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TESTING FOR CONTAGION AMONG FINANCIAL MARKETS

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Piraeus, February 2015

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Abstract

This study investigates whether contagion occurred during the global financial crisis among EU and US financial markets. The methodology used to test for contagion is the Forbes and Rigobon cross-correlation test, the Li and Zhu non-parametric test, the Fry et al. coskewness test and the Hsiao cokurtosis and covolatility tests. These tests are applied to a set of bank sector CDS, insurance sector CDS, sovereign bond, equity and volatility indices for the time period from 2004 to 2012. The findings indicate significant evidence of contagion especially through the channels of higher order moments.

Keywords

Cokurtosis, Correlation, Coskewness, Covolatility, Financial Contagion, Financial Crisis

Table of Contents

1. Introduction

1.1 The global financial crisis

The 2007-2008 financial crisis which originated in the US subprime mortgage market and spread with devastating effects to the rest of the sectors of US economy and the global financial markets, is considered to be the most serious recession since World War II. The global financial crisis was triggered in February 2007 when HSBC announced an impairment of the magnitude of $10.5 billion, due to losses linked to US subprime mortgages, this led to a decline in the US housing prices after a steady growth that lasted for almost a decade.

The problem in the mortgage market which was a relatively small part of the US economy spread to other financial sectors through Collateralized Mortgage Obligations (CMOs) which are a type of collateralized debt obligations (CDOs). CMOs are structured securities, divided in tranches with different term and interest rates, which are backed by mortgages or a pool of mortgages and issued by non-commercial financial institutions, which were allowed to operate unregulated by the federal government. The problems in the mortgage market became more pronounced by credit default swaps (CDS), which were used as an insurance contract for the various CMOs. The plunge of the prices in the mortgage markets caused the CMOs to drop in value and since the demand of CMOs was very low they were no longer being traded, making it difficult to price them. This triggered the protection payments of the CDSs, and caused financial institutions to suffer great losses.

The beginning of the global financial crisis was on September 15, 2008 when Lehman Brothers filed for Chapter 11 bankruptcy. This is the largest bankruptcy filing in the US history. The default of Lehman caused turmoil to the global financial markets, leading to the failure of a number of financial institutions and investors selling high risk assets, such as stocks and derivative securities, causing a sharp drop in asset prices.

The above show that a shock in a small part of the US economy was transmitted to the rest of the sectors of the economy and then spread globally. Such market comovements can have adverse effects to investors wishing to differentiate their portfolios, as well as on the decisions of domestic and international policy makers. This highlights the importance of studying contagion.

This study focuses on the international effects that the global financial crisis had on the financial markets. The equity, volatility, sovereign bond, bank sector CDS and insurance sector CDS markets for the EU and the US will be examined, with each market represented by an index. However, in order to be able to examine the effects of contagion across financial markets, a clear definition of contagion must be given and a review of the methodologies used to find evidence of contagion be made.

1.2 Definition of Contagion

Contagion occurs when a shock that has occurred in one market, is transferred to other markets. The early literature on this topic did not distinguish between interdependence, which is the connection markets share even during tranquil economic periods and contagion, whose definition is given below. There are five definitions of contagion that are most common in literature and are categorized by **Pericoli and Sbracia (2003)** as follows:

1. Contagion is a significant increase to the probability of a crisis occurring in one market, as a result of a crisis taking place in another market. This definition of contagion is mostly used for exchange rate shocks. The factors that trigger contagion in this definition are not specific and can be anything such as trade links, shocks to common market variables, irrational behavior etc.

2. Contagion occurs when there are volatility spillovers from the country where the initial shock happened, to other countries. During recessions the volatility of asset prices is increased and contagion occurs through the transmission of volatility from one market to another. This definition of contagion can be interpreted as the transmission of uncertainty across financial markets.

3. Contagion occurs when the fact that asset prices of different markets move in the same direction cannot be explained by the fundamentals. In this case the crisis spreads by moving between multiple equilibria, while fundamentals cannot fully explain this change.

This definition may also apply to problems among agents that arise from incomplete information and uncertainty.

4. Contagion is the significant increase of asset price co-movements in a market or group of markets, when a crisis has occurred in another market. This definition separates between standard co-movement, which is interdependence and increased co-movement, which is considered contagion. The following definition makes a similar distinction.

5. Lastly, another definition of contagion by Forbes and Rigobon is “shift-contagion”, which is defined as a significant increase in cross-market linkages after a shock to an individual market. For example some of those links might only be active during the period of the crisis or they may already exist but they intensify during a crisis. This definition implies that if two markets are highly correlated after a shock it is not necessarily contagion, but instead it is interdependence. It is only contagion if the correlation between the two markets increases significantly after the shock.

1.3 Empirical methodologies on contagion

There are several different methodologies used throughout the literature examining the international transmission mechanism of crises and the existence of contagion. Based on the classification utilized by **Pericoli and Sbracia (2003)** and **Dungey, Fry and González-Hermosillo (2005)**, as well as the methodologies encountered in the literature for financial contagion, there are six different methodologies that have been used to measure the transmission of shocks across international financial markets: correlation breakdown, ARCH and GARCH models, probit and logit models, the leading indicators approach, Markov switching models and tests for changes in the cointegration vector.

The first methodology uses cross-correlation coefficients, in order to test whether contagion occurred. These tests measure whether the cross-correlation between the asset returns of two markets has increased during the post-crisis period compared to the tranquil period prior to the crisis. If the cross-correlation shows a significant increase during the crisis period then contagion has occurred. The first major paper using cross-correlation coefficients to test for contagion by **King and Wahwani (1990)**, who use daily stock returns from the US, UK and Japan for the period from 1987 to 1988 and find that the correlation of returns across markets increased due to the high stock price volatility in the US. **Forbes and Rigobon (2002)**, argue that tests for contagion based on the cross-correlation coefficient are biased due to the presence of heteroskedasticity in market returns, which leads to increased evidence of contagion. They develop a test which corrects for the aforementioned bias and apply it to examine whether contagion occurred during the three financial crises of US in 1987, Mexico in 1994 and Hong Kong in 1997 or if there was strong interdependence. They find that for all the crises the hypothesis of contagion having occurred is rejected. More recently, **Fry, Martin and Tang (2010)** develop a new class of tests for financial contagion based on changes in asymmetric dependence (coskewness). They apply these tests on the real estate and equity markets in order to examine whether contagion occurred after the crisis in Hong Kong in 1997 and the US subprime mortgage crisis in 2007. The empirical results reveal that the coskewness based tests identify additional transmission channels, which are not detected by tests based on correlation. **Hsiao (2012)** and **Fry-McKibbin and Hsiao (2014)** develop tests based on changes in extremal dependence (cokurtosis and covolatility). These tests are applied to the equity and banking sectors to examine whether contagion occurred during the global financial crisis of 2008-2009. They found that contagion transmits from the US banking sector to the global equity markets and to the global banking sector. Finally, **Li and Zhu (2014)** propose an alternative test to the Forbes and Rigobon test, which is not based on the Pearson correlation coefficient, but instead on Kendall’s tau. This non-parametric test does not assume the absence of omitted variables and endogeneity. Furthermore, they do not assume that the data is normally distributed. They use data of stock market indices in order to test for contagion during the Asian crisis in 1997 and during the US subprime mortgage crisis in 2007. Using the Forbes and Rigobon test they find no evidence that contagion has occurred during any of the two crises. On the other hand, using the test based on Kendall’s tau, they find that there are significant increases in the cross-market linkages for both crises.

A second method for investigating the transmission of shocks across financial markets is using an ARCH or GARCH framework to model the variance transmission mechanisms between markets. This is important because specifying the dynamics of volatility, which can be indicative of a crisis, can lead to a better understanding of contagion. Among the original papers which used this methodology in order to test for contagion is the one written by **Hamao, Masulis and Ng (1990)**, who use a GARCH-M model in order to examine the relationship of daily opening and closing prices of major stock indexes for the UK, US and Japan. They find evidence of volatility spillovers from the US and the UK stock markets to the Japanese stock market. Another of the earliest papers using the ARCH/GARCH framework is written by **Engle, Ito and Lin (1990)**, who examine the causes of the yen/dollar intraday volatility. They test for two hypotheses; heat waves (volatility with country-specific autocorrelation) and meteor showers (volatility spillovers from one market to other markets). They accept the hypothesis of meteor showers and find that news from Japan has the largest impact on the volatility spillovers.

Another approach used for the empirical analysis of financial contagion are probit and logit models. **Eichengreen, Rose and Wyplosz (1996)** made an influential approach to the empirical analysis of contagion by using data for a set of industrial countries for the period from 1959 to 1993 in order to test for contagious currency crisis. The authors create an index of exchange rate market pressure (ERP), by constructing a weighted average of exchange rate changes, reserve changes and interest rate changes. They use a binary probit model with additional independent variables to control for the effects of macroeconomic and political events, to predict the probability of a crisis occurring. They find that the occurrence of a currency crisis in one country increases the probability of a speculative attack in other countries.

The ability of a set of macroeconomic and financial indicators to predict the occurrence of a crisis correctly is another approach to financial contagion. One of the first papers to use the leading indicators approach was written by **Calvo and Reinhart (1995)**, who examine how emerging markets in Asia and Latin America are affected by economic developments of their neighboring countries and the transmission of shocks across financial markets. By using principal component analysis, they find that the comovement among equity and Brady bond returns for emerging markets increased in Latin America after the crisis in Mexico. However, regional patterns where different, which suggests that contagion effects may be regional and not global. They also found that the capital account balance is significantly affected by changes in the US interest rates. **Kaminsky, Lizondo and Reinhart (1998)**, examine the forecasting ability of a group of economic indicators for the occurrence of a currency crisis. They construct a variable ERP using several indicators with unusual behavior in the pre-crisis periods. They find that real exchange rates, domestic credit and inflation are the best indicators.

A fifth method to examine the international transmission of shocks is using Markov switching models, which test for the presence of multiple equilibria. **Jeanne (1997)** uses a model of currency crisis in which for a set of fundamentals multiple equilibria arise and define three different probabilities of currency devaluation. This model is applied to the franc/mark exchange rate, for the period from 1991 to 1993. The results show that after the speculative attacks in August 1992 the fundamentals of France entered a multiple equilibria zone, which makes it more likely for the French economy to jump to the highest probability of devaluation.

The final method is to test for changes in the cointegration vector between markets, in order to examine for cross-market linkages. **Longin and Solnik (1995)** use excess stock returns of seven major markets over the period from 1960 to 1990, in order to test whether the international conditional correlation is constant or if it increases during the crisis period. They observe that the covariance and correlation matrices change during the sample period. Specifically, they find that correlation between US returns and other countries increased over the period. Another approach is to apply Granger causality tests. **Sander and Kleimeier (2003)**, use data US sovereign bond spreads, in order to examine the changes and the direction of causality, for time periods of the Asian and Russian crises. They construct a VAR model and provide evidence of crisis causation by applying a Granger-causality approach. They find that the Asian crisis affected causality patterns on a regional level. On the other hand, the Russian crisis changed causality patterns at a regional and an international level.

This study investigates whether contagion occurred during the global financial crisis among EU and US financial markets. The financial markets are represented by a set of bank sector CDS, insurance sector CDS, sovereign bond, equity and volatility indices. Contagion is defined as “shift-contagion”, which is a significant increase in cross-market linkages after a shock to an individual market. The following five tests are applied: the Forbes and Rigobon cross-correlation test, the Li and Zhu non-parametric test, the Fry et al. coskewness test and the Hsiao cokurtosis and covolatility tests.

The remaining of the paper proceeds as follows; Section 2 is the literature review on the topic of financial contagion, categorized based on which methodology is used, Section 3 describes the tests for contagion, in Section 4 the data used and the descriptive statistics are presented, in Section 5 the tests for contagion are applied and the results are analyzed, while Section 6 concludes.

2. Literature Review

Among the first papers where the current empirical research of contagion originates from is the one written by **Grubel and Fadner (1971)**. They examine the interaction and strength of the factors which make foreign assets attractive to US portfolio holders. One of the factors is that the returns of the foreign assets are influenced by business cycles, catastrophes and government policies whose effects are limited mostly to the economies where they occurred. The other factor is the effect which fluctuations of the exchange rate have to the variance of returns of the foreign assets. The authors construct the variance-covariance matrices of returns using data from US, UK and German subindices for the period from January 1965 to June 1967, in order to investigate the relationship of the two factors. They found that correlation among assets in an increasing function of holding period length. They also found that the absolute level of correlation between assets within the same country is greater than that between pairs of domestic and foreign assets, for any time period. Furthermore, they compare the correlation among pairs of identical industries in the US, the UK and Germany. Their findings support that the more the industry's activities are related to international trade the greater is the sensitivity of its earnings to conditions throughout the world. On the other hands industries whose activity is mostly based on domestic demand, are not affected as much by international incidents. Finally, they study the effect that the exchange rate fluctuations have on the value of the asset and find for the period under investigation the standard deviation of returns from holding foreign assets with or without exchange rate adjustments are statistically not different.

The following is a survey of the empirical literature on the topic of financial contagion, which is categorized in groups based on the methodology and type of analysis used by the authors.

2.1 Correlation breakdown

The authors of the following articles test for structural breaks in correlation; this methodology is also referred to as studies on correlation breakdown.

The first major paper using correlation breakdowns is written by **King and Wahwani (1990)**. They use hourly stock market data from the United States, United Kingdom and Japan for the period from July 1987 to February 1988, in order to investigate why after the US stock market crash, almost all stock markets fell together, despite the different economic circumstances. They define excessive transmission of shocks as a change in the covariance matrix of stock returns. They find that correlations across markets increased significantly after an increase in volatility due to the Wall Street stock market crash in 1987, which supports the hypothesis that contagion has occurred between the three stock markets.

Forbes and Rigobon (2002), investigate whether contagion occurred during the three financial crises of United States in 1987, Mexico in 1994 and Hong Kong in 1997 or if there already was strong interdependence between the markets. They use a VAR model in order to filter the stock returns and then calculate the cross-correlation matrix of the residuals. The authors show that tests for contagion based on cross-market correlation coefficients are biased, because Pearson correlation coefficient is conditional on the market volatility during the crisis period. They correct for the bias of the correlation coefficient caused due to the presence of heteroskedasticity in stock market returns, by assuming a linear relationship between the market returns. Furthermore, they use the statistic they created to test for contagion and find that in all cases the hypothesis of contagion having occurred is rejected. This means that the increase in cross-correlations after a shock to one market was due to the normal interdependence among stock markets during the crisis period and not to the change in cross-market linkages. Finally, they point out that they adjust the correlation coefficient for the bias caused by heteroskedasticity and further adjustments should be made for the presence of endogeneity and omitted variables.

