	(20.72)	(21.08)	(30.78)	(47.87)	(49.55)	(34.30)	(17.92)	(54.07)	(19.15)	(38.14)	(20.15)
2003–2006	3.70	3.70	2.70	8.60	8.00	6.10	4.20	4.30	4.90	8.50	1.40	8.20	4.50
	(18.52)	(19.37)	(18.23)	(44.41)	(25.02)	(42.71)	(41.19)	(27.68)	(14.35)	(53.02)	(14.31)	(29.26)	(26.16)
2007–2009	8.10	8.70	6.00	20.10	18.60	13.30	9.80	10.10	11.30	19.70	3.30	19.10	10.60
	(18.83)	(22.37)	(16.14)	(24.11)	(24.01)	(28.38)	(31.15)	(26.31)	(15.50)	(33.39)	(13.88)	(28.30)	(17.81)

Notes: The yearly $\Delta CoVaR$ measures in this table are the average of daily $\Delta CoVaR$ values per year. The parentheses are the corresponding t-statistics. $\Delta IBOR_t^j$ is the changes in European country j's IBOR at time t, and ΔTED_{t-1}^{US} is the change in US Treasury Eurodollar spread at time $t-1$. The state variables of global risk factors at time $t-1$, $\mathbf{M}_{t-1}$, includes the changes in European interbank offered rates at time $t-1$ ($\Delta IBOR_{t-1}^j$), the return of West Texas Intermediate crude oil prices at time $t-1$ (Oil_{t-1}), and returns of Chicago Broad Options Exchange gold price index at time $t-1$ ($Gold_{t-1}$).

***, **, and * indicate statistical significance at 1%, 5%, and 10% levels, respectively.

Table 5
CoVaR and $\Delta CoVaR$ for each European Country with lagged ΔTED and 95% quantile.

Country *j*	UK	Germany	France	Swiss	Austria	Belgium	Finland	Netherlands	Portugal	Ireland	Italy	Greece	Spain
Quantile estimation: $\Delta IBOR_t^j = \alpha^{j\|US} + \beta^{j\|US}\Delta TED_{t-1}^{US} + \mathbf{M}_{t-1}\hat{\gamma}^{j\|US} + \varepsilon_t^{j\|US}$													
Intercept	0.0018***	0.0026***	0.0023***	0.0021***	0.0022***	0.0027***	0.0025***	0.0027***	0.0022***	0.0003	0.0028***	0.0020***	0.0028***
ΔTED_{t-1}^{US}	0.0470	0.0300	0.0246	0.0727***	0.1090**	0.0188	0.0396	0.0186	0.0584*	0.1210***	0.0252	0.0779***	0.0286
$\Delta IBOR_{t-1}^j$	−0.0029***	−0.0041***	−0.0034***	−0.0032***	−0.0052***	−0.0038***	−0.0039***	−0.0042***	−0.0069***	−0.0076***	−0.0049***	−0.0037***	−0.0044***
Oil_{t-1}	0.0000	0.0000	0.0001	0.0001**	0.0001*	−0.0000	−0.0000	0.0000	0.0001**	0.0001*	0.0001***	−0.0000	0.0001***
$Gold_{t-1}$	0.0001**	−0.0001	−0.0000	−0.0000	0.0002**	−0.0000	−0.0000	−0.0001	0.0001*	0.0000***	−0.0000	0.0001***	−0.0001*
95% $\Delta CoVaR$ values by individual year and averages over 2003–2006 and 2007–2009													
$\Delta CoVaR = CoVaR_t^{j\|US}(95\%) - CoVaR_t^{j\|US}(50\%)$; $CoVaR_t^{j\|US}(q) = VaR_{q,t}^j \| VaR_{q,t}^{US} = \hat{\alpha}^{j\|US} + \hat{\beta}^{j\|US}\Delta TED_{t-1}^{US} + \mathbf{M}_{t-1}\hat{\gamma}^{j\|US}$													
2003	2.80	1.80	1.50	4.40	6.60	1.10	2.40	1.10	3.50	7.30	0.70	4.70	1.70
	(13.28)	(11.83)	(9.81)	(21.04)	(17.36)	(7.30)	(32.10)	(8.02)	(10.92)	(31.96)	(3.11)	(19.61)	(6.59)
2004	1.80	1.20	1.00	2.80	4.20	0.70	1.50	0.70	2.30	4.70	0.40	3.00	1.10
	(7.85)	(10.27)	(8.08)	(15.99)	(12.23)	(5.93)	(53.41)	(6.43)	(7.93)	(27.45)	(2.55)	(14.64)	(5.31)
2005	1.60	1.10	0.90	2.50	3.80	0.70	1.40	0.60	2.00	4.20	0.40	2.70	1.00
	(9.71)	(9.43)	(7.54)	(15.57)	(11.74)	(5.60)	(40.32)	(6.19)	(7.56)	(25.56)	(2.43)	(14.15)	(5.12)
2006	1.90	1.20	1.00	2.90	4.40	0.80	1.60	0.70	2.30	4.90	0.40	3.10	1.10
	(6.12)	(10.35)	(11.05)	(23.75)	(9.84)	(5.64)	(37.40)	(5.51)	(7.10)	(28.92)	(3.46)	(11.25)	(4.96)
2007	2.10	1.40	1.10	3.30	4.90	0.90	1.80	0.80	2.60	5.50	0.50	3.50	1.30
	(8.51)	(6.28)	(6.60)	(17.96)	(11.21)	(4.38)	(10.26)	(4.43)	(6.23)	(14.66)	(2.13)	(12.26)	(2.18)
2008	3.50	2.20	1.80	5.30	7.90	1.40	2.90	1.30	4.20	8.80	0.80	5.70	2.10
	(6.42)	(8.68)	(9.53)	(8.80)	(8.66)	(4.60)	(17.39)	(4.86)	(6.03)	(18.55)	(2.78)	(10.01)	(4.97)
2009	7.90	4.60	4.20	11.10	16.70	3.20	6.00	2.80	8.90	18.50	1.70	11.90	4.40
	(18.07)	(24.21)	(15.70)	(14.92)	(27.56)	(11.81)	(55.48)	(16.05)	(18.34)	(46.96)	(6.27)	(32.43)	(9.10)
2003–2006	2.00	1.30	1.10	3.20	4.70	0.80	1.70	0.80	2.50	5.30	0.50	3.40	1.20
	(17.16)	(20.44)	(17.51)	(35.42)	(24.58)	(12.15)	(56.80)	(12.87)	(16.53)	(49.98)	(5.63)	(28.22)	(10.97)
2007–2009	4.00	2.70	2.10	6.60	9.90	1.60	3.60	1.70	5.30	10.90	1.00	7.00	2.60
	(15.01)	(19.29)	(16.21)	(18.78)	(22.19)	(10.25)	(30.83)	(12.56)	(15.53)	(33.03)	(6.36)	(24.81)	(8.74)

