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A high-frequency analysis of return and volatility spillovers in the European sovereign bond market

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ABSTRACT

Using high-frequency data from the MTS trading platform, we examine return and volatility spillover effects across different maturities in the European sovereign bond market over tranquil and crisis periods. The longer-term benchmark securities of core countries are the largest net volatility transmitters, whereas the shorter-term benchmarks of periphery countries are the leading net receivers of volatility shocks. Moreover, the short-end and the long-end of the yield curve in both regions emerge as the sole net recipients of return spillovers. We note that bonds of periphery countries become volatility spillover transmitters during important macroeconomic events such as credit rating downgrades and financial assistance packages to financially distressed countries.

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1. Introduction

The European sovereign debt crisis offers a unique opportunity to study the behaviour of bond market volatility and returns over both tranquil and crisis periods. Contagion effects can be explained as a consequence of spillover effects, the latter being a necessary condition – but not a sufficient one – for contagion to exist (Allen and Gale 2000). We follow Fleming, Kirby, and Ostdiek (1998) and Jørgensen and Valseth (2011) and define spillovers as changes in volatility or returns in one market due to a transmission of market-specific information from another market. If spillover effects are strong, they can create a crisis situation in a particular market which can be exported to other markets and become a contagion. As contagion spreads from one region to another spillovers are amplified and keep the contagion going, thus there is great necessity to properly measure and interpret such spillovers. Spillover effects propagate through different transmission channels such as flight-to-quality and flight-to-liquidity which are documented in global bond markets during periods of stress, as investors rebalance their portfolios towards more liquid and less risky benchmark securities (a discussion is provided in Vayanos 2004; Connolly, Stivers, and Sun 2005; Baur and Lucey 2009).[1] Although contagion and spillover effects are closely interrelated terms we do not study contagion in this paper, instead we focus on the measurement and characterization of return and volatility spillovers across eurozone sovereign bond markets.

This study contributes to the existing literature in a number of ways. First, to the best of our knowledge, it is the first study to employ a comprehensive high-frequency dataset provided by MTS (Mercato dei Titoli di Stato), Europe's major government bond electronic trading platform. Earlier studies have focused on lower frequency datasets such as weekly or daily (Alter and Beyer 2014; Claeys and Vašiček 2014; Fernández-Rodríguez, Gómez-Puig, and Sosvilla-Rivero 2015; Cronin, Flavin, and Sheenan 2016; Garcia-de-Andoain and Kremer 2017).

The recent availability of high-frequency data has improved our understanding of bond market trading, as it facilitates the construction of more efficient return and volatility measures. There are many advantages associated with the use of high-frequency data. The number of observations in a high-frequency dataset exceed by far

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those belonging to a low frequency dataset. As Dacorogna et al. (2001) argue, the daily number of high-frequency observations in a highly liquid financial market is equivalent to a number of daily observations within 30 years. From a statistical point of view, the higher the number of time-series observations the higher is the degrees of freedom for a given statistical test, and the lower the threshold for a significant result, which leads to more accurate estimators. Moreover, with the use of high-frequency data existing but also new econometric techniques can now fully capture extreme events in financial markets, such as those occured during the European sovereign debt crisis. Gargano, Pettenuzzo, and Timmermann (2019) highlight the advantages associated with the use of high-frequency data as compared with data of lower frequencies. The number of observations that can be productively employed increases, parameter estimation error reduces and the identification of short-term dynamics in the lower moments of bond returns becomes possible.

The use of high-frequency data enables the construction of more accurate and model-free *ex-post* inter-daily volatility measurements. Andersen and Bollerslev (1998) building on continuous-time stochastic volatility frameworks demonstrate that high-frequency data allow for the construction of improved *ex-post* volatility measurements via the summation of squared intraday returns. These model-free realized volatility measurements which are based on high-frequency returns, allow for a significant reduction in noise and an improvement in temporal stability compared to measures constructed from lower frequency returns, e.g. daily or monthly.[2] Andersen, Bollerslev, Diebold, and Ebens (2001) and Andersen, Bollerslev, Diebold, and Labys (2001) and Barndorff-Nielsen and Shephard (2002) prove that realized volatility is directly observable using frequently sampled intraday returns, in contrast to quadratic variation, realized volatility's underlying theoretical counterpart. Moreover, the authors demonstrate that realized volatility and covariance measures provide model-free unbiased estimators of the conditional variance and covariance. In other words, realized volatility does not depend upon any distributional assumptions or assumptions related to the price of volatility risk, as in the case of ARCH or stochastic volatility models. As the sampling frequency of returns approaches infinity, realized volatility becomes free from measurement error.

Our second contribution is that no previous study has examined spillover effects across the maturity spectrum of the European sovereign bond market. We deem appropriate to include the longest 30-year maturities in our analysis and not only bonds of maturities up to 10 years for the following reasons. First, previous research has shown that 30-year benchmarks behave autonomously especially during periods of stress, compared to their shorter-term counterparts (O'Sullivan and Papavassiliou 2019, 2020). Also, the average daily return for the 30-year benchmark drops to one-half of its pre-crisis level during the crisis but remains positive, whereas the average daily returns of benchmarks of shorter maturities become negative during the crisis period. Second, it is important to study different segments of the yield curve as it tends to invert before economic downturns and indicates when investors are pessimistic about longer term economic growth, in other words it signals the occurrence of flights-to-liquidity (flights-to-safety) as yields on shorter-term bonds rise above those of longer-term bonds. Therefore, for the aforementioned reasons, we prefer to analyse spillover effects across the maturity spectrum of the European sovereign bond market. By doing so, we are able to study the magnitude of financial shocks across different maturities and quantify the importance of short-term versus longer-term benchmarks in the propagation of those shocks.

Our third contribution has to do with the fact that previous studies have mainly focussed on yield spillovers across countries in the eurozone whereas our study examines both return and volatility spillovers, thus it provides robust evidence for policy on the role destabilizing shocks have played in the unfolding crisis from a different perspective. Finally, we investigate the behaviour of return and volatility spillovers across the maturity spectrum around important macroeconomic events that took place during the period under study. It is of substantial importance to identify whether spillover effects strengthen or weaken around important events, such as sovereign credit rating downgrades and financial assistance packages to distressed eurozone economies.

The strength of spillovers depends on the level of capital market integration within the euro-area. Spillovers among eurozone sovereign bonds are strongly linked by the common monetary policy transmission channel and by the European Financial Stability Facility (EFSF) which was established by euro-area member states as a firewall for financially traumatized markets (see Alter and Beyer 2014 for a discussion). Given the strong linkages among euro-area sovereign bond markets and the increased risk of contagion that comes as a result, we would expect substantial spillover effects both between and within core and periphery countries during the crisis period.[3] However, there can exist an inverse relationship between integration and contagion. A different interpretation is provided by Baur