Fry, Martin and Tang (2010), propose new tests of contagion which identify transmission channels of financial crises through changes in coskewness of the distribution of returns. These tests also make use of the Forbes and Rigobon unadjusted correlation coefficient which corrects for the bias of heteroskedasticity. They apply these tests using data from the real estate and equity markets after the crisis in Hong Kong in

1997 and the US subprime mortgage crisis in 2007. The empirical results reveal that the coskewness based tests identify additional transmission channels, which are not detected by tests based on correlation, such as the Forbes and Rigobon test for contagion. Specifically, for the Hong Kong crises the difference between the correlation and coskewness contagion tests is that for the real estate and equity markets in Singapore the coskewness test finds significant evidence of contagion, whereas the correlation test does not support the hypothesis that contagion has occurred. The coskewness tests for contagion also detect additional linkages for the US subprime crisis. The channels detected are from the US real estate market to the volatility of Australian real estate and from the volatility of US real estate market to the real estate market of Germany, as well as to the equity and real estate markets of Hong Kong. Finally, contagion from the US real estate market to the UK equity market can be detected through the correlation test and not the coskewness tests for contagion.

Anderson (2011), focuses on a sample of 150 corporate investment grade CDS contracts, which are included in one or more rolls of the CDX North American Investment Grade index 8-12, in order to investigate why CDS correlations increases during the credit crisis, specifically he investigates whether the increase in correlations was a function of fundamental values or not. He finds increased co-movement between CDS spread changes during the crisis, by testing the intraclass correlation coefficient, the average Spearman's correlation coefficient and the average fraction of firms that move together each week, which all increased during the crisis. He then tests for excess correlation and finds that only a small fraction of the increase in correlation can be explained by changes in the fundamental values that determine credit risk, therefore, he examines whether liquidity risk, counterparty risk or risk premiums are the reason that correlations increased. First, he investigates liquidity risk and in order to do this he adds several liquidity proxies into the fundamental model and repeats the test for contagion, the results show that liquidity contributed to the increase in correlations but it is not the main source of contagion. Next, he turns to counterparty risk and adds several proxies of aggregate dealer risk into the factor model, however the results provide no evidence that counterparty risk was a significant source of contagion. Finally, he investigates the impact that risk premiums had on CDS correlations, by estimating the jump-to-default risk premium from a sample of healthy firms, whose CDS spreads have low exposure to liquidity risk, adding the change in this measure to the factor model. He finds that changes in the risk premium account for approximately 18% of the time-series variation in CDS spread changes and also explains the increase in excess correlation, which suggests that risk premiums are the main source of contagion.

Junior, Miranda and Tabak (2012), test for contagion within bank sector indices, equity indices and sovereign CDS spreads, for the Global Financial Crisis and the European Sovereign Debt Crisis. In order to test for contagion they use the Forbes and Rigobon correlation test for contagion and the Fry et al. coskewness based contagion test. The authors instead of exogenously defining the date when the shock occurred and then separating the sample to pre- and post-crisis periods, they create an endogenous test for contagion, where they define a test window of fixed length and move it across the entire sample period. The length of the pre-crisis period is set to two years, while four, six and eight months are the three alternative lengths of the post-crisis period. Their findings indicate that contagion occurred during the Global Financial Crisis within the banking sector indexes across most of the countries from 2008 to 2009. They also found contagion in equity markets; however it was concentrated at the end of each contagion period. For the European Sovereign Debt Crisis they tested for contagion transmitting from Greece, Portugal, Spain, Italy and Ireland and found that contagion is also widespread throughout the banking sector, the equity indexes and CDS spreads. Finally, they examine contagion specifically for Brazil and found that for the Global Financial Crisis contagion occurred first in the banking sector and following the collapse of Lehmann Brothers contagion spread throughout the equity market, while for the European Sovereign Debt Crisis contagion was transmitted to Brazil mostly from Portugal, Spain, Italy and Greece.

Hsiao (2012) and Fry-McKibbin and Hsiao (2014), develop the cokurtosis and the covolatility tests for financial contagion which are based on changes in extremal dependence of two markets between the pre- and post-crisis period. These two tests were created by using the framework developed by Fry, Martin and Tang for the coskewness test. Then the Fry et al. coskewness test and the cokurtosis and covolatility tests are applied to the equity and banking sectors to examine whether contagion occurred during the global financial crisis of 2008-2009. The authors use daily data of equity and banking equity indices for Hong Kong, Korea, France, Germany, the UK, Chile, Mexico and the US for the period from April 2005 to August 2009, which is then divided in to two sub periods. The findings show that contagion transmits from the US banking sector to the global equity markets and to the global banking sector. Furthermore, extremal dependence tests (cokurtosis and covolatility) capture contagion more frequently than the asymmetric dependence tests (coskewness) during extreme events.

Hui and Chan (2014), argue that the coskewness test is not always enough to capture the full scope contagion and that additional transmission channels may be detected raising the order of moment by one, therefore they use a cokurtosis test for contagion. They apply the cokurtosis tests in order to test whether contagion occurred between equity and real estate markets during the global financial crisis. They use equity and stock index data for Hong Kong, the US and the UK for the period from July 2004 to June 2012, and apply the three contagion tests: the Forbes-Rigobon correlation test, the coskewness test and the cokurtosis test. They find that the cokurtosis test can reveal additional transmission channels of contagion than the Forbes-Rigobon correlation test and even the coskewness test. Specifically, the direction of contagion among countries is that, shocks are transmitted from the US to Hong Kong and the UK, which transmits shocks Hong Kong. Furthermore, their findings suggest that contagion effects are stronger within the equity market than the real estate market, which become more noticeable by using the cokurtosis test. Finally, they find evidence that contagion is significant between the US equity and real estate market, which is contrary to the study performed by Fry, Martin and Tang found little evidence of contagion from the US real estate to the equity and real estate markets of other countries.

Li and Zhu (2014), propose an alternative test to the Forbes and Rigobon test, which is not based on the Pearson correlation coefficient. Instead, the authors use Kendall’s tau to measure the co-movements between markets and build a test for financial contagion. Similarly to the Forbes-Rigobon test for contagion the Li and Zhu test avoids the bias caused by the presence of heteroskedacity in market returns, but does not assume that there are neither omitted variables, nor endogeneity. Furthermore, they do not assume that the data is normally distributed, since their test does not rely on the bivariate normal distribution. They run Monte Carlo simulation studies and find that the test has reasonable size and has good power to detect financial contagion. They use daily data of stock market indices for five Asian countries, the G7 countries and four Latin American countries, in order to test for contagion during the Asian crisis in 1997 and during the US subprime mortgage crisis in 2007. Using the Forbes and Rigobon test they find no evidence that contagion has occurred during any of the two crises. On the other hand, using the test based on Kendall’s tau, they find that there are significant increases in the cross-market linkages between Hong Kong and most of the Asian countries, Latin American countries and the G7 countries. Finally, for the US subprime crisis the linkages between the US and most of the G7 countries increased significantly.

2.2 ARCH and GARCH models

The following papers use generalized autoregressive conditional heteroskedastic (GARCH) models in order to examine whether contagion has occurred.

Among the original papers that used the ARCH/GARCH framework in order to test for contagion is the one written by **Hamao, Masulis and Ng (1990)**, who use a GARCH model in order to examine the relationship of daily opening and closing prices of major stock indexes for the London, New York and Tokyo stock markets. They examine the transmission mechanisms of the conditional mean and conditional variance in stock prices across international stock markets. The authors use daily and intraday stock returns, measured from close-to-open and open-to-close, for the period from April 1985 to March 1988, to analyze the transmission of volatility after the stock market crash of October 1987. By using a GARCH(1,1)-M model, they find evidence of volatility spillover effects from the US and the UK stock markets to the Japanese stock market. An intriguing finding is that while these spillover effects are statistically significant, spillovers in other directions after or before the crisis of 1987 are much weaker.

Another of the earliest papers using this methodology to test for contagion is written by **Engle, Ito and Lin (1990)**, who examine the causes of the yen/dollar intraday volatility. Specifically, they test for two hypotheses; heat waves and meteor showers. In the heat wave hypothesis, they test if the volatility of the exchange rate has only country-specific autocorrelation. On the other hand, the meteor shower hypothesis is the phenomenon of volatility spillovers from one market to other markets. They use intraday yen/dollar exchange rate from October 1985 to September 1986, in order to examine whether news in the US market can predict volatility in the Japanese market several hours later. A change in policy of the Federal Reserve that will have its major impact in the US market is an example of a heat wave, while the effects of a money supply announcement in US, which will be felt across all markets, is an example of a meteor shower. Although Japanese news seem to have the largest impact on volatility, using a GARCH model they reject the heat wave hypothesis.

Coudert and Gex (2010), use daily data on the CDSs present in the four US and European 5-year CDS indices, for a total of 224 CDSs plus the CDSs of GM and Ford added to the list, in order to test for an increase in correlations between the CDSs during the Ford and GM crisis. Firstly, they compare the CDS correlations during the crisis with those of the reference period, by adjusting them by taking account for the increase in volatility. Secondly, they calculate the conditional correlations by using a EWMA and DCC-GARCH model and then they test for their increase in the in the crisis period and during the first week. The CDS premia of both companies increased, while the CDS premia of the rest of the European and US firms also rose. They also found that the correlations between the majorities of CDSs in the sample including those of GM increased significantly during the crisis. Furthermore, the average correlations between the CDS premia and those of Ford and GM increased during the 2005 crisis, however there is little evidence of shift-contagion since the correlations adjusted for biases caused by the volatility are not significantly higher, which means that the transmission channels where not changed by the crisis, but the high volatility and interdependence raised most correlations.

Wang and Moore (2012), use weekly observations of CDS spreads on five-year sovereign bonds for 38 developed and emerging markets, in order to study whether the collapse of Lehman Brothers has strengthened the linkage among the developing markets with the U.S. market and whether it has changed the integration of emerging markets. They use the dynamic conditional correlation derived from the multivariate GARCH model, in order to explore the dynamic co-movement of the CDS spreads between the U.S. and other markets. They also investigate the channels through which the linkage of the credit markets is enhanced, the domestic stock returns and interest rates, in a linear regression framework. The results show that DCC is higher in developed markets than in emerging markets, although the level of correlation increased across all countries after the collapse of the Lehman Brothers. They also found that the increase in DCC across both developed and emerging markets can be attributed to the domestic stock returns. Finally, the DCC increased across all countries with the common factor of falling U.S. interest rates in the post-Lehman shock period.

Fender, Hayo and Neuenkirch (2012), use daily spreads of 80 emerging market sovereign CDS denominated in dollars, in order to measure spillover effects before and after a crisis, using GARCH models they establish the impact of a broad range of potential influences, particularly that of international financial variables. They find that common factors play a role for daily CDS spread changes across emerging financial markets; they also find that daily CDS spreads for emerging market sovereigns are more related to global and regional risk premia, than to country specific risk factors, such as macroeconomic variables and country ratings. Measures of U.S. bond, equity, CDX High yield returns and emerging market credit returns are the most important factors which drive CDS spreads. Lastly, they find that CDS spreads are more strongly influenced by spillover effects during a financial crisis, than during a more tranquil period.

2.3 Probit and logit models

Probit and logit models are another methodology used to test for contagion.

Eichengreen, Rose and Wyplosz (1996) made an influential approach to the empirical analysis of contagion. They use a panel of quarterly data for twenty industrial countries for the period from 1959 to 1993 in order to test for contagious currency crisis. They test whether the probability of a crisis occurring in a country at a point in time is increased by the occurrence of crises in other countries at the same time, after controlling for the effects of political and economic fundamentals. The authors create an index of exchange rate market pressure (ERP), by constructing a weighted average of exchange rate changes, reserve changes and interest rate changes. Furthermore, they weight the three components of the index, based on the volatility of each, so as one of them cannot dominate the index. As a dependent variable, they define an indicator variable, 'crisis dummy', which takes the value of one for a speculative attack and zero otherwise. The authors estimate a binary probit model with additional independent variables to control for the effects of macroeconomic and political events. Such events include inflation, growth of domestic credit, election outcomes, unemployment rate and more. Their findings suggest that the occurrence of a currency crisis in one country increases the probability of a speculative attack in other countries by the significant amount of eight percent. This effect is statistically significant and the crisis dummy is the most important and robust variable in the model. The authors also explore two alternative channels of transmission for contagion: trade linkages and macroeconomic similarities. They find that when they include both indicators the effect of contagion through trade channels is stronger than that of contagion spreading as a result of macroeconomic similarities.

Fazio (2007) uses monthly data of macroeconomic fundamentals commonly used in literature of currency crises for 14 emerging market economies for the period from January 1990 to December 1999. The author estimates a series of bivariate probit models and then applies significance tests to the cross-correlation equation. In the first stage the author identifies extreme interdependence due to common factors, in the second stage the cross-correlation dependence due to common factors is excluded and for the final stage the author accounts for a number of fundamentals which are good predictors for currency crises and tries to draw conclusions on the cross-correlation equation due to omitted variables. This way the author is able to distinguish between extreme interdependence and extreme contagion. The findings indicate that contagion occurred between countries that are in the same region, while a reduction in speculative pressure between countries from a different region was detected.

Ismailescu and Kazemi (2010), use daily data of US$ denominated CDS, written on 22 high-yield sovereign reference entities, for the period 2001 to 2009, and apply standard event study methodology, in order to investigate the effect of announcements about the change of sovereign credit rating on the CDS spreads of the event countries, as well as their spillover effects on the CDS spreads of other emerging markets. By using a logistic model, they found that CDS premiums have a strong response to positive credit rating announcements, while on the other hand they respond weakly to negative announcements, which suggests that investors can use changes in CDS spreads to estimate the probability of a credit rating event. Furthermore, they find that while positive events display spillover effects in the two-day period surrounding the event, negative announcements have no impact on CDS spreads of other economies. Finally, the transmission mechanisms of the spillover effects are the common lending center and the competition in trade markets.

2.4 Leading indicators

The articles below use the leading indicators approach to measure the effect of contagion.