Notes: The yearly $\Delta CoVaR$ measures in this table are the average of daily $\Delta CoVaR$ values per year. The parentheses are the corresponding *t*-statistics. $\Delta IBOR_t^j$ is the changes in European country *j*'s IBOR at time *t*, and ΔTED_{t-1}^{US} is the change in US Treasury Eurodollar spread at time $t-1$. The state variables of global risk factors at time $t-1$, $\mathbf{M}_{t-1}$, includes the changes in European interbank offered rates at time $t-1$ ($\Delta IBOR_{t-1}^j$), the return of West Texas Intermediate crude oil prices at time $t-1$ (Oil_{t-1}), and returns of Chicago Broad Options Exchange gold price index at time $t-1$ ($Gold_{t-1}$).

***, **, and * indicate statistical significance at 1%, 5%, and 10% levels, respectively.

Table 6
CoVaR and $\Delta CoVaR$ for each European Country with asymmetric indicator, contemporaneous ΔTED and 99% quantile.

Country j	UK	Germany	France	Swiss	Austria	Belgium	Finland	Netherlands	Portugal	Ireland	Italy	Greece	Spain
Quantile estimation: $\Delta IBOR_t^j = \alpha^{j\|US} + \beta_1^{j\|US}\Delta TED_t^{US}\boldsymbol{I}(\Delta TED_t^{US}\geq 0) + \beta_2^{j\|US}\Delta TED_t^{US}\boldsymbol{I}(\Delta TED_t^{US} < 0) + \mathbf{M}_{t-1}\hat{\gamma}^{j\|US} + \varepsilon_t^{j\|US}$													
Intercept	0.0002	0.0010***	0.0009***	0.0007***	0.0016***	0.0010***	0.0010***	0.0011***	0.0001	0.0006**	0.0015***	0.0003	0.0013***
$\Delta TED_t^{US}\boldsymbol{I}(\Delta TED\geq 0)$	0.7927*	0.5518***	0.5607***	0.3891***	0.7346***	0.6729***	0.6422***	0.7509***	0.8220***	1.0563***	0.4025	0.8237***	0.5905***
$\Delta TED_t^{US}\boldsymbol{I}(\Delta TED < 0)$	−0.1936	0.0365	0.0329	0.0027	0.0220	−0.0579	−0.0133	0.1208	0.1195	−0.1392	0.2129	0.1123	0.1076**
$\Delta IBOR_{t-1}^j$	−0.0013	0.0043	0.0048	0.0052	0.0036	0.0033**	0.0038	0.0024	0.0038	0.0040	−0.0010	−0.0007	0.0042
Oil_{t-1}	−0.0000	−0.0000	−0.0000	0.0000	−0.0001	−0.0001	−0.0001	−0.0000	−0.0000	−0.0001	−0.0000	−0.0002**	−0.0000
$Gold_{t-1}$	0.0002	−0.0002***	−0.0002**	−0.0001	−0.0003**	−0.0002***	−0.0002***	−0.0002**	−0.0002*	−0.0004***	−0.0002*	−0.0002**	−0.0002***
99% $\Delta CoVaR$ values by individual year and averages over 2003–2006 and 2007–2009													
$\Delta CoVaR = CoVaR_t^{j\|US}(99\%) - CoVaR_t^{j\|US}(50\%)$; $CoVaR_t^{j\|US}(q) = VaR_{q,t}^j \| VaR_{q,t}^{US} = \hat{\alpha}^{j\|US} + \hat{\beta}_1^{j\|US}\Delta TED_t^{US}\boldsymbol{I}(\Delta TED_t^{US}\geq 0) + \hat{\beta}_2^{j\|US}\Delta TED_t^{US}\boldsymbol{I}(\Delta TED_t^{US} < 0) + \mathbf{M}_{t-1}\hat{\gamma}^{j\|US}$													
2003	27.60	18.80	19.10	13.30	25.10	23.20	22.00	25.40	27.80	36.50	13.20	27.90	19.90
	(123.48)	(79.18)	(90.80)	(88.44)	(77.83)	(89.53)	(91.30)	(97.34)	(109.09)	(95.99)	(78.99)	(78.97)	(79.48)