One of the first papers to use the leading indicators approach was written by **Calvo and Reinhart (1995)**, who examine how emerging markets in Asia and Latin America are affected by economic developments of their neighboring countries and the role which financial markets play in the transmission of shocks. They use principle component analysis in order to explore the issue of comovement, for two groups of time series; seven Latin American markets and six Asian markets, during the period of the Mexican crisis in 1994. From these they construct a smaller set of time series, the principal components, which explain as much of the variance of the original time series as possible. If there is there is high comovement in the original series, the number of the principal components that will be needed to explain a large portion of the variance will be lower. They find evidence that the comovement across weekly equity and Brady bond returns for emerging markets increased in Latin America after the crisis in Mexico. Furthermore, while comovements increased in both regions, regional patterns where different, this suggests that contagion effects may be regional and not global. They also found that the capital account balance is significantly affected by changes in the US interest rates. Finally, they found that capital account developments in larger countries have increased impact on the smaller countries in the region, while the significance of effect of the capital account developments of Mexico alone to other countries in the region depends on the period of the sample chosen.

Kaminsky, Lizondo and Reinhart (1998), investigate the forecasting ability of a group of financial and macroeconomic indicators for the occurrence of a currency crisis. They construct a variable ERP using several indicators with unusual behavior in the pre-crisis periods. The authors define the crisis period as a month in which the variable ERP takes extreme values. For each indicator the authors establish a certain threshold, so that the indicator releases a warning 'signal', that a currency crisis might take place within the following 24 months, whenever it is larger than the established threshold. The threshold values are computed in such a way as to balance between the risk of having too many false signals and the risk of missing the occurrence of a currency crisis. The indicators that have been proven useful in anticipating crises include exports, output, the real exchange rate, changes in international reserves, equity returns, credit and more. Finally, on average the indicators mentioned above provide signals in advance, which is helpful for applying preemptive policy measures.

Longstaff, Pan, Pedersen, Singleton (2007), use monthly market quotations for sovereign CDS contracts on the external debt of 26 developed and emerging-market countries for the period 2000-2007, in order to examine the nature of sovereign credit risk. Firstly, they find that most of the variation in sovereign credit spreads is due to common regional and global factors and that idiosyncratic or country specific variation is only a fraction of the total variation of the sovereign credit spreads. Specifically, from principal component analysis they find that more than 30% of the variation in sovereign CDS spreads is explained by a single factor that affects most of the countries in the sample. The first factor has a correlation of -70% with the U.S. stock returns and 66% with the changes in the VIX volatility index. Also, more than 50% of the variation in sovereign CDS spreads is explained by three common factors. By a multivariable cluster analysis based on the correlation matrix they found that there is a strong regional or geographical structure to sovereign credit risk. In order to determine the common sources in sovereign credit spreads, they regress the changes in sovereign CDS spreads on four explanatory variables namely: local economic variables, global financial market variables, global risk premia and global investment-flow variables. They find that all four categories affect the CDS spread changes; however, global factors and global risk premia have a more significant role than local economic variables. They also find that excess sovereign credit returns are mostly compensation for bearing the risk of the global factors that drive sovereign credit spreads. Finally, a significant amount of the excess returns from sovereign credit can be forecast by using U.S equity, volatility and bond market risk premia.

Jorion and Zhang (2007), use daily stock return data and quotes on 5-year CDS spreads for over 1.000 North American reference entities, in order to measure intra-industry credit contagion. They define “contagion effect” as positive default correlations and “competitive effect” as negative default correlations, these two effects can coexist and the observed effect will be a net result of the two. They define credit events as bankruptcies, which in United States are: Chapter 11 reorganization, which protects a firm from its creditors while it works out a formal plan of reorganization and Chapter 7 liquidation, which forces the liquidation of the assets of the firm in economic distress, and “jump events” which are extreme upward jumps in CDS spreads. They find different patterns of industry CDS spread and stock price responses to the above three credit events and that contagion and competition effects are associated with industry characteristics. They also provide evidence that contagion effects are better observed in the CDS market than the stock market. For each event they construct an industry portfolio as an equally weighted portfolio of firms. They test for changes in credit risk of industry rivals around credit events and apply the standard event study method to the CDS spread of the above portfolios. They compute the cumulative CDS spread changes and their cross-sectional mean and standard deviation for the full sample. They also report measures such as rating-adjusted CDS spread and calculate the cumulative abnormal spread changes as before. Furthermore, they report results using stock prices by calculating the cumulative abnormal returns, prior to the credit event. They find that Chapter 11 bankruptcies create contagion effects as indicated by increases in spreads of industry competitors. Chapter 7 bankruptcies are, on the other hand associated with competitive events. The above findings result using CDS data, but similar findings are also observed from equity prices.

Finally, they find that “jump events” from CDS spreads leads to the strongest evidence of credit contagion across the industry.

Jorion and Zhang (2009), use data of stock prices, CDS spreads of creditors and bankruptcy fillings listing the top unsecured creditors, credit amounts and credit types for over 250 public bankruptcies, for the period of 1999 to 2005, to analyze counterparty risk as a different channel of credit contagion, by examining how a borrower’s financial distress affects its creditors. They examine industrial firms where exposures take the form of trade credit, which is direct lending in a supplier-customer relationship. They also examine financial firms, where exposures take the form of loans and bonds. They construct an equally-weighted portfolio of firms for each event and then apply the standard event study method. They find negative stock price responses of creditors to their borrower’s bankruptcy announcements, as well as increases in CDS spreads. Movements in stock prices and in CDS spreads are adjusted for industry effects and credit rating effects, in order to isolate counterparty effects. They find that the average abnormal equity return to decrease around the bankruptcy filing, which translates into a loss for the median creditor, also CDS spreads increased at the same time. They also track creditor firms that experience credit loss and find that creditors with large exposures are more likely to also suffer from financial distress further on than other firms, after controlling for sector, size and credit rating. Furthermore, through cross-sectional analysis they found that counterparty effects can be explained by variables such as, the size of exposure, the recovery rate and previous stock returns correlations. They also found evidence that counter party effects are stronger if the debtor is a major customer of the creditor and when the debtor liquidates rather than when it reorganizes. Finally, by running simulations of portfolio credit losses, with and without counterparty risk, they found that counterparty risk affects the shape of the default distribution, which explains the observed default clustering.

Eichengreen, Mody, Nedeljkovic and Sarno (2012), use end-of-day weekly 5-year CDS spreads of 45 financial institutions in the U.S., the U.K., Germany, Switzerland, France, Italy, Netherlands, Spain and Portugal, for the period 2002 to 2008, in order to find how the Subprime Crisis effected the global banking system. They use a dynamic factor model of CDS spreads and through principal component analysis they estimate the common determinants behind the variations of the CDS spreads of different banks. Furthermore, they investigate the association between the common factors on the one hand and on the other hand, the real economy variables outside the financial system, and transactional relationships between banks and other parts of the financial system. They find that the share of common factors was high even prior to the beginning of the Subprime Crisis. The common factors are connected to U.S. high yield spreads. The common factors where responsible for the rise of the variance between the start of the crisis in 2007 and the default of Lehman's Brothers in 2008. During that time the association with measures of bank credit risk increased. They reached the conclusion that banks fortunes were linked even in normal times, but the importance of common factors rose during the beginning of the crisis and the rescue of Bear Stearns. The period following the failure of Lehman Brothers saw a further increase in those interdependences. There were also spillovers, as opposed to co-movements from CDS spreads of U.S. banks to those of E.U. banks.

Beirne and Fratzscher (2013), examine the extent to which the financial markets have been overpricing the sovereign risk in the Eurozone and the role which contagion has played as far as sovereign risk is concerned. In order to do that they use data for three different measures of sovereign risk: sovereign CDS spreads, government bond yield spreads and S&P sovereign credit ratings, as well as macroeconomic fundamental variables for 31 advanced and emerging markets for the period from 1999 to 2011. They found that important fundamental variables such as the current account balance, the fiscal deficit, economic growth and the level of public debt, do not explain as well the pricing of sovereign risk for the countries in the euro area periphery as they do for other advanced and emerging countries for the pre-crisis period. On the other hand, during the post-crisis period the pricing of sovereign risk was much more sensitive to the fundamental variables. They also found that "regional contagion" was not as important, since the transmission of sovereign shock across Eurozone countries was not particularly evident. Furthermore, they found fundamentals contagion to be one of the main reasons which explain the increase in sovereign risk during the crisis. By analyzing the clustering effects during sharp unexplained changes in the pricing of sovereign risk, they find evidence of "pure contagion", concentrated especially during the peak of the financial crisis.

2.5 Markov switching models

Another strand of the empirical literature on contagion uses Markov switching models, which test for the presence of multiple equilibria.

Jeanne (1997) uses a model of currency crisis in which for a certain set of fundamentals multiple equilibria arise and define three different probabilities of currency devaluation. In this setting, jumps between multiple equilibria coincide to jumps between the devaluation probabilities. The author defines a currency crisis as a situation in which the probability of devaluation increases unexpectedly to unusually high levels. The model is applied to the exchange rate of the French franc with the German marc, using monthly data for the time period from January 1991 to July 1993, in order to examine the relationship between the fundamentals and the devaluation expectations of the currency due to several speculative attacks in 1992 and 1993. The macroeconomic variables which are part of the fundamentals are the unemployment rate, the real exchange rate and the trade balance GDP ratio. The empirical results show that after August 1992 the fundamentals of France entered a multiple equilibria zone, which is evident by the rising of the unemployment rate and the appreciation of the real exchange rate, this makes it more likely for the economy to jump to the highest probability of devaluation. Finally, the approach used by the author is better at tracking the devaluation expectations of the French franc than a simple linear regression model.

Guo, Chen and Huang (2011), investigate the role that, the stock market crash, the rise of the oil prices, the numerous defaults of the CDS market and subprime mortgage meltdown, played in the global financial crisis. Specifically, they use weekly data on stock price, CDS index, oil price and real estate index for the period from October 2003 to March 2009. In order to examine the impact of the various shocks across the four markets within the economic system, they apply a Markov switching vector autoregressive model (MS-VAR). The reason they chose this methodology is because the effects of the shocks on each market are not stable of the time, due to occasional regime shifts. They found that the contagion among the four markets is characterized by nonlinearity with two different regimes. The “risky” regime, which has the higher mean and volatility, is prevalent in the market chaos. Furthermore, their findings are that the duration of the “stable” regime is twice as long as that of the “risky” regime and that all the market variables are more prone to shocks during the “risky” regime. Finally, they found that the CDS market is strongly affected by the stock market but not as much by the housing market during the “risky” regime, while the influence of the housing market shock on stock market volatility lessens during the crisis period and that the stock market is an important factor to the variability of the prices in the energy market.

2.6 Cointegration techniques

Lastly, the following articles test for changes in the cointegration vector between markets, in order to examine for cross-market linkages.

Longin and Solnik (1995) use monthly excess returns of seven major stock markets over the period from 1960 to 1990, in order to test whether the international conditional correlation is constant or if it increases during the crisis period. The period examined covers several different business cycles, such as the steady economic growth during the sixties, the oil crisis and the stock market crash of 1987. They observe that the covariance and correlation matrices change during the sample period. The authors model the asset return dynamics using a multivariate GARCH(1,1) model for each pair of markets, in order to capture some of the evolution of the conditional covariance structure. They also include information variables in the mean and variance equations which are observable at the start of the period; these are the dividend yield, the short- and long- term interest rates and a January seasonal. They test for the null hypothesis of constant correlation, which is rejected. Furthermore, their findings indicate that international correlation between markets has followed an upward trend over the past 30 years and that correlation has a positive relation to conditional volatility. Finally, they find evidence that variables such as dividend yield and interest rate contain information about future volatility and correlation which is not contained in past returns alone.

Sander and Kleimeier (2003), use data of daily spreads of US dollar denominated sovereign bonds which are perceived as a measure of country credit risk and can serve as indicators of the effects of a crisis, in order to examine the changes and the direction of causality. They distinguish four different sub-periods, pre and post the Asian crisis and pre and post the Russian crisis, and show how causality patterns have changed over time. They construct a VAR model and provide evidence of crisis causation by applying a Granger-causality approach. Their findings show that the Asian crisis created new and changed existing causality patterns on a regional level. On the other hand, the Russian crisis changed causality patterns not only in a regional, but at an international level as well.

Kalbaska and Gatkowski (2012), use data on five-year CDS contracts issued on the bonds of nine sovereigns (Portugal, Ireland, Italy, Greece, Spain, Germany, France, the U.K. and the U.S.), in order to examine sovereign risk and the financial contagion that occurred in Europe. Through a EWMA correlation analysis they found that there were several waves of contagion and correlations increased after the credit crisis of 2007 and confirmed the role of the financial crisis to the sovereign default risk. Furthermore, they constructed a VAR model and applied the Granger-causality test and reached the conclusion that cross-country interdependencies increased after the financial crisis, compared to the previous more tranquil economic period. Specifically, they found that the CDS markets of Ireland and Spain have the biggest impact in the European CDS market; on the other hand the CDS market of U.K. does not affect that much the EU. Finally, the adjusted correlation analysis shows that, core EU countries (Germany, France and the U.K.) have both high capacity to trigger contagion, yet more assets to absorb the shock if they are triggered by other countries, however, Greece, Ireland, Italy, Spain and especially Portugal have lower capacity to trigger contagion and much fewer assets and therefore much more sensitive to a shock.

Hammoudeh, Bhar and Liu (2013), use daily time series for the U.S. five-year CDS sector indices for the banking, financial services and insurance sectors, the bank risk premium, the bank liquidity premium, the corporate default risk and the ten-year inflation expectations, that covers the pre- and post-financial crisis period, in order to investigate how the three sectors' CDS spreads interact with each other, to explore the feedback from the financial CDS spread to the above variables and to observe the impact of the first quantitative easing on the above six measures of risk. They write the VAR(6) process in VECM representation and examine the latter if it shows cointegration in this system, in order to study the short- and long-term deviations of the spreads from equilibrium. The results show that the own and cross-effects among the CDSs and the other risk measures are significant and that contagion is dominant after the crisis. Finally, they found that the system has become less stable during the Great Recession and that the first quantitative easing decreases the systems risk but increases inflationary expectations.

Tamakoshi and Hamori (2014), use daily series on five-year banking, insurance and financial sector CDS indexes, and apply the cross-correlation function, in order to investigate the volatility and mean spillovers between the three United States sectors. They first test for structural breaks in the variances of the CDS index series and then test for causality-in-variance while removing causality-in-mean effects. They found evidence of causality-in-mean effects passing from the banking to the insurance and financial services sector CDS indexes and from the financial services to the insurance sector CDS index. Lastly, they found significant causality-in-variance effects running from the financial services sector CDS index to the banking sector CDS index, which implies that the financial sector CDS index can be used as an indicator for volatility spillovers.

Avino and Cotter (2014), use a sample of sovereign CDS and bank CDS daily mid-quotes from CMA for six major European economies, namely France, Germany, Italy, Portugal, Sweden and Spain, in order to investigate the relationship between sovereign and bank CDS spreads and their ability to convey accurate signals on the default risk of the European countries and their respective banking systems. They separate the effects of noise and liquidity shocks from those related to the speed of adjustment to new information and find that both sovereign and bank CDS spreads have an important price discovery role during the period 2004-2013. They base their analysis on a VECM and test for co-integration using the Johansen co-integration test. Their findings are that, both bank and sovereign CDS spreads contribute to the price discovery, however the most developed countries (Germany and Sweden) show a leading role of bank CDS spreads during the whole period. Furthermore, sovereign CDS spreads of the countries with worse financial conditions (Portugal, Spain and Italy) lead the price discovery during the sub-prime crisis. Lastly, during the tranquil period before the crisis, bank CDS spreads play a leading role.

Gündüz and Kaya (2014), use the observations of 10-year senior sovereign CDSs for ten European Union countries, in order to study their behavior before and during the crisis. They focus on parametric methods in order to model the long memory parameters of the CDS spread changes and their volatility using a dual long memory model, which is a combination of ARFIMA and FIGARCH models. They employ Granger causality methods in order to test for causal relationships between CDS uncertainty and various variables such as sovereign CDS levels and local stock market returns and volatility. They also focus on the spillover effects between Eurozone sovereign CDSs by using a dynamic conditional correlation model and by using a two-stage estimation methodology. Firstly, they show that there is no long memory behavior of the sovereign CDS spread changes for either the pre-crisis or the crisis periods, on the other hand they found persistent volatility patterns for the economies in the periphery of the Eurozone. Secondly, they found a causal relationship between CDS uncertainty and the pricing of sovereign risk, also the causality running from CDS uncertainty to stock market volatility shows that the financial crisis has developed a transmission mechanism from sovereign risk to the real economy for the peripheral countries. Lastly, they highlight the existence of co-movement of CDS spread changes across all countries and that during the crisis the probability of contagion increased especially among the peripheral countries of the Eurozone.

3. Tests for Contagion

This section describes several of the tests that have been developed to examine whether a significant increase in cross-market linkages is observed after a shock to an individual market has occurred. The **Forbes and Rigobon (2012)** test for contagion is based on the Pearson correlation coefficient and finds evidence of contagion if the cross-correlation has increased significantly between the pre- and post-crisis period. The statistic tests whether a shock in the returns of the source market transmitted to the returns of the recipient market. **Fry, Martin and Tang (2010)** propose another test for contagion based on the second order of moments, namely skewness. Their coskewness based test checks for contagion between the returns of one market to the volatility (squared returns) of the second market. Using the framework developed by Fry et al., **Hsiao (2012)** created another line of tests based on higher order of moments; kurtosis and volatility. The cokurtosis test examines the relationship between one market's returns and another market's skewness (cubed returns). The covolatility test explores how shocks transmit from the volatility of one market to the volatility of the second market. Finally, **Li and Zhu (2014)** propose a non-parametric test based on Kendall's tau, which measures the concordance between two variables, instead of the Pearson correlation coefficient.

3.1 The Forbes and Rigobon (FR) correlation test for contagion

Tests for contagion based on the cross-market Pearson correlation coefficient are biased due to the presence of heteroskedasticity in market returns. An increase in market volatility can affect estimates of cross-correlation coefficients. This can be problematic because tests that do not adjust for the aforementioned bias in the correlation coefficient, often find evidence of contagion. The authors show how the variance affects the correlation coefficient, a way to calculate this bias and also how to correct it.

They test for contagion from market *i* to market *j*. Furthermore, they make the assumptions that there are no omitted variables and endogeneity. They divide the sample into two sets so that the variance of the first group σ_x^2 is lower and the variance of the second group σ_{y}^{2} is higher. In terms of testing for contagion, the low-variance group refers to the tranquil period prior to the crisis, while the high-variance group refers to the period after the occurrence of the shock. The correlation between the asset returns for the two markets is ρ_x for the non-crisis period (low-variance group) and ρ_y post-crisis period (high-variance group). If a shock occurs in market *i* and there is an increase in the volatility of the asset returns then: $\sigma_{y,\mathrm{i}}^{2} > \sigma_{x,\mathrm{i}}^{2}$, while the transmission channels between market *i* and market *j* remain the same, then $\rho_y > \rho_x$ gives the false appearance of contagion. As a result, tests for contagion based on cross-correlation can lead to the wrong conclusion, because the estimates of the correlation coefficient are biased and conditional on the variance of the market returns. Forbes and Rigobon find a way to adjust for this bias by defining contagion as an increase in the unconditional correlation coefficient, which is given by the following equation:

$$v_y = \frac{\rho_y}{\sqrt{1+\delta(1-\rho_y^2)}}, \quad (1)$$

where

$$\delta = \frac{\sigma_{y,\mathrm{i}}^{2} - \sigma_{x,\mathrm{i}}^{2}}{\sigma_{x,\mathrm{i}}^{2}} \quad (2)$$

The unconditional correlation v_y is the conditional correlation ρ_y scaled by the nonlinear function δ which is the relative change in variance in the asset returns of the source country. During periods of high volatility in market *i*, the conditional correlation between the two markets will be greater than the unconditional correlation. Even if the unconditional correlation coefficient remains constant during both pre- and post-crisis periods, the conditional correlation coefficient will increase after a shock has occurred, due to bias caused by the presence of heteroskedasticity in the market returns.

They estimate a VAR model and use the variance-covariance estimates from this model to calculate the cross-correlation coefficient between the market where the shock originated and each of the other markets. These are based on the unconditional correlation coefficient from equation (1). They use *t*-tests to examine if there is a significant increase in any of the correlation coefficients during the crisis period.

If v_y is the adjusted correlation during the crisis period and ρ_x is the correlation during the non-crisis period, the hypotheses are:

$$\begin{aligned} H_0 &: v_y = \rho_x \\ H_1 &: v_y > \rho_x \end{aligned} \tag{3}$$

The null hypothesis indicates that no contagion has occurred, while the alternative hypothesis means that contagion has taken place.

The t-statistic used for testing the above hypotheses is given by the following equation:

$$FR_1(i \to j) = \frac{\hat{v}_y - \hat{\rho}_x}{\sqrt{\frac{1}{T_y} - \frac{1}{T_x}}}, \tag{4}$$

where T_y and T_x are the sample sizes of the crisis period and pre-crisis period respectively. The standard error in equation (4) derives from assuming that the two samples are drawn from independent normal distributions. To improve the finite sample properties of the test statistic the authors suggest using the Fisher transformation:

$$FR_2(i \to j) = \frac{\frac{1}{2} ln\left(\frac{1 + \hat{v}_y}{1 - \hat{v}_y}\right) - \frac{1}{2} ln\left(\frac{1 + \hat{\rho}_x}{1 - \hat{\rho}_x}\right)}{\sqrt{\frac{1}{T_y - 3} + \frac{1}{T_x - 3}}} \tag{5}$$

It is important to note that Forbes and Rigobon focus on fixing only one of the problems with the cross-correlation coefficient: heteroskedasticity. Adjustment also needs to be made for the bias caused by the presence of endogeneity or omitted variables.

3.2 The Li and Zhu non-parametric test for contagion

Forbes and Rigobon test is based on the assumptions that there are neither omitted variables, nor endogeneity and it is also limited to the case of a bivariate normal distribution between two markets. However an increase in asset correlations could occur due to changes in omitted variables, such as economic fundamental variables, even if contagion is not present. Furthermore, FR test statistic is based on the Pearson correlation coefficient, which may not be sufficient test for contagion, due to the mistaken assumption of normality in asset prices. Li and Zhu use Kendall's tau to measure the co-movements between markets and build a test for financial contagion. Similarly to the FR test for contagion the Li and Zhu test avoids the bias caused by the presence of heteroskedacity in market returns which is associated with the Pearson correlation coefficient, this is because Kendall's tau is based on the measure of concordance between two variables, which reflects the direction two variables move up or down together. Their test does not rely on the bivariate normal distribution, which makes it more flexible to use for a larger variety of data sets. Also, Kendall's tau does not assume that there is a regression relationship between two variables; therefore the problem of omitted variables is avoided.

Let $\{x_t, y_t\}_{t=1}^{T_1}$ and $\{x_t, y_t\}_{t=T_1+1}^{T_1+T_2}$ denote the observations of two asset returns for the pre- and post-crisis periods respectively. They express Kendall's tau as τ during the tranquil period prior to the crisis and as τ^h for the period during the crisis. The use the following hypotheses to test whether contagion has occurred:

$$H_0 : \tau \geq \hat{\tau}_2^h \\ H_1 : \tau < \hat{\tau}_2^h \tag{6}$$

The null hypothesis means that financial contagion has not occurred, while the alternative hypothesis means that contagion exists.

The nonparametric estimators for Kendall's tau, for the pre- and the post-crisis periods respectively are:

$$\hat{\tau}_1 = \frac{2\sum_{i=1}^{T_1-1}\sum_{j=i+1}^{T_1} Q((x_i, y_i),(x_j, y_j))}{T_1(T_1-1)} \text{ and} \tag{7}$$

$$\hat{\tau}_2^h = \frac{2\sum_{i=T_1+1}^{T_1+T_2-1}\sum_{j=i+1}^{T_1+T_2} Q((x_i, y_i),(x_j, y_j))}{T_2(T_2-1)} \tag{8}$$

where,

$$Q((x_i, y_i),(x_j, y_j)) = \begin{cases} 1 \text{ if } (y_j - y_i)(x_j - x_i) > 0 \\ -1 \text{ if } (y_j - y_i)(x_j - x_i) < 0 \end{cases} \tag{9}$$

The test statistic used for testing the above hypotheses is given by the following equation:

$$CT_{T_1,T_2} = \frac{\sqrt{T_1}(\tau_1 - \hat{\tau}_2^h)}{\hat{\sigma}_1} \tag{10}$$

where,

$$\hat{\sigma}_1 = \sqrt{\frac{2}{T_1 - 1}\left[\frac{2(T_1 - 2)}{T_1(T_1 - 1)^2}\sum_{i=1}^{T_1}\left(d_i - \bar{d}\right)^2 + 1 - \hat{\tau}_1^2\right]} \tag{11}$$

where

$$d_i = \sum_{\substack{t=1 \\ t\neq i}} Q((x_i, y_i),(x_t, y_t)) \text{ and } \bar{d} = \frac{1}{T_1}\sum_{i=1}^{T_1} d_i \tag{12}$$

The null hypothesis for a given significant level α is rejected if $CT_{T_1,T_2} < Z_a$ where Z_a is the number for which $P(Z \geq Z_a) = a$ and Z is a standard normal random variable. Similarly, the null hypothesis is rejected when: $\hat{\tau}_1 < \hat{\tau}_2^h - Z_a\hat{\sigma}_1/\sqrt{T_1}$

The Li and Zhu test has good power to detect whether financial contagion has occurred compared to the FR test which is more conservative and can sometimes miss evidence of contagion when it actually exists.

Higher order moments in univariate distributions of asset returns during financial crises, such as skewness and kurtosis, give additional information on the subject of investor risk-return preferences. The importance of identifying the role of higher order moments also applies to identifying the importance of comovements amongst moments in multivariate distributions, such as coskewness and cokurtosis.

3.3 The Fry, Martin and Tang coskewness test for contagion

Correlations alone may not be able to capture the complete contagion pattern; therefore the authors extend to higher order of moments, such as coskewness, in order to obtain more details. They argue that after a shock has occurred, risk-averse investors would shift towards positive skewness by trading off smaller returns for positive skewness. The aim of the asymmetric dependence tests of contagion by Fry, Martin and Tang (2010) is to identify whether there is a statistically significant change in coskewness between the pre- and post-crisis period after controlling for the market fundamentals.

They test for contagion from market i to market j, where x is the low volatility pre-crisis period and y is the high volatility post-crisis period. The asset returns are r_i and r_j for markets i and j respectively. The means are μ_x and μ_y, while the standard deviations are denoted by σ_x and σ_y, for the tranquil period and for the period after the shock respectively. The correlation between the two asset returns is denoted as ρ_x (low variance period) and ρ_y (high variance period). Finally, the sample sizes of the pre-crisis and crisis periods are T_x and T_y respectively.

They developed two variants of the coskewness based test, CS_{12} and CS_{21}, which build on the Forbes and Rigobon test and are specified depending on whether the asset prices at the source market of the crisis are expressed in terms of returns or squared returns in order to calculate coskewness. The coskewness statistics for testing for contagion from market i to market j (or specifically, from the value of i to the volatility of j and from the volatility of i to the value of j) are given by the following equations:

$$CS_{12}(i \to j; r_i^1, r_j^2) = \left(\frac{\hat{\psi}_y(r_i^1, r_j^2) - \hat{\psi}_x(r_i^1, r_j^2)}{\sqrt{\frac{4\hat{v}_y + 2}{T_y} + \frac{4\hat{\rho}_x^2 + 2}{T_x}}} \right)^2 \qquad (13)$$

The CS_{12} test for contagion tests whether there is a significant decrease of the returns in the source market and an increase of the volatility in the second market. This implies that the crisis in the source market has been identified with positive skewness (investors seek low-risk assets and accept lower returns), while contagion in the second market takes the form of increased volatility.

$$CS_{21}(i \to j; r_i^2, r_j^1) = \left(\frac{\hat{\psi}_y(r_i^2, r_j^1) - \hat{\psi}_x(r_i^2, r_j^1)}{\sqrt{\frac{4\hat{v}_y + 2}{T_y} + \frac{4\hat{\rho}_x^2 + 2}{T_x}}} \right)^2 \qquad (14)$$

The CS_{21} test for contagion tests whether there is a significant increase of the volatility in the source market and a significant decrease of the average returns in the second market, which means that the increased volatility in the source market affects investors in the second market, who prefer low-risk assets with lower returns seeking positive skewness.