2004	19.20	13.20	13.40	9.30	17.60	16.20	15.40	17.90	19.60	25.40	9.40	19.60	14.00
	(83.38)	(58.48)	(67.28)	(63.12)	(56.01)	(62.88)	(64.64)	(68.41)	(76.73)	(67.10)	(57.92)	(57.57)	(63.53)
2005	18.90	13.00	13.20	9.20	17.30	16.00	15.20	17.60	19.30	25.10	9.30	19.40	13.90
	(109.81)	(66.06)	(77.41)	(74.52)	(62.99)	(71.77)	(74.35)	(78.93)	(90.24)	(76.82)	(65.31)	(65.77)	(71.18)
2006	20.10	13.80	14.10	9.80	18.40	17.00	16.20	18.80	20.60	26.70	9.90	20.60	14.80
	(62.51)	(44.00)	(49.49)	(53.05)	(42.75)	(47.66)	(48.61)	(51.20)	(56.09)	(50.21)	(45.15)	(48.27)	(47.04)
2007	20.80	14.40	14.60	10.10	19.10	17.60	16.70	19.50	21.40	27.60	10.40	21.40	15.30
	(86.15)	(45.72)	(47.19)	(47.30)	(50.45)	(55.22)	(53.13)	(64.09)	(64.62)	(60.86)	(59.29)	(59.86)	(49.15)
2008	36.00	24.80	25.20	17.50	33.10	30.40	29.00	33.70	36.90	47.80	17.80	37.00	26.50
	(37.93)	(34.66)	(37.52)	(34.65)	(33.38)	(35.61)	(36.20)	(36.94)	(39.26)	(36.79)	(32.53)	(33.21)	(36.40)
2009	61.50	42.30	43.00	29.90	56.40	51.90	49.40	57.40	62.80	81.60	30.30	63.00	45.10
	(132.04)	(106.94)	(117.87)	(124.20)	(103.53)	(112.49)	(114.39)	(118.96)	(128.01)	(117.73)	(104.46)	(104.38)	(104.62)
2003–2006	21.40	14.70	14.90	10.40	19.60	18.10	17.20	19.90	21.80	28.40	10.50	21.80	15.60
	(129.17)	(101.42)	(111.49)	(112.25)	(98.69)	(107.67)	(109.53)	(112.81)	(121.05)	(112.20)	(99.23)	(102.00)	(105.33)
2007–2009	39.60	27.30	27.70	19.30	36.30	33.40	31.80	37.00	40.50	52.50	19.60	40.60	29.10
	(54.91)	(53.14)	(54.44)	(53.16)	(52.62)	(53.93)	(54.11)	(54.20)	(55.18)	(54.50)	(51.39)	(52.27)	(53.51)

Notes: The yearly $\Delta CoVaR$ measures in this table are the average of daily $\Delta CoVaR$ values per year. The parentheses are the corresponding *t*-statistics. $\Delta IBOR_t^j$ is the changes in European country *j*'s IBOR at time *t*, and ΔTED_t^{US} is the change in US Treasury Eurodollar spread at time *t*. $\boldsymbol{I}(\Delta TED_t > 0)$ is an indicator function that equals 1 if the changes in ΔTED is positive, that is the increase in TED spread, and zero otherwise, while $\boldsymbol{I}(\Delta TED_t < 0)$ is, in contrast, is an indicator function that equals 1 if the changes in ΔTED is negative, that is the decrease in TED spread, and zero otherwise. The state variables of global risk factors at time $t-1$, $\mathbf{M}_{t-1}$, includes the changes in European interbank offered rates at time $t-1$ ($\Delta IBOR_{t-1}^j$), the return of West Texas Intermediate crude oil prices at time $t-1$ (Oil_{t-1}), and returns of Chicago Broad Options Exchange gold price index at time $t-1$ ($Gold_{t-1}$).
***, **, and * indicate statistical significance at 1%, 5%, and 10% levels, respectively.