Where,

$$\hat{\psi}_y(r_i^m, r_j^n) = \frac{1}{T_y} \sum_{t=1}^{T_y} \left(\frac{y_{i,t} - \hat{\mu}_{y,i}}{\hat{\sigma}_{y,i}} \right)^m \left(\frac{y_{j,t} - \hat{\mu}_{y,j}}{\hat{\sigma}_{y,j}} \right)^n, \qquad (15)$$

$$\hat{\psi}_x(r_i^m, r_j^n) = \frac{1}{T_x} \sum_{t=1}^{T_x} \left(\frac{x_{i,t} - \hat{\mu}_{x,i}}{\hat{\sigma}_{x,i}} \right)^m \left(\frac{x_{j,t} - \hat{\mu}_{x,j}}{\hat{\sigma}_{x,j}} \right)^n \qquad (16)$$

and $\hat{v}_y$ is the FR adjusted unconditional correlation coefficient.

To test whether there is a significant change in coskewness, they formulate the following hypotheses:

$$H_0: \psi_y\left(r_i^m, r_j^n\right) = \psi_x\left(r_i^m, r_j^n\right) \quad (17)$$
$$H_1: \psi_y\left(r_i^m, r_j^n\right) \neq \psi_x\left(r_i^m, r_j^n\right)$$

Under the null hypothesis of no contagion, tests of contagion based on changes in coskewness are asymptotically distributed as

$$CS_{12}(i \to j), CS_{21}(i \to j) \overset{d}{\to} X_1^2$$

The framework Fry, Martin and Tang presented can also be used to create more test for contagion using higher co-moments such as cokurtosis.

3.4 The Hsiao cokurtosis test for contagion

The coskewness test is not always enough to capture the full scope contagion. Additional transmission channels may be detected raising order of moment by one.

The author tests for contagion from market *i* to market *j*, where *x* is the tranquil period prior to the crisis (low variance), while *y* is the period during the crisis (high variance). The asset returns are r_i and r_j for markets *i* and *j* respectively. The correlation between the two asset returns is denoted as ρ_x (tranquil period) and ρ_y (crisis period). Finally, the sample sizes of the pre-crisis and crisis periods are T_x and T_y respectively.

Two types of cokurtosis tests where created by using the framework developed by Fry, Martin and Tang for the coskewness tests, which are based on the Forbes and Rigobon test for contagion. The first type of statistic CK_{13} is to detect the shocks originating from the asset returns of the source market *i* to the cubed returns of market *j*. The second type of statistic CK_{31} is to measure the shock transmitting from the cubed asset returns of the source market *i* to the returns of market *j*. The cokurtosis statistics for testing for contagion from market *i* to market *j* are given by the following two equations:

$$CS_{13}\left(i \to j; r_i^1, r_j^3\right) = \left(\frac{\hat{\xi}_y\left(r_i^1, r_j^3\right) - \hat{\xi}_x\left(r_i^1, r_j^3\right)}{\sqrt{\frac{18\hat{v}_y^2 + 6}{T_y} + \frac{18\hat{\rho}_y^2 + 6}{T_x}}}\right)^2 \tag{18}$$

and

$$CS_{31}\left(i \to j; r_i^3, r_j^1\right) = \left(\frac{\hat{\xi}_y\left(r_i^3, r_j^1\right) - \hat{\xi}_x\left(r_i^3, r_j^1\right)}{\sqrt{\frac{18\hat{v}_y^2 + 6}{T_y} + \frac{18\hat{\rho}_y^2 + 6}{T_x}}}\right)^2 \quad , \tag{19}$$

where,

$$\hat{\xi}_y\left(r_i^m, r_j^n\right) = \frac{1}{T_y}\sum_{t=1}^{T_y}\left(\frac{y_{i,t} - \hat{\mu}_{y,i}}{\hat{\sigma}_{y,i}}\right)^m \left(\frac{y_{j,t} - \hat{\mu}_{y,j}}{\hat{\sigma}_{y,j}}\right)^n - (3\hat{v}_y), \tag{20}$$

$$\hat{\xi}_x\left(r_i^m, r_j^n\right) = \frac{1}{T_x}\sum_{t=1}^{T_x}\left(\frac{x_{i,t} - \hat{\mu}_{x,i}}{\hat{\sigma}_{x,i}}\right)^m \left(\frac{x_{j,t} - \hat{\mu}_{x,j}}{\hat{\sigma}_{x,j}}\right)^n - (3\hat{\rho}_x) \tag{21}$$

and $\hat{v}_y$ is the FR adjusted unconditional correlation coefficient.

To test whether there is a significant change in cokurtosis, the following hypotheses are made:

$$H_0: \xi_y\left(r_i^m, r_j^n\right) = \xi_x\left(r_i^m, r_j^n\right) \tag{22}$$
$$H_1: \xi_y\left(r_i^m, r_j^n\right) \neq \xi_x\left(r_i^m, r_j^n\right)$$

Under the null hypothesis of no contagion, tests of contagion based on changes in cokurtosis are asymptotically distributed as

$$CS_{13}(i \to j), CS_{31}(i \to j) \xrightarrow{d} X_1^2$$

3.5 The Hsiao covolatility test for contagion

Changes in the relation between the volatility of the returns of one market with the volatility of the returns of another market from negative to positive after the shock has occurred, reveals the volatility smile effect through the covolatility channel in the crisis period. During the crisis period a high covolatility means that the returns are high risk, which is undesirable by the investors.

The author tests for contagion from market *i* to market *j*, where *x* is the tranquil period, while *y* is the volatile period after the crisis has occurred. The asset returns are r_i and r_j for markets *i* and *j* respectively. The correlation between the two asset returns is denoted as ρ_x and ρ_y for the pre- and post-crisis period respectively. Finally, the sample sizes of the two periods are T_x and T_y.

The covolatility test detects shocks transmitted from the volatility of returns of the source market *i* to the volatility of returns of another market *j*. The covolatility statistic for testing for contagion from market *i* to market *j* is given by the following equation:

$$CV_{22}(i \to j; r_i^2, r_j^2) = \left(\frac{\hat{\xi}_y(r_i^2, r_j^2) - \hat{\xi}_x(r_i^2, r_j^2)}{\sqrt{\frac{4\hat{v}_y^4 + 16\hat{v}_y^2 + 4}{T_y} + \frac{4\hat{\rho}_x^4 + 16\hat{\rho}_x^2 + 4}{T_x}}} \right)^2, \qquad (23)$$

where,

$$\hat{\xi}_y(r_i^2, r_j^2) = \frac{1}{T_y} \sum_{t=1}^{T_y} \left(\frac{y_{i,t} - \hat{\mu}_{y,i}}{\hat{\sigma}_{y,i}} \right)^2 \left(\frac{y_{j,t} - \hat{\mu}_{y,j}}{\hat{\sigma}_{y,j}} \right)^2 - (1 + 2\hat{v}_y^2), \qquad (24)$$

$$\hat{\xi}_x(r_i^2, r_j^2) = \frac{1}{T_x} \sum_{t=1}^{T_x} \left(\frac{x_{i,t} - \hat{\mu}_{x,i}}{\hat{\sigma}_{x,i}} \right)^2 \left(\frac{x_{j,t} - \hat{\mu}_{x,j}}{\hat{\sigma}_{x,j}} \right)^2 - (1 + 2\hat{\rho}_x^2) \qquad (25)$$

To test whether there is a significant change in covolatility, the following hypotheses are made:

$$H_0: \xi_y\left(r_i^2, r_j^2\right) = \xi_x\left(r_i^2, r_j^2\right) \tag{26}$$
$$H_1: \xi_y\left(r_i^2, r_j^2\right) \neq \xi_x\left(r_i^2, r_j^2\right)$$

Under the null hypothesis of no contagion, tests of contagion based on changes in covolatility are asymptotically distributed as

$$CV_{22}(i \rightarrow j) \stackrel{d}{\rightarrow} X_1^2$$

It is important to note that both the Fry, Martin and Tang coskewness test and the Hsiao cokurtosis and covolatility tests are based on the Forbes and Rigobon adjusted correlation coefficient, therefore they follow the same assumptions of no omitted variables and absence of endogeneity.

4. Data and descriptive statistics

This section describes the data which were selected for the contagion tests to be applied to them. Daily observations are used for equity index, volatility index, government bond index, insurance sector CDS index and bank sector CDS index for both the EU and the US. Specifically the following indices were chosen (see Table 1):

Table 1
The financial sector indices.

	Europe	United States
Equity Index	EURO STOXX 50 Index (DJES50I)	S&P 500 Index (S&PCOMP)
Volatility Index	EURO STOXX 50 Volatility Index (VSTOXXI)	CBOE Volatility Index (CBOEVIX)
Sovereign Bond Index	EMU Benchmark 5 yr. DS Gov. Index (BMEM05Y)	US Benchmark 5 yr. DS Gov. Index (BMUS05Y)
Bank Sector CDS Index	EU Bank Sector 5 yr. DS CDS Index (EUBANCD)	US Bank Sector 5 yr. DS CDS Index (USBANCD)
Insurance Sector CDS Index	EU Insur. Sector 5 yr. DS CDS Index (EUINSCD)	US Insur. Sector 5 yr. DS CDS Index (USINSCD)

All the above indices were retrieved from Datastream, and the code inside the bracket below the name of the index indicates the Datastream mnemonic of the index.

The two equity indices are: the EURO STOXX 50 index, which consists of the fifty most liquid stocks from twelve Eurozone countries and the S&P 500, which is a market-value weighted index of the five hundred largest companies in the US. The VSTOXX is a volatility index based on option prices on the EURO STOXX 50 index, while the CBOE volatility index, also known as the new VIX, is based on options written on the S&P 500 index. The bond indices used are based on five-year sovereign bonds. Finally, the credit default swaps indices are based on Thomson Reuter's five-year CDS data for the EU and US bank and insurance sectors.

The event which denotes the beginning of the crisis period usually takes the form of a speculative attack followed by increased stock market volatility, important news announcements, the default of a major financial institution, capital flight to a safer currency or the default on sovereign debt. In this case the event is considered to be

September 15, 2008, which is the date when Lehman Brothers filed for Chapter 11 bankruptcy. The whole timeline is set from January 15, 2004 to January 14, 2012, for a total of 2088 observations for each of the ten time series. The sample period was chosen to be from four years before the crisis to four years after the crisis, this way the eight-year time period is long enough in order to perform the tests for contagion. Therefore the sample is divided into two periods at the date when the shock occurred; the pre-crisis period from January 15, 2004 to September 15, 2008 and the post-crisis period from September 16, 2008 to January 14, 2012, for a total of 1044 observations for each sub-period.

The time series are tested for the presence of unit root. The Augmented Dickey-Fuller (ADF) test suggests that all series, except the US insurance sector CDS index, are non-stationary. In order to achieve stationarity the continuously compounded daily returns of the indices are calculated. Let $r_{i,t}$ be the daily closing price of an index *i* on the day *t*. The continuously compounded daily returns of an index *i* on the day *t*, $s_{i,t}$, is calculated using the following equation:

$$s_{i,t} = \ln\left(\frac{r_{i,t}}{r_{i,t-1}}\right) \tag{27}$$

The mean, standard deviation, skewness, kurtosis and correlation coefficients of $s_{i,t}$ for the pre- and post-crisis periods are shown in Table 2 which can be found in the Appendix. It can be seen that all of the indices became more volatile, since the standard deviation of the ten indices increased during the period after the shock, compared to the tranquil period.

5. Empirical Application and Results

The tests of contagion described in Section 3 are now applied, in order to identify potential linkages which appeared during the global financial crisis. There are three cases of contagion examined: 1.Contagion among EU financial markets, 2.Contagion among US financial markets and 3.Contagion across EU and US financial markets.

In order to compute the Forbes and Rigobon test statistics, as well as the adjusted unconditional correlation coefficient needed for the coskewness, cokurtosis and covolatility tests, the daily market returns are filtered with a Vector Autoregressive (VAR) model. A twenty-nine lag VAR model is chosen. The Lagrange Multiplier autocorrelation test indicates no autocorrelations in the residuals at the 1% significance level. The residuals estimated from the VAR(29) model are used in computing the Forbes and Rigobon statistic in (5), the coskewness statistics in (13) and (14), the cokurtosis statistics in (18) and (19) and the covolatility statistic in (23). The same assumptions as Forbes and Rigobon are made that there are no omitted variables or endogeneity between markets. On the other hand, the statistic of the Li and Zhu non-parametric test for contagion in (10) is computed using the market returns, since Kendall’s tau does not require that a regression relationship exists between two markets.

Tables 3 to 7 found in the Appendix present the results of the Forbes and Rigobon correlation, the Li and Zhu non-parametric, the Fry et al. coskewness and the Hsiao cokurtosis and covolatility tests for contagion. These tests are applied to EU and US financial market indices, in order to describe how the transmission mechanism changed and examine whether contagion exists after the global financial crisis occurred. When looking at a table the first column indicates the source market, while the first line features the recipient market. By dividing the table into four quarters it becomes easier to observe the effects of contagion within EU/US market and across EU and US markets. The figures are test statistics, while those in brackets are p-values. The null hypothesis is ‘No Contagion’ and the rejection of H_0 means that contagion has occurred.

5.1 Results of the Forbes and Rigobon (FR) correlation test

Table 3 presents the empirical results of the **Forbes and Rigobon (2012)** test. This test examines if shocks transmit from the returns of one market to the returns of the second market, based on a significant increase in cross-correlation. From the table we see that 26 out of the 90 entries have a p-value less than the 5% significance level.

Inspection of the table reveals that contagion in the EU region transmits from the EUROSTOXX 50 to the bank and insurance sector CDS indices and from the insurance sector CDS to the bank sector CDS. Furthermore, the equity index is affected by both CDS indices as well as the bond index. For the US contagion was evident especially from and towards the insurance sector CDS index, with the exception of the equity index which was affected by the bank CDS index. As for contagion across both regions, it is evident from US insurance CDS to all the European indices, with the exception of the equity index. On the other hand, the US insurance CDS index was affected by both EU CDS indices and the volatility index. In addition, contagion transmitted to the EUROSTOXX 50 from the US bank CDS, sovereign bond and volatility indices. Finally, contagion spread from the EU bank CDS index to the S&P 500 and between the sovereign bond indices of both regions.

5.2 Results of the Li and Zhu non-parametric test

The **Li and Zhu (2014)** non-parametric test uses Kendall's tau, which measures the concordance between two markets and does not assume that the returns follow the normal distribution and the absence of omitted variables or endogeneity. This test measures if two variables move together, but unlike the **Forbes and Rigobon (2002)** test it does not check for the direction of transmission of the shock. Results are shown in Table 4, where we see that 30 out of the 45 entries have a p-value less than the 5% significance level, indicating significant evidence of contagion after the default of Lehman Brothers. By taking into account that this test does not examine if contagion transmits from market i to market j or vice versa, a conclusion can be reached that this tests reveals additional channels of contagion. Specifically, 66.7% of the cases tested using the Li and Zhu test reject the null hypothesis of 'No Contagion', contrary to the 28.9% using the Forbes and Rigobon test.

For the EU and US CDS market contagion was evident across all indices except the two equity indices. A similar pattern of contagion with the CDS indices is depicted by both sovereign bond indices, with the exception that no evidence of contagion was found within the bond market. Increased comovement was detected between the EUROSTOXX 50 and the S&P 500, as well as between each equity index and its respective volatility index. Finally, both volatility indices show significant increases in the cross-market linkages, although no evidence of contagion was found between the EU equity index and the VIX and between the US equity index and the VSTOXX.

5.3 Results of the Fry, Martin and Tang coskewness test

Fry, Martin and Tang (2010), argue that correlations are not enough to fully reveal the pattern of contagion and that important information can be obtained from higher order of moments, such as skewness, which tends to shift from negative to positive after a crisis. They develop two types of tests based on coskewness: the CS12 statistic tests for contagion transmitting from the returns of the source market to the volatility (squared returns) of the recipient market, while the CS21 statistic tests for contagion originating from the volatility of the first market to the returns of the second market, displaying opposite directions of contagion.

Results for the CS12 test are shown in table 5.a, where we see that 56 entries have a p-value less than the 5% significance level. Results for the CS21 test are shown in table 5.b, where we see that 56 entries have a p-value less than the 5% significance level. The coskewness tests show that contagion was more widespread compared to the Forbes and Rigobon test results.

Inspecting the results from the CS12 test table, a significant increase in cross-market linkages is detected across the EU region, from the returns of an index to the volatility of another index. The European bank and insurance sector CDS indices were affected by all of the EU indices. On the other hand, contagion did not spread towards the sovereign bond index from any of the other indices. Furthermore, contagion transmitted from all

EU indices to the EUROSTOXX 50, while the volatility index was affected by the bank sector CDS and equity indices. For the US similar results were observed. Contagion spread to the US bank CDS sector from all US indices, while the US insurance sector CDS index was affected by the bank CDS and sovereign bond indices. Contagion spread to the US bond index from the two CDS indices and from the US equity index. However, the VIX was not affected by any US market, while the S&P 500 was affected only by the bank CDS index.

Contagion was also significant across both regions, with EU and US bank CDS being affected by all of the US and EU markets respectively. Similar pattern can be detected for the EU insurance CDS, except that contagion did not occur from sovereign bonds. The EMU and US sovereign bond indices were not affected by the US and EU volatility indices respectively, while the former was unaffected by the US insurance sector CDS. Additionally, the European equity index was affected by all US markets except the two CDS indices, while the S&P 500 was affected by both EU CDS indices. Generally, few comovements were detected for the volatility indices, with contagion spreading from the VSTOXX and EMU sovereign bond index to the VIX.

The CS21 test reports similar results with the previous test, since they mirror each other. Contagion was evident from the volatility of the EU bank and insurance CDS indices to the returns of the rest of the EU markets. On the other hand, the EMU sovereign bond index did not affect any of the other indices. Furthermore, contagion transmitted from the EUROSTOXX 50 to the rest of the European indices and from the volatility index to the bank sector CDS and equity indices. For the US, contagion spread from the bank sector CDS index to the rest of the markets and from the insurance CDS index to the bank and sovereign bond indices. Contagion also appeared from the US sovereign bond index to both CDS indices and the equity index, while the S&P 500 affected only the bank sector CDS index.

Contagion is also prominent between the two regions, being particularly widespread from the European and US bank and insurance sector CDS indices to the US and EU markets respectively, with the bond index of each region being unaffected by the insurance CDS index of the other region. Contagion originating from the US bond index spread to all EU markets except the volatility index and from the EMU bond index towards all indices except the US insurance CDS index and the VIX. The CS21 coskewness test detects contagion from the S&P 500 to both EU CDS indices and from the EUSTOXX 50 to all US markets except for the two US CDS indices. However, contagion did not transmit from the VSTOXX towards any US index, while the VIX affected the sovereign bond and volatility indices of the EU region.

5.4 Results of the Hsiao cokurtosis test

Hsiao (2012) created a test for contagion based on cokurtosis. Asset returns typically have “fat tails” and after a shock occurs kurtosis rises. The author develops two types of tests based on cokurtosis: the CK13 statistic tests for contagion transmitting from the returns of the source market to the skewness (cubic returns) of the recipient market, while the CK31 statistic tests for contagion originating from the skewness of the first market to the returns of the second market.

Results for the CK13 test can be found in table 6.a, where we see that 77 entries have a p-value less than the 5% significance level. Results for the CK31 test are depicted in table 6.b, where we see that 75 entries have a p-value less than the 5% significance level. By observing the results one can reach the conclusion that the effects of contagion as reported by the cokurtosis test are even greater than those of the previous tests.

By examining the results of the CK13 test for contagion, significant changes can be observed between return and skewness across all indices. The EU bank sector CDS, insurance sector CDS, equity and volatility indices were each affected by all EU indices, with the exception of the EUROSTOXX 50 which was not affected by the VSTOXX. On the other hand, contagion transmitted to the sovereign bond index only from the equity index. In the US contagion transmitted among all markets after the global financial crisis.

Compared to the previous tests contagion was even more widespread across financial markets. Shocks originating from European financial markets returns spread toward all US financial markets skewness, with the exception of the S&P 500 being unaffected by both EU CDS indices and the VIX by the EUROSTOXX 50. On the other hand, the effects of contagion spread towards the EU bank and insurance CDS indices from all US indices, while the EMU sovereign bond index was affected by its US counterpart and the US bank CDS index. Additionally, contagion transmits from all US markets, except the sovereign bond index, to the EU equity index. Lastly, contagion spread to the VSTOXX from the US insurance CDS, equity and volatility indices.

Equivalent results are obtained by the application of the CK31 test. In the EU region, changes in the transmission mechanism of shocks were prominent from the bank CDS, insurance CDS and equity indices. The bond index affected only the equity index, while contagion spread from the volatility index to all indices with the exception of the equity index. Contagion was widespread among all financial markets in the US, except that contagion did not transmit from the skewness of the US insurance CDS index to the returns of the S&P 500.

Increased comovements were also detected between EU and US financial markets. Contagion effects spread from EU and US bank and insurance CDS indices towards all US and EU financial markets respectively. Furthermore, contagion transmits from the US sovereign bonds to all EU markets and from the EUROSTOXX 50 to US indices. However, the EMU sovereign bond index affected all US markets except the equity and volatility index and the S&P 500 affected only the respective EU equity index. Finally, contagion spread from the VIX to all EU indices and from the VSTOXX to the US bank CDS and volatility markets.

5.5 Results of the Hsiao covolatility test

Another test developed by **Hsiao (2012)** is based on covolatility. The CV22 statistic tests for contagion transmitting from the volatility (squared returns) of the source market to the volatility of the recipient market. Results for the CV22 test can be found in table 7, where we see that 76 entries have a p-value less than the 5% significance level.

In the EU region the effects of the global financial crisis are widespread. Contagion transmits from the bank CDS to the insurance CDS, equity and volatility indices and from the insurance CDS to the bank CDS, equity and volatility indices. Furthermore, contagion spreads from the EU equity index to all the EU indices, while in the case of the VSTOXX shocks transmit to all indices except the EUROSTOXX 50. Additionally, the sovereign bond index affected the equity and volatility indices. On the other hand, in the US contagion was spread among all financial markets.

Based on the covolatility test contagion across both regions was similarly extensive. Effects were evident between the US bank CDS index and all EU indices, between the US sovereign bond index and all EU markets, between EMU sovereign bond index and the US financial markets and between EUROSTOXX 50 and all US indices. Furthermore, contagion appeared between the US insurance CDS index and all EU markets, with the exception of EU bank sector CDS index and the EU volatility index. In addition, contagion spread between the US insurance CDS index, its European counterpart, the EMU bond index and the equity index. Contagion also transmitted between the S&P 500 and all EU indices, except the bank CDS index and from the US equity index to the EU volatility index. Finally, contagion spread between the VIX and all EU indices except the insurance sector CDS index.

6. Summary and Concluding Remarks

This study uses the Forbes and Rigobon correlation, Li and Zhu non-parametric, the Fry et al. coskewness and the Hsiao cokurtosis and covolatility tests to examine contagion across EU and US financial markets. The crisis selected to apply the tests is the recent global financial crisis, which is considered to have begun by the bankruptcy of Lehman Brothers on September 15, 2008. The data used are bank sector CDS, insurance sector CDS, sovereign bond, equity and volatility indices for the time period from January 15, 2004 to January 14, 2012.

The Forbes-Rigobon test showed that contagion occurred both within and among EU and US financial markets, with US insurance sector CDS and EU equities being the most affected. However, by applying the Li and Zhu test additional cross market linkages are revealed, specifically contagion was prominent in both EU and US CDS and volatility indices; on the other hand the equity indices for both regions show significant increase in comovements with only a few of the other markets. The coskewness test exposes additional channels of contagion not appearing on the previous two tests, particularly across the two regions. The results from the tests based on extremal dependence (cokurtosis and covolatility) capture more comovements than the preceding tests. The cokurtosis test reveals that contagion was widespread within the US market, but also transmitted between US and EU indices. Finally, the covolatility test finds significant contagion especially within the US and across both regions with the CDS, equity and bond markets being greatly affected.

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Appendix

Table of descriptive statistics

Table 2
The descriptive statistics

Descriptive statistics for the pre-crisis period										
	EUBACDS	EUINCDS	EMUSVBO	EUSTOXX	VSTOXX	USBACDS	USINCDS	USSVBO	SPX	VIX
Mean	0.00249	0.00129	-0.00001	0.00012	0.00067	0.00249	0.00236	0.00003	0.00005	0.00081
Std. Dev.	0.03597	0.04119	0.00184	0.01029	0.05218	0.05184	0.04092	0.00270	0.00901	0.06294
Skewness	1.08343	2.15014	-0.00364	-0.44000	0.86925	-1.29980	0.37288	0.11097	-0.35873	0.70450
Kurtosis	13.52152	30.95665	4.46548	8.23201	6.10058	31.48781	10.81201	6.21038	5.92657	8.84771
Pre-crisis period correlation										
	EUBACDS	EUINCDS	EMUSVBO	EUSTOXX	VSTOXX	USBACDS	USINCDS	USSVBO	SPX	VIX
EUBACDS	EUBACDS	0.72234	0.25889	-0.27970	0.22759	0.25855	0.47809	0.16923	-0.11494	0.07295
EUINCDS	0.72234	EUINCDS	0.21822	-0.24623	0.24796	0.23395	0.44325	0.14435	-0.12052	0.10481
EMUSVBO	0.25889	0.21822	EMUSVBO	-0.41113	0.33382	0.23485	0.21193	0.57167	-0.25156	0.18963
EUSTOXX	-0.27970	-0.24623	-0.41113	EUSTOXX	-0.81312	-0.31983	-0.29414	-0.31168	0.48355	-0.40025
VSTOXX	0.22759	0.24796	0.33382	-0.81312	VSTOXX	0.26928	0.24540	0.26541	-0.43123	0.45215
USBACDS	0.25855	0.23395	0.23485	-0.31983	0.26928	USBACDS	0.41385	0.20792	-0.30103	0.24239
USINCDS	0.47809	0.44325	0.21193	-0.29414	0.24540	0.41385	USINCDS	0.21967	-0.27450	0.22736
USSVBO	0.16923	0.14435	0.57167	-0.31168	0.26541	0.20792	0.21967	USSVBO	-0.39973	0.30151
SPX	-0.11494	-0.12052	-0.25156	0.48355	-0.43123	-0.30103	-0.27450	-0.39973	SPX	-0.80914
VIX	0.07295	0.10481	0.18963	-0.40025	0.45215	0.24239	0.22736	0.30151	-0.80914	VIX
Descriptive statistics for the post-crisis period										
	EUBACDS	EUINCDS	EMUSVBO	EUSTOXX	VSTOXX	USBACDS	USINCDS	USSVBO	SPX	VIX
Mean	0.00067	0.00011	0.00017	-0.00019	-0.00042	-0.00082	-0.00067	0.00015	0.00020	-0.00075
Std. Dev.	0.04019	0.04564	0.00236	0.01867	0.06374	0.05409	0.09494	0.00323	0.01715	0.07185
Skewness	-0.15719	-5.37533	-0.03285	0.13490	0.78845	0.02789	-13.31658	-0.14018	-0.26795	0.71784
Kurtosis	22.51380	92.85061	4.46621	7.18374	5.95402	24.86864	343.39414	8.29233	10.25302	6.62651
Pre-crisis period correlation										
	EUBACDS	EUINCDS	EMUSVBO	EUSTOXX	VSTOXX	USBACDS	USINCDS	USSVBO	SPX	VIX
EUBACDS	EUBACDS	0.60832	0.36477	-0.44636	0.40099	0.32821	0.11397	0.22223	-0.27716	0.30077
EUINCDS	0.60832	EUINCDS	0.36786	-0.45636	0.40668	0.32986	0.16366	0.23029	-0.29239	0.29589
EMUSVBO	0.36477	0.36786	EMUSVBO	-0.57288	0.49242	0.36373	0.15568	0.51138	-0.37422	0.37924
EUSTOXX	-0.44636	-0.45636	-0.57288	EUSTOXX	-0.77119	-0.50831	-0.17755	-0.39571	0.66127	-0.56285
VSTOXX	0.40099	0.40668	0.49242	-0.77119	VSTOXX	0.43517	0.16356	0.31991	-0.46778	0.60427
USBACDS	0.32821	0.32986	0.36373	-0.50831	0.43517	USBACDS	0.20890	0.33023	-0.45004	0.44172
USINCDS	0.11397	0.16366	0.15568	-0.17755	0.16356	0.20890	USINCDS	0.09676	-0.16462	0.18187
USSVBO	0.22223	0.23029	0.51138	-0.39571	0.31991	0.33023	0.09676	USSVBO	-0.40409	0.36259
SPX	-0.27716	-0.29239	-0.37422	0.66127	-0.46778	-0.45004	-0.16462	-0.40409	SPX	-0.76845
VIX	0.30077	0.29589	0.37924	-0.56285	0.60427	0.44172	0.18187	0.36259	-0.76845	VIX