Table 7

CoVaR and $\Delta CoVaR$ for each European Country with asymmetric indicator, contemporaneous ΔTED and 95% quantile.

Country j	UK	Germany	France	Swiss	Austria	Belgium	Finland	Netherlands	Portugal	Ireland	Italy	Greece	Spain
Quantile estimation: $\Delta IBOR_t^j = \alpha^{j\|US} + \beta_1^{j\|US}\Delta TED_t^{US}\boldsymbol{I}(\Delta TED_t^{US}\geq 0) + \beta_2^{j\|US}\Delta TED_t^{US}\boldsymbol{I}(\Delta TED_t^{US} < 0) + \mathbf{M}_{t-1}\hat{\gamma}^{j\|US} + \varepsilon_t^{j\|US}$													
Intercept	−0.0007***	0.0006***	0.0004***	0.0003***	0.0009***	0.0007***	0.0006***	0.0005***	−0.0006***	−0.0004***	0.0005***	−0.0004***	0.0007***
$\Delta TED_t^{US}\boldsymbol{I}(\Delta TED\geq 0)$	0.3553***	0.3300***	0.3620***	0.3511***	0.5864***	0.2621***	0.3067***	0.3638***	0.7818***	0.9672***	0.5153***	0.4873***	0.3379***
$\Delta TED_t^{US}\boldsymbol{I}(\Delta TED < 0)$	−0.0855	0.1557***	0.1526***	0.1191*	0.1238	0.0747	0.1307***	0.1215*	0.1559**	0.0519	0.0562	0.2590***	0.1272***
$\Delta IBOR_{t-1}^j$	0.0007	−0.0017	0.0006	0.0025	0.0020	−0.0001	−0.0015	−0.0018	−0.0011	0.0005	0.0005	−0.0001	−0.0002
Oil_{t-1}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000
$Gold_{t-1}$	0.0002**	−0.0002***	−0.0002***	−0.0001***	−0.0003***	−0.0001***	−0.0001***	−0.0002***	−0.0001	−0.0003***	−0.0002***	−0.0001**	−0.0002***
95% $\Delta CoVaR$ values by individual year and averages over 2003–2006 and 2007–2009													
$\Delta CoVaR = CoVaR_t^{j\|US}(95\%) - CoVaR_t^{j\|US}(50\%)$; $CoVaR_t^{j\|US}(q) = VaR_{q,t}^j \| VaR_{q,t}^{US} = \hat{\alpha}^{j\|US} + \hat{\beta}_1^{j\|US}\Delta TED_t^{US}\boldsymbol{I}(\Delta TED_t^{US}\geq 0) + \hat{\beta}_2^{j\|US}\Delta TED_t^{US}\boldsymbol{I}(\Delta TED_t^{US} < 0) + \mathbf{M}_{t-1}\hat{\gamma}^{j\|US}$													
2003	9.00	7.70	8.50	8.30	14.10	6.30	7.20	8.70	18.90	23.70	12.60	11.30	8.00
	(48.02)	(42.22)	(55.67)	(62.02)	(52.77)	(49.04)	(52.33)	(43.61)	(128.73)	(83.75)	(65.27)	(75.12)	(45.31)
2004	5.40	4.80	5.30	5.10	8.60	3.80	4.40	5.30	11.50	14.40	7.70	7.00	4.90
	(31.83)	(27.95)	(36.49)	(40.52)	(33.94)	(31.25)	(34.27)	(28.59)	(77.82)	(52.30)	(41.95)	(51.19)	(30.22)
2005	5.40	4.80	5.30	5.20	8.70	3.90	4.50	5.40	11.60	14.50	7.70	7.10	5.00
	(35.55)	(32.23)	(43.66)	(49.59)	(39.90)	(36.41)	(40.32)	(32.90)	(132.48)	(67.16)	(50.90)	(66.88)	(35.23)
2006	5.30	4.70	5.20	5.10	8.60	3.80	4.40	5.30	11.40	14.20	7.60	7.00	4.90
	(25.34)	(22.68)	(30.41)	(37.61)	(27.50)	(25.45)	(28.49)	(23.16)	(91.68)	(46.93)	(35.90)	(52.60)	(25.12)
2007	5.60	5.10	5.60	5.50	9.20	4.10	4.80	5.70	12.20	15.20	8.10	7.50	5.30
	(31.03)	(28.53)	(38.67)	(38.88)	(33.45)	(33.37)	(34.21)	(29.05)	(94.16)	(58.33)	(45.42)	(63.69)	(33.22)
2008	8.70	7.80	8.50	8.30	14.00	6.20	7.20	8.60	18.70	23.30	12.40	11.40	8.00
	(20.02)	(18.84)	(25.62)	(27.99)	(23.13)	(20.88)	(22.96)	(19.18)	(54.15)	(37.08)	(29.84)	(41.53)	(21.47)
2009	16.30	14.40	15.90	15.50	26.10	11.60	13.50	16.10	34.80	43.50	23.10	21.20	14.90
	(55.15)	(52.38)	(64.10)	(72.48)	(60.17)	(56.58)	(61.88)	(53.41)	(99.90)	(82.45)	(71.58)	(81.32)	(56.14)
2003–2006	6.30	5.50	6.10	5.90	10.00	4.40	5.10	6.10	13.30	16.70	8.90	8.10	5.70
	(61.08)	(54.41)	(68.06)	(75.87)	(64.79)	(60.52)	(64.08)	(55.66)	(105.63)	(88.02)	(76.14)	(85.93)	(58.73)
2007–2009	10.20	9.10	10.10	9.80	16.50	7.30	8.50	10.20	22.00	27.40	14.60	13.40	9.40
	(41.15)	(39.25)	(45.62)	(47.22)	(44.12)	(42.07)	(43.26)	(39.81)	(55.00)	(51.93)	(48.67)	(51.47)	(42.12)

Notes: The yearly $\Delta CoVaR$ measures in this table are the average of daily $\Delta CoVaR$ values per year. The parentheses are the corresponding t-statistics. $\Delta IBOR_t^j$ is the changes in European country j's IBOR at time t, and ΔTED_t^{US} is the change in US Treasury Eurodollar spread at time t. $I_{(\Delta TED_t>0)}$ is an indicator function that equals 1 if the changes in ΔTED is positive, that is the increase in TED spread, and zero otherwise, while $I_{(\Delta TED_t<0)}$ is, in contrast, is an indicator function that equals 1 if the changes in ΔTED is negative, that is the decrease in TED spread, and zero otherwise. The state variables of global risk factors at time $t-1$, $\mathbf{M}_{t-1}$, includes the changes in European interbank offered rates at time $t-1$ ($\Delta IBOR_{t-1}^j$), the return of West Texas Intermediate crude oil prices at time $t-1$ (Oil_{t-1}), and returns of Chicago Broad Options Exchange gold price index at time $t-1$ ($Gold_{t-1}$).

***, **, and * indicate statistical significance at 1%, 5%, and 10% levels, respectively.

Table 8
CoVaR and $\Delta CoVaR$ for each European Country with asymmetric indicator, lagged ΔTED and 99% quantile.