Table of the Forbes and Rigobon correlation test results

Table 3

The Forbes and Rigobon test for contagion results, based on the residuals of the VAR(29) model

Tests for contagion from source market i to recipient market j, based on increases in cross-correlation

	Recipient Market Returns									
Source Market Returns	EUBACDS	EUINCDS	EMUSVBO	EUSTOXX	VSTOXX	USBACDS	USINCDS	USSVBO	SPX	VIX
EUBACDS	EUBACDS	0.0846 [0.5337]	3.9458 [1.0000]	**-7.4614 [0.0000]**	6.8648 [1.0000]	3.9892 [1.0000]	**-5.1562 [0.0000]**	0.6064 [0.7279]	**-3.6734 [0.0001]**	5.0982 [1.0000]
EUINCDS	**-2.2167 [0.0133]**	EUINCDS	2.7296 [0.9968]	**-4.2043 [0.0000]**	3.4848 [0.9998]	2.3648 [0.9910]	**-4.2073 [0.0000]**	0.6004 [0.7259]	-1.2608 [0.1037]	2.2305 [0.9871]
EMUSVBO	2.5348 [0.9944]	2.6909 [0.9964]	EMUSVBO	**-3.2597 [0.0006]**	2.6000 [0.9953]	3.1842 [0.9993]	-1.2594 [0.1039]	**-3.9269 [0.0000]**	-1.0766 [0.1408]	2.7471 [0.9970]
EUSTOXX	**-2.7662 [0.0028]**	**-1.7596 [0.0392]**	-0.2136 [0.4154]	EUSTOXX	7.3660 [1.0000]	-1.4706 [0.0707]	4.1193 [1.0000]	1.2579 [0.8958]	-1.5065 [0.0660]	1.9607 [0.9750]
VSTOXX	4.9922 [1.0000]	3.2416 [0.9994]	2.3720 [0.9912]	3.2620 [0.9994]	VSTOXX	3.0718 [0.9989]	**-2.2970 [0.0108]**	0.4957 [0.6900]	1.0406 [0.8510]	1.5584 [0.9404]
USBACDS	3.9721 [1.0000]	3.4905 [0.9998]	4.4660 [1.0000]	**-5.7478 [0.0000]**	4.7254 [1.0000]	USBACDS	**-3.0141 [0.0013]**	4.0912 [1.0000]	**-4.9572 [0.0000]**	4.4086 [1.0000]
USINCDS	**-6.5877 [0.0000]**	**-5.6957 [0.0000]**	**-2.3602 [0.0091]**	4.6736 [1.0000]	**-3.4197 [0.0003]**	**-5.5221 [0.0000]**	USINCDS	**-4.3578 [0.0000]**	4.6901 [1.0000]	**-4.3294 [0.0000]**
USSVBO	0.1227 [0.5488]	0.9100 [0.8186]	**-3.0906 [0.0010]**	**-1.6923 [0.0453]**	1.2213 [0.8890]	3.3646 [0.9996]	**-3.6028 [0.0002]**	USSVBO	-0.3767 [0.3532]	1.6623 [0.9518]
SPX	-0.7202 [0.2357]	0.2125 [0.5841]	0.7394 [0.7702]	-0.9418 [0.1732]	3.3178 [0.9995]	-0.8618 [0.1944]	3.8735 [0.9999]	2.3088 [0.9895]	SPX	7.5454 [1.0000]
VIX	4.3347 [1.0000]	2.6897 [0.9964]	3.3656 [0.9996]	**-2.4731 [0.0067]**	3.0138 [0.9987]	3.4742 [0.9997]	**-2.2721 [0.0115]**	1.6687 [0.9524]	2.3838 [0.9914]	VIX

Notes: The null hypothesis is 'No Contagion'. The figures are test statistics values, while those in brackets are p-values.
Figures in bold indicate the rejection of the null hypothesis of "No Contagion" at the 5% significance level.
EUBACDS, USBACDS and EUINCDS, USINCDS are the bank sector CDS indices and the insurance sector CDS indices for the EU and the US respectively.
EMUSVBO, USSVBO are the sovereign bond indices for the EMU and the US respectively. EUSTOXX, SPX and VSTOXX, VIX are the equity indices and volatility indices for the EU and the US respectively.

Table of the Li and Zhu non-parametric test results

Table 4

The Li and Zhu non-parametric test for contagion results, based on the asset returns

	EUBACDS	EUINCDS	EMUSVBO	EUSTOXX	VSTOXX	USBACDS	USINCDS	USSVBO	SPX	VIX
EUBACDS	EUBACDS	**-146.7134 [0.0000]**	**-112.0071 [0.0000]**	156.0784 [1.0000]	**-147.0810 [0.0000]**	**-111.6011 [0.0000]**	**-37.3966 [0.0000]**	**-66.2582 [0.0000]**	117.3547 [1.0000]	**-124.8661 [0.0000]**
EUINCDS		EUINCDS	**-82.5955 [0.0000]**	142.5488 [1.0000]	**-105.0189 [0.0000]**	**-92.1701 [0.0000]**	**-44.4736 [0.0000]**	**-55.9952 [0.0000]**	103.0347 [1.0000]	**-102.6767 [0.0000]**
EMUSVBO			EMUSVBO	116.0489 [1.0000]	**-111.3147 [0.0000]**	**-86.8663 [0.0000]**	**-54.1515 [0.0000]**	18.4595 [1.0000]	104.7671 [1.0000]	**-84.9019 [0.0000]**
EUSTOXX				EUSTOXX	**-19.4297 [0.0000]**	145.2988 [1.0000]	86.5682 [1.0000]	73.0003 [1.0000]	**-117.4817 [0.0000]**	66.9319 [1.0000]
VSTOXX					VSTOXX	**-113.3342 [0.0000]**	**-78.2552 [0.0000]**	**-74.3566 [0.0000]**	54.6389 [1.0000]	**-63.4535 [0.0000]**
USBACDS						USBACDS	**-25.7091 [0.0000]**	**-84.4366 [0.0000]**	176.1929 [1.0000]	**-158.0205 [0.0000]**
USINCDS							USINCDS	**-28.0133 [0.0000]**	110.4893 [1.0000]	**-100.9346 [0.0000]**
USSVBO								USSVBO	90.2721 [1.0000]	**-72.2808 [0.0000]**
SPX									SPX	**-16.34925 [0.0000]**
VIX										VIX

Notes: The null hypothesis is 'No Contagion'. The figures are test statistics values, while those in brackets are p-values.
Figures in bold indicate the rejection of the null hypothesis of "No Contagion" at the 5% significance level.
EUBACDS, USBACDS and EUINCDS, USINCDS are the bank sector CDS indices and the insurance sector CDS indices for the EU and the US respectively. EMUSVBO, USSVBO are the sovereign bond indices for the EMU and the US respectively. EUSTOXX, SPX and VSTOXX, VIX are the equity indices and volatility indices for the EU and the US respectively.

Tables of the Fry, Martin and Tang coskewness test results

Table 5.a

The Fry, Martin and Tang CS12 coskewness test for contagion results, based on the residuals of the VAR(29) model

Tests for contagion based on shocks transmitting from the returns of the source market i to the volatility in the recipient market j

		Recipient Market Volatility									
		EUBACDS	EUINCDS	EMUSVBO	EUSTOXX	VSTOXX	USBACDS	USINCDS	USSVBO	SPX	VIX
Source Market Returns	EUBACDS	EUBACDS	**1304.9572**	1.7054	**35.8625**	**5.7896**	**41.2384**	**188.6121**	**8.9343**	**5.2271**	0.8132
			[0.0000]	[0.1916]	**[0.0000]**	**[0.0161]**	**[0.0000]**	**[0.0000]**	**[0.0028]**	**[0.0222]**	[0.3672]
	EUINCDS	**413.6954**	EUINCDS	3.5217	**16.4335**	1.1579	**163.8685**	**4.7749**	**8.3859**	**6.9337**	3.4311
		[0.0000]		[0.0606]	**[0.0001]**	[0.2819]	**[0.0000]**	**[0.0289]**	**[0.0038]**	**[0.0085]**	[0.0640]
	EMUSVBO	**18.8443**	**84.7577**	EMUSVBO	**4.8164**	0.2149	**79.1071**	0.8990	**24.9422**	0.4663	**6.3270**
		[0.0000]	**[0.0000]**		**[0.0282]**	[0.6429]	**[0.0000]**	[0.3431]	**[0.0000]**	[0.4947]	**[0.0119]**
	EUSTOXX	**47.4569**	**60.9156**	3.4152	EUSTOXX	**15.1838**	**49.3319**	**5.3835**	**21.8789**	0.2674	0.7951
		[0.0000]	**[0.0000]**	[0.0646]		**[0.0001]**	**[0.0000]**	**[0.0203]**	**[0.0000]**	[0.6051]	[0.3726]
	VSTOXX	**54.1667**	**103.4058**	0.0204	**25.5339**	VSTOXX	**48.2931**	**65.3912**	2.7771	0.0507	**7.2878**
		[0.0000]	**[0.0000]**	[0.8863]	**[0.0000]**		**[0.0000]**	**[0.0000]**	[0.0956]	[0.8219]	**[0.0069]**
	USBACDS	**34.3599**	**17.9498**	**5.8523**	2.1755	0.0440	USBACDS	**16.4976**	**27.9919**	**9.8778**	2.3413
		[0.0000]	**[0.0000]**	**[0.0156]**	[0.1402]	[0.8338]		**[0.0000]**	**[0.0000]**	**[0.0017]**	[0.1260]
	USINCDS	**32.8486**	**52.5842**	1.7896	0.5465	1.7062	**146.3580**	USINCDS	**25.9555**	0.0603	0.5487
		[0.0000]	**[0.0000]**	[0.1810]	[0.4597]	[0.1915]	**[0.0000]**		**[0.0000]**	[0.8061]	[0.4589]
	USSVBO	**8.8357**	1.5516	**16.4226**	**10.7750**	0.8111	**174.1397**	**58.5646**	USSVBO	1.0600	0.4425
		[0.0030]	[0.2129]	**[0.0001]**	**[0.0010]**	[0.3678]	**[0.0000]**	**[0.0000]**		[0.3032]	[0.5059]
	SPX	**22.8390**	**46.9794**	**5.5277**	**5.9814**	1.2630	**44.2181**	0.4498	**29.4733**	SPX	0.1051
		[0.0000]	**[0.0000]**	**[0.0187]**	**[0.0145]**	[0.2611]	**[0.0000]**	[0.5024]	**[0.0000]**		[0.7458]
	VIX	**31.2513**	**56.8310**	0.0003	**4.1985**	2.1518	**8.9737**	3.6896	2.1353	1.2960	VIX
		[0.0000]	**[0.0000]**	[0.9855]	**[0.0405]**	[0.1424]	**[0.0027]**	[0.0548]	[0.1439]	[0.2549]	

Notes: The null hypothesis is 'No Contagion'. The figures are test statistics values, while those in brackets are p-values.
Figures in bold indicate the rejection of the null hypothesis of "No Contagion" at the 5% significance level.
EUBACDS, USBACDS and EUINCDS, USINCDS are the bank sector CDS indices and the insurance sector CDS indices for the EU and the US respectively. EMUSVBO, USSVBO are the sovereign bond indices for the EMU and the US respectively. EUSTOXX, SPX and VSTOXX, VIX are the equity indices and volatility indices for the EU and the US respectively.

Table 5.b

The Fry, Martin and Tang CS21 coskewness test for contagion results, based on the residuals of the VAR(29) model

Tests for contagion based on shocks transmitting from the volatility of the source market i to the returns in the recipient market j

		Recipient Market Returns									
		EUBACDS	EUINCDS	EMUSVBO	EUSTOXX	VSTOXX	USBACDS	USINCDS	USSVBO	SPX	VIX
Source Market Volatility	EUBACDS	EUBACDS	**396.5535** **[0.0000]**	**18.2373** **[0.0000]**	**42.3169** **[0.0000]**	**51.6972** **[0.0000]**	**34.3462** **[0.0000]**	**32.5362** **[0.0000]**	**8.7634** **[0.0031]**	**21.4488** **[0.0000]**	**30.6946** **[0.0000]**
	EUINCDS	**1361.3669** **[0.0000]**	EUINCDS	**84.6896** **[0.0000]**	**57.5973** **[0.0000]**	**102.8269** **[0.0000]**	**18.3885** **[0.0000]**	**51.9104** **[0.0000]**	1.5591 [0.2118]	**45.7224** **[0.0000]**	**57.3727** **[0.0000]**
	EMUSVBO	1.7621 [0.1844]	3.5245 [0.0605]	EMUSVBO	3.1845 [0.0743]	0.0203 [0.8866]	**6.0251** **[0.0141]**	1.7758 [0.1827]	**16.7029** **[0.0000]**	**5.3234** **[0.0210]**	0.0003 [0.9854]
	EUSTOXX	**40.2185** **[0.0000]**	**17.3803** **[0.0000]**	**5.1655** **[0.0230]**	EUSTOXX	**27.2155** **[0.0000]**	2.4078 [0.1207]	0.5445 [0.4606]	**11.4822** **[0.0007]**	**6.0472** **[0.0139]**	**4.6116** **[0.0318]**
	VSTOXX	**6.0661** **[0.0138]**	1.1645 [0.2805]	0.2161 [0.6420]	**14.2456** **[0.0002]**	VSTOXX	0.0458 [0.8305]	1.6923 [0.1933]	0.8237 [0.3641]	1.2037 [0.2726]	2.2114 [0.1370]
	USBACDS	**41.2548** **[0.0000]**	**159.9589** **[0.0000]**	**76.8378** **[0.0000]**	**44.5717** **[0.0000]**	**46.4377** **[0.0000]**	USBACDS	**142.2491** **[0.0000]**	**171.2633** **[0.0000]**	**40.1593** **[0.0000]**	**8.7732** **[0.0031]**
	USINCDS	**190.4230** **[0.0000]**	**4.8369** **[0.0279]**	0.9060 [0.3412]	**5.4032** **[0.0201]**	**65.9303** **[0.0000]**	**16.9741** **[0.0000]**	USINCDS	**58.7531** **[0.0000]**	0.4529 [0.5010]	3.7730 [0.0521]
	USSVBO	**9.0081** **[0.0027]**	**8.3457** **[0.0039]**	**24.5237** **[0.0000]**	**20.5314** **[0.0000]**	2.7347 [0.0982]	**28.4621** **[0.0000]**	**25.8722** **[0.0000]**	USSVBO	**27.8452** **[0.0000]**	2.1357 [0.1439]
	SPX	**5.5659** **[0.0183]**	**7.1243** **[0.0076]**	0.4842 [0.4865]	0.2645 [0.6070]	0.0531 [0.8177]	**10.8761** **[0.0010]**	0.0598 [0.8067]	1.1220 [0.2895]	SPX	1.3982 [0.2370]
	VIX	0.8279 [0.3629]	3.3987 [0.0652]	**6.2375** **[0.0125]**	0.7239 [0.3949]	**7.0913** **[0.0077]**	2.3948 [0.1217]	0.5365 [0.4639]	0.4424 [0.5060]	0.0974 [0.7550]	VIX

Notes: The null hypothesis is 'No Contagion'. The figures are test statistics values, while those in brackets are p-values.
Figures in bold indicate the rejection of the null hypothesis of "No Contagion" at the 5% significance level.
EUBACDS, USBACDS and EUINCDS, USINCDS are the bank sector CDS indices and the insurance sector CDS indices for the EU and the US respectively.
EMUSVBO, USSVBO are the sovereign bond indices for the EMU and the US respectively. EUSTOXX, SPX and VSTOXX, VIX are the equity indices and volatility indices for the EU and the US respectively.