Country j	UK	Germany	France	Swiss	Austria	Belgium	Finland	Netherlands	Portugal	Ireland	Italy	Greece	Spain
Quantile estimation: $\Delta IBOR_t^j = \alpha^{j\|US} + \beta_1^{j\|US}\Delta TED_{t-1}^{US} I_{(\Delta TED_{t-1}^{US}\geq 0)} + \beta_2^{j\|US}\Delta TED_{t-1}^{US} I_{(\Delta TED_{t-1}^{US}<0)} + \mathbf{M}_{t-1}\hat{\gamma}^{j\|US} + \varepsilon_t^{j\|US}$													
Intercept	0.0001	0.0014***	0.0013***	0.0010***	0.0018***	0.0013***	0.0012***	0.0016***	0.0006	0.0013***	0.0015***	0.0005**	0.0016***
$\Delta TED_{t-1}^{US}\boldsymbol{I}(\Delta TED\geq 0)$	0.5157***	0.2268***	0.2147*	0.3070***	0.4462	0.3299	0.2567	0.4247***	0.5530	0.4995*	0.3896	0.4081*	0.4370***
$\Delta TED_{t-1}^{US}\boldsymbol{I}(\Delta TED < 0)$	−0.3895*	−0.1571	−0.1270	−0.0123	−0.1688	−0.0699	−0.1793	0.0001	−0.2360	−0.2867	−0.3545	−0.3941	−0.0157
$\Delta IBOR_{t-1}^j$	−0.0019	−0.0035*	−0.0034	0.0047**	−0.0050	−0.0038	−0.0032	−0.0048***	−0.0064	−0.0062	−0.0048	−0.0001	−0.0048*
Oil_{t-1}	0.0000	−0.0001	−0.0001	0.0000	0.0000	−0.0002	−0.0001	−0.0002*	0.0002	0.0002	−0.0001	−0.0001	−0.0001
$Gold_{t-1}$	0.0003***	0.0002	0.0001	0.0000	0.0001	0.0001	0.0001	0.0002***	0.0003	−0.0001	0.0000	0.0003***	0.0001
99% $\Delta CoVaR$ values by individual year and averages over 2003–2006 and 2007–2009													
$\Delta CoVaR = CoVaR_t^{j\|US}(99\%) - CoVaR_t^{j\|US}(50\%)$; $CoVaR_t^{j\|US}(q) = VaR_{q,t}^j \| VaR_{q,t}^{US} = \hat{\alpha}^{j\|US} + \hat{\beta}_1^{j\|US}\Delta TED_{t-1}^{US}\boldsymbol{I}(\Delta TED_{t-1}^{US}\geq 0) + \hat{\beta}_2^{j\|US}\Delta TED_{t-1}^{US}\boldsymbol{I}(\Delta TED_{t-1}^{US} < 0) + \mathbf{M}_{t-1}\hat{\gamma}^{j\|US}$													
2003	18.70	8.20	7.70	10.50	15.70	11.50	9.30	14.50	19.60	17.90	14.30	15.00	15.00
	(65.08)	(36.12)	(49.74)	(109.44)	(103.90)	(44.36)	(42.39)	(44.40)	(54.67)	(73.68)	(89.10)	(54.48)	(68.77)
2004	12.80	5.60	5.30	7.40	10.90	8.00	6.30	10.20	13.50	12.30	9.70	10.20	10.50
	(45.44)	(31.91)	(43.07)	(81.70)	(79.69)	(39.88)	(37.41)	(39.71)	(41.23)	(60.40)	(79.12)	(41.42)	(72.57)
2005	12.50	5.50	5.20	7.30	10.70	7.90	6.20	10.00	13.30	12.00	9.50	10.00	10.30
	(55.08)	(34.84)	(47.17)	(110.27)	(90.27)	(44.21)	(41.25)	(44.12)	(44.75)	(64.54)	(89.74)	(45.62)	(82.10)
2006	13.30	5.80	5.50	7.70	11.40	8.40	6.60	10.70	14.10	12.80	10.10	10.60	11.00
	(35.99)	(31.89)	(36.40)	(68.50)	(59.26)	(46.62)	(38.26)	(38.82)	(34.48)	(64.85)	(69.44)	(33.20)	(64.77)
2007	13.60	6.00	5.70	8.00	11.70	8.60	6.80	11.10	14.50	13.20	10.30	10.80	11.40
	(47.71)	(26.91)	(28.57)	(51.84)	(43.15)	(36.96)	(32.34)	(34.72)	(32.26)	(41.26)	(43.09)	(43.62)	(43.99)
2008	23.80	10.40	9.90	13.90	20.30	15.00	11.80	19.10	25.30	22.90	18.10	18.90	19.70
	(27.82)	(23.15)	(25.30)	(37.81)	(33.89)	(28.28)	(26.24)	(26.64)	(25.08)	(36.80)	(34.89)	(26.48)	(33.84)
2009	40.70	17.90	16.90	23.60	34.80	25.60	20.20	32.60	43.20	39.20	30.90	32.50	33.60
	(88.47)	(64.69)	(79.85)	(150.14)	(116.98)	(79.49)	(74.60)	(78.19)	(74.84)	(104.24)	(123.18)	(79.75)	(100.74)
2003–2006	14.30	6.30	5.90	8.20	12.20	8.90	7.10	11.30	15.10	13.70	10.90	11.40	11.70
	(86.46)	(62.74)	(78.13)	(133.03)	(119.97)	(77.68)	(72.52)	(75.01)	(78.06)	(107.29)	(120.92)	(78.24)	(109.35)
2007–2009	26.20	11.50	10.80	15.20	22.40	16.40	13.00	21.00	27.80	25.20	19.90	20.80	21.70
	(49.36)	(43.30)	(45.52)	(54.44)	(51.59)	(47.81)	(46.45)	(46.51)	(45.38)	(52.11)	(52.83)	(48.33)	(50.98)

Notes: The yearly $\Delta CoVaR$ measures in this table are the average of daily $\Delta CoVaR$ values per year. The parentheses are the corresponding t-statistics. $\Delta IBOR_t^j$ is the changes in European country j's IBOR at time t, and ΔTED_{t-1}^{US} is the change in US Treasury Eurodollar spread at time $t-1$. $\boldsymbol{I}(\Delta TED_{t-1} > 0)$ is an indicator function that equals 1 if the changes in ΔTED is positive, that is the increase in TED spread, and zero otherwise, while $\boldsymbol{I}(\Delta TED_{t-1} < 0)$ is, in contrast, is an indicator function that equals 1 if the changes in ΔTED is negative, that is the decrease in TED spread, and zero otherwise. The state variables of global risk factors at time $t-1$, $\mathbf{M}_{t-1}$, includes the changes in European interbank offered rates at time $t-1$ ($\Delta IBOR_{t-1}^j$), the return of West Texas Intermediate crude oil prices at time $t-1$ (Oil_{t-1}), and returns of Chicago Broad Options Exchange gold price index at time $t-1$ ($Gold_{t-1}$).
***, **, and * indicate statistical significance at 1%, 5%, and 10% levels, respectively.

Table 9
CoVaR and $\Delta CoVaR$ for each European Country with asymmetric indicator, lagged ΔTED and 95% quantile.

Country *j*	UK	Germany	France	Swiss	Austria	Belgium	Finland	Netherlands	Portugal	Ireland	Italy	Greece	Spain
Quantile estimation: $\Delta IBOR_t^j = \alpha^{j\|US} + \beta_1^{j\|US}\Delta TED_{t-1}^{US}\boldsymbol{I}(\Delta TED_{t-1}^{US} \geq 0) + \beta_2^{j\|US}\Delta TED_{t-1}^{US}\boldsymbol{I}(\Delta TED_{t-1}^{US} < 0) + \mathbf{M}_{t-1}\hat{\gamma}^{j\|US} + \varepsilon_t^{j\|US}$													
Intercept	−0.0007***	0.0007***	0.0005***	0.0003***	0.0011***	0.0007***	0.0007***	0.0006***	−0.0004***	−0.0002	0.0007***	−0.0002***	0.0008***
$\Delta TED_{t-1}^{US} I_{(\Delta TED \geq 0)}$	0.4590***	0.1232*	0.2106***	0.2259**	0.2901***	0.0965	0.1126	0.1725**	0.3757***	0.6329***	0.1660	0.2268***	0.1706*
$\Delta TED_{t-1}^{US} I_{(\Delta TED < 0)}$	−0.1855*	0.0033	−0.0467	−0.0314	−0.0145	−0.0110	0.0088	−0.0401	−0.0435	−0.2156	−0.0602	−0.0720	−0.0077
$\Delta IBOR_{t-1}^j$	−0.0002	−0.0021	−0.0021	0.0045	−0.0033	−0.0019	−0.0019	−0.0023	−0.0042	−0.0046	−0.0025	0.0006	0.0001
Oil_{t-1}	0.0001	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0000	0.0001
$Gold_{t-1}$	0.0002***	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	−0.0001	0.0000	0.0001	0.0000
95% $\Delta CoVaR$ values by individual year and averages over 2003–2006 and 2007–2009													
$\Delta CoVaR = CoVaR_t^{j\|US}(95\%) - CoVaR_t^{j\|US}(50\%)$; $CoVaR_t^{j\|US}(q) = VaR_{q,t}^j \| VaR_{q,t}^{US} = \hat{\alpha}^{j\|US} + \hat{\beta}_1^{j\|US}\Delta TED_{t-1}^{US}\boldsymbol{I}(\Delta TED_{t-1}^{US} \geq 0) + \hat{\beta}_2^{j\|US}\Delta TED_{t-1}^{US}\boldsymbol{I}(\Delta TED_{t-1}^{US} < 0) + \mathbf{M}_{t-1}\hat{\gamma}^{j\|US}$													
2003	11.80	3.00	5.30	5.70	7.20	2.40	2.80	4.40	9.40	16.20	4.30	5.80	4.20
	(45.09)	(68.88)	(88.89)	(68.06)	(77.25)	(33.54)	(64.41)	(85.57)	(60.65)	(91.98)	(47.76)	(77.83)	(46.06)
2004	7.10	1.80	3.20	3.40	4.40	1.50	1.70	2.60	5.70	9.70	2.60	3.50	2.60
	(28.98)	(57.66)	(63.02)	(48.13)	(56.34)	(25.35)	(53.83)	(68.48)	(42.65)	(63.06)	(35.30)	(54.32)	(33.73)
2005	7.00	1.80	3.20	3.40	4.40	1.50	1.70	2.60	5.70	9.70	2.50	3.50	2.60
	(32.54)	(68.89)	(81.21)	(67.61)	(70.65)	(27.98)	(63.65)	(88.31)	(49.81)	(83.74)	(39.94)	(67.15)	(39.49)
2006	7.00	1.80	3.20	3.40	4.30	1.40	1.70	2.60	5.60	9.50	2.50	3.40	2.50
	(22.99)	(64.47)	(66.08)	(62.48)	(79.95)	(23.85)	(50.24)	(75.90)	(39.88)	(94.91)	(49.48)	(47.99)	(44.84)
2007	7.30	1.90	3.30	3.60	4.60	1.50	1.80	2.70	5.90	10.10	2.60	3.60	2.70
	(29.37)	(20.44)	(31.84)	(26.33)	(29.68)	(15.86)	(19.94)	(25.94)	(26.17)	(44.64)	(21.78)	(37.50)	(47.28)
2008	11.30	3.00	5.20	5.50	7.00	2.30	2.70	4.20	9.10	15.60	4.10	5.60	4.10
	(18.34)	(31.06)	(35.93)	(22.86)	(38.25)	(15.92)	(27.02)	(36.10)	(26.21)	(48.70)	(30.09)	(36.19)	(35.60)
2009	21.20	5.60	9.60	10.30	13.10	4.40	5.10	7.90	17.10	29.20	7.70	10.40	7.70
	(51.30)	(85.53)	(87.99)	(99.96)	(84.62)	(47.64)	(83.43)	(96.18)	(68.39)	(94.23)	(63.55)	(76.67)	(62.70)
2003–2006	8.20	2.10	3.70	4.00	5.10	1.70	1.90	3.00	6.60	11.30	3.00	4.00	3.00
	(57.17)	(84.74)	(93.92)	(91.26)	(90.19)	(49.77)	(80.12)	(94.54)	(75.18)	(98.64)	(69.03)	(89.06)	(68.67)
2007–2009	13.40	3.50	6.10	6.50	8.30	2.80	3.20	5.00	10.80	18.30	4.80	6.60	4.90
	(39.32)	(44.59)	(49.18)	(45.02)	(48.66)	(34.09)	(43.28)	(48.51)	(44.02)	(53.20)	(43.96)	(50.91)	(48.89)