Tables of the Hsiao cokurtosis test results

Table 6.a

The Hsiao CK13 cokurtosis test for contagion results, based on the residuals of the VAR(29) model

Tests for contagion based on shocks transmitting from the returns of the source market i to the skewness in the recipient market j

	Recipient Market Skewness									
Source Market Returns	EUBACDS	EUINCDS	EMUSVBO	EUSTOXX	VSTOXX	USBACDS	USINCDS	USSVBO	SPX	VIX
EUBACDS	EUBACDS	**10205.5493 [0.0000]**	3.3303 [0.0680]	**225.5743 [0.0000]**	**87.7892 [0.0000]**	**3993.3732 [0.0000]**	**46997.3575 [0.0000]**	**229.7007 [0.0000]**	2.4847 [0.1150]	**266.0402 [0.0000]**
EUINCDS	**10.9016 [0.0010]**	EUINCDS	0.0469 [0.8285]	**302.1652 [0.0000]**	**88.7319 [0.0000]**	**5253.5752 [0.0000]**	**1266.0075 [0.0000]**	**170.6686 [0.0000]**	0.2013 [0.6537]	**151.7649 [0.0000]**
EMUSVBO	**164.5394 [0.0000]**	**3211.1228 [0.0000]**	EMUSVBO	**13.6850 [0.0002]**	**10.3225 [0.0013]**	**3481.8121 [0.0000]**	**55.6346 [0.0000]**	**48.7625 [0.0000]**	**8.1464 [0.0043]**	**38.4251 [0.0000]**
EUSTOXX	**1350.9614 [0.0000]**	**5.4857 [0.0192]**	**20.8134 [0.0000]**	EUSTOXX	**7.6546 [0.0057]**	**1252.6006 [0.0000]**	**6320.2112 [0.0000]**	**29.5538 [0.0000]**	**18.2400 [0.0000]**	1.8010 [0.1796]
VSTOXX	**636.9361 [0.0000]**	**934.5984 [0.0000]**	0.0485 [0.8258]	0.6210 [0.4307]	VSTOXX	**1058.7510 [0.0000]**	**16549.7257 [0.0000]**	**95.1658 [0.0000]**	**7.9933 [0.0047]**	**160.1791 [0.0000]**
USBACDS	**720.4021 [0.0000]**	**555.3689 [0.0000]**	**128.2553 [0.0000]**	**55.0823 [0.0000]**	3.0162 [0.0824]	USBACDS	**1042.3779 [0.0000]**	**775.1362 [0.0000]**	**50.9177 [0.0000]**	**10.1452 [0.0014]**
USINCDS	**258.1775 [0.0000]**	**809.1019 [0.0000]**	0.7929 [0.3732]	**23.5787 [0.0000]**	**5.6084 [0.0179]**	**3126.9628 [0.0000]**	USINCDS	**131.4078 [0.0000]**	**61.3145 [0.0000]**	**82.7473 [0.0000]**
USSVBO	**39.5020 [0.0000]**	**1944.7984 [0.0000]**	**11.6272 [0.0006]**	0.1508 [0.6978]	2.2798 [0.1311]	**5557.7519 [0.0000]**	**24231.7604 [0.0000]**	USSVBO	**51.3448 [0.0000]**	**44.9288 [0.0000]**
SPX	**93.8494 [0.0000]**	**2793.2024 [0.0000]**	0.0618 [0.8037]	**55.2229 [0.0000]**	**8.1319 [0.0043]**	**1622.1271 [0.0000]**	**6.8172 [0.0090]**	**174.2880 [0.0000]**	SPX	**109.2706 [0.0000]**
VIX	**523.2154 [0.0000]**	**4687.2087 [0.0000]**	1.5200 [0.2176]	**53.8935 [0.0000]**	**3.9397 [0.0472]**	**555.5531 [0.0000]**	**216.6959 [0.0000]**	**129.2309 [0.0000]**	**4.5020 [0.0339]**	VIX

Notes: The null hypothesis is 'No Contagion'. The figures are test statistics values, while those in brackets are p-values.
Figures in bold indicate the rejection of the null hypothesis of "No Contagion" at the 5% significance level.
EUBACDS, USBACDS and EUINCDS, USINCDS are the bank sector CDS indices and the insurance sector CDS indices for the EU and the US respectively. EMUSVBO, USSVBO are the sovereign bond indices for the EMU and the US respectively. EUSTOXX, SPX and VSTOXX, VIX are the equity indices and volatility indices for the EU and the US respectively.

Table 6.b

The Hsiao CK31 cokurtosis test for contagion results, based on the residuals of the VAR(29) model

Tests for contagion based on shocks transmitting from the skewness of the source market i to the returns in the recipient market j

		Recipient Market Returns									
		EUBACDS	EUINCDS	EMUSVBO	EUSTOXX	VSTOXX	USBACDS	USINCDS	USSVBO	SPX	VIX
Source Market Skewness	EUBACDS	EUBACDS	**4.2124** **[0.0401]**	**125.9232** **[0.0000]**	**914.1756** **[0.0000]**	**520.5707** **[0.0000]**	**719.1109** **[0.0000]**	**308.6156** **[0.0000]**	**45.9222** **[0.0000]**	**40.4028** **[0.0000]**	**477.3229** **[0.0000]**
	EUINCDS	**11006.7363** **[0.0000]**	EUINCDS	**3202.8250** **[0.0000]**	**20.4576** **[0.0000]**	**913.1051** **[0.0000]**	**632.0790** **[0.0000]**	**890.8443** **[0.0000]**	**1927.6549** **[0.0000]**	**2849.3896** **[0.0000]**	**4685.8598** **[0.0000]**
	EMUSVBO	0.2737 [0.6009]	0.0661 [0.7971]	EMUSVBO	**4.0878** **[0.0432]**	0.0006 [0.9808]	**165.0089** **[0.0000]**	**4.8313** **[0.0279]**	**8.2721** **[0.0040]**	2.2551 [0.1332]	0.4283 [0.5128]
	EUSTOXX	**411.8107** **[0.0000]**	**417.9933** **[0.0000]**	**39.9449** **[0.0000]**	EUSTOXX	**6.7039** **[0.0096]**	**139.9112** **[0.0000]**	**17.6478** **[0.0000]**	**5.6220** **[0.0177]**	**60.8413** **[0.0000]**	**116.3696** **[0.0000]**
	VSTOXX	**128.7490** **[0.0000]**	**93.9086** **[0.0000]**	**11.7011** **[0.0006]**	0.9193 [0.3377]	VSTOXX	**11.1597** **[0.0008]**	1.0704 [0.3008]	0.6615 [0.4160]	1.1020 [0.2938]	**7.5610** **[0.0060]**
	USBACDS	**3997.7163** **[0.0000]**	**4912.8684** **[0.0000]**	**3196.3905** **[0.0000]**	**863.7125** **[0.0000]**	**908.5522** **[0.0000]**	USBACDS	**2709.7671** **[0.0000]**	**5323.9687** **[0.0000]**	**1184.4812** **[0.0000]**	**503.8142** **[0.0000]**
	USINCDS	**46946.1509** **[0.0000]**	**1171.8624** **[0.0000]**	**38.2154** **[0.0000]**	**6252.1087** **[0.0000]**	**16410.8432** **[0.0000]**	**910.0259** **[0.0000]**	USINCDS	**24068.7898** **[0.0000]**	2.8512 [0.0913]	**299.3964** **[0.0000]**
	USSVBO	**216.5230** **[0.0000]**	**178.6960** **[0.0000]**	**55.8375** **[0.0000]**	**61.7753** **[0.0000]**	**107.2359** **[0.0000]**	**834.5213** **[0.0000]**	**152.0334** **[0.0000]**	USSVBO	**226.4056** **[0.0000]**	**129.1255** **[0.0000]**
	SPX	1.9354 [0.1642]	1.2715 [0.2595]	1.3000 [0.2542]	**15.4146** **[0.0001]**	1.3221 [0.2502]	**124.1670** **[0.0000]**	**76.0761** **[0.0000]**	**25.0859** **[0.0000]**	SPX	0.0262 [0.8715]
	VIX	**298.1019** **[0.0000]**	**138.2572** **[0.0000]**	**30.8240** **[0.0000]**	**16.6085** **[0.0000]**	**173.1750** **[0.0000]**	**6.0482** **[0.0139]**	**126.6202** **[0.0000]**	**44.9973** **[0.0000]**	**142.8798** **[0.0000]**	VIX

Notes: The null hypothesis is 'No Contagion'. The figures are test statistics values, while those in brackets are p-values.
Figures in bold indicate the rejection of the null hypothesis of “No Contagion” at the 5% significance level.
EUBACDS, USBACDS and EUINCDS, USINCDS are the bank sector CDS indices and the insurance sector CDS indices for the EU and the US respectively.
EMUSVBO, USSVBO are the sovereign bond indices for the EMU and the US respectively. EUSTOXX, SPX and VSTOXX, VIX are the equity indices and volatility indices for the EU and the US respectively.

Tables of the Hsiao covolatility test results

Table 7

The Hsiao CV22 covolatility test for contagion results, based on the residuals of the VAR(29) model

Tests for contagion based on shocks transmitting from the volatility of the source market i to the volatility in the recipient market j

		Recipient Market Volatility									
		EUBACDS	EUINCDS	EMUSVBO	EUSTOXX	VSTOXX	USBACDS	USINCDS	USSVBO	SPX	VIX
Source Market Volatility	EUBACDS	EUBACDS	**229.0042 [0.0000]**	0.1343 [0.7140]	**523.4539 [0.0000]**	**319.0015 [0.0000]**	**1857.7615 [0.0000]**	0.0148 [0.9033]	**276.9509 [0.0000]**	0.0047 [0.9453]	**240.3779 [0.0000]**
	EUINCDS	**279.2648 [0.0000]**	EUINCDS	0.1144 [0.7351]	**127.3315 [0.0000]**	**74.4697 [0.0000]**	**2633.5919 [0.0000]**	**574.2173 [0.0000]**	**376.0310 [0.0000]**	**65.3388 [0.0000]**	1.2170 [0.2700]
	EMUSVBO	1.3213 [0.2504]	0.1275 [0.7210]	EMUSVBO	**5.3438 [0.0208]**	**5.5035 [0.0190]**	**743.7651 [0.0000]**	**318.4083 [0.0000]**	**32.3276 [0.0000]**	**15.7635 [0.0001]**	**6.5429 [0.0105]**
	EUSTOXX	**794.0756 [0.0000]**	**174.5262 [0.0000]**	**17.2999 [0.0000]**	EUSTOXX	**6.4540 [0.0111]**	**150.0218 [0.0000]**	**216.5305 [0.0000]**	**14.1746 [0.0002]**	**26.2023 [0.0000]**	**47.5982 [0.0000]**
	VSTOXX	**389.9922 [0.0000]**	**77.5239 [0.0000]**	**6.1637 [0.0130]**	0.6788 [0.4100]	VSTOXX	**213.3711 [0.0000]**	1.2672 [0.2603]	**35.4593 [0.0000]**	**7.9394 [0.0048]**	**13.0765 [0.0003]**
	USBACDS	**1858.3367 [0.0000]**	**2572.8145 [0.0000]**	**740.1643 [0.0000]**	**180.8278 [0.0000]**	**224.6080 [0.0000]**	USBACDS	**2023.2604 [0.0000]**	**3433.3329 [0.0000]**	**649.0286 [0.0000]**	**119.2335 [0.0000]**
	USINCDS	0.0098 [0.9211]	**573.3773 [0.0000]**	**316.8324 [0.0000]**	**215.5231 [0.0000]**	0.8925 [0.3448]	**2068.6425 [0.0000]**	USINCDS	**126.7997 [0.0000]**	**306.0751 [0.0000]**	**143.9048 [0.0000]**
	USSVBO	**274.9222 [0.0000]**	**376.8565 [0.0000]**	**36.2392 [0.0000]**	**25.0474 [0.0000]**	**38.7807 [0.0000]**	**3495.0496 [0.0000]**	**127.6909 [0.0000]**	USSVBO	**112.1813 [0.0000]**	**37.0098 [0.0000]**
	SPX	2.0295 [0.1543]	**58.6039 [0.0000]**	**10.3402 [0.0013]**	**23.0982 [0.0000]**	3.0884 [0.0789]	**643.5686 [0.0000]**	**307.7305 [0.0000]**	**95.1297 [0.0000]**	SPX	**17.5741 [0.0000]**
	VIX	**261.9767 [0.0000]**	1.7202 [0.1897]	**4.8246 [0.0281]**	**17.6952 [0.0000]**	**17.7032 [0.0000]**	**112.4716 [0.0000]**	**150.3453 [0.0000]**	**37.0417 [0.0000]**	**34.4434 [0.0000]**	VIX

Notes: The null hypothesis is 'No Contagion'. The figures are test statistics values, while those in brackets are p-values.
Figures in bold indicate the rejection of the null hypothesis of “No Contagion” at the 5% significance level.
EUBACDS, USBACDS and EUINCDS, USINCDS are the bank sector CDS indices and the insurance sector CDS indices for the EU and the US respectively. EMUSVBO, USSVBO are the sovereign bond indices for the EMU and the US respectively. EUSTOXX, SPX and VSTOXX, VIX are the equity indices and volatility indices for the EU and the US respectively.