Notes: The yearly $\Delta CoVaR$ measures in this table are the average of daily $\Delta CoVaR$ values per year. The parentheses are the corresponding *t*-statistics. $\Delta IBOR_t^j$ is the changes in European country *j*'s IBOR at time *t*, and ΔTED_{t-1}^{US} is the change in US Treasury Eurodollar spread at time $t-1$. $\boldsymbol{I}(\Delta TED_{t-1} > 0)$ is an indicator function that equals 1 if the changes in ΔTED is positive, that is the increase in TED spread, and zero otherwise, while $\boldsymbol{I}(\Delta TED_{t-1} < 0)$ is, in contrast, is an indicator function that equals 1 if the changes in ΔTED is negative, that is the decrease in TED spread, and zero otherwise. The state variables of global risk factors at time $t-1$, $\mathbf{M}_{t-1}$, includes the changes in European interbank offered rates at time $t-1$ ($\Delta IBOR_{t-1}^j$), the return of West Texas Intermediate crude oil prices at time $t-1$ (Oil_{t-1}), and returns of Chicago Broad Options Exchange gold price index at time $t-1$ ($Gold_{t-1}$).
***, **, and * indicate statistical significance at 1%, 5%, and 10% levels, respectively.

sectors. In addition, it is helpful for providing a reference index for investors, financial regulators, and risk managers to point out the level of risk contagion effect or additive liquidity problems or to acquire more information when financial institutions are exposed to extreme distress.

4. Conclusion

Systemic risk and interconnection among institutions is one of the main reasons to the risk propagation around the world during 2007–2009 credit crunch. In this study, we tend to explore the global risk propagation beyond normal interdependence by capturing and quantitatively measuring the interest rate risk contagion. Specifically, we adopt quantile regression to capture the European country's additional liquidity risk caused by the propagation risk from the US credit market. Furthermore, by using a modified CoVaR model to quantitatively measure the degree to which each of the European country's liquidity risk conditional on the difference in US financial market credit risk between normal state or under distress. The $\Delta CoVaR$ value indicates the percentage change in interest rate risk conditional on another financial market, which is the additional interest rate risk change that the European money markets face when credit risks in the US shift from a normal state toward a more severely risky state. The properties of CoVaR model for looking at upside risk in distribution of changes in interest rate is that it can consider different risk preference and varied percentiles free from distribution assumptions.

The value of $\Delta CoVaR$ from the model is the difference between VaR conditional on the US financial markets being in a normal state and VaR conditional on the US system being in distress. We find that the European country's additional liquidity risk propagated from the US credit market increased since 2007 and became more sever during 2008–2009. The results are similar after considering different quantiles for risk preferences, the time-lag effects, and the asymmetric influences from the increase or decrease in interest rate spreads. Our model can successfully capture the magnitude of additional liquidity risk faced by the European market, propagated from the US credit market. The empirical results are consistent with the argument that credit risk and liquidity risk are tightly linked (e.g., Billio et al., 2010; Diamond & Rajan, 2005) and the theoretical views that credit insolvency in one country exacerbates other countries' liquidity risks (e.g., Diamond & Rajan, 2005; Pais & Stork, 2011). Future research can be extended to institution level to foresee whether the risk management and capital reserves can effectively consider sufficient additional risk propagated from external sectors, thereby identifying which one should be noticed as the systemically important financial institutions.

Acknowledgements

We would like to thank valuable comments provided by Professor Wen-Liang Hsieh from National Chiao Tung University, Professor Tzu-Pu Chang from Academia Sinica, Mr. Chien-Ling Cheng from Shanghai Commercial and Savings Bank, and anonymous journal reviewers. We also appreciate research funding provided by National Science Council Taiwan (Grant number: NSC 102-2410-H-001-009-MY2 and NSC 101-2410-H-224-001).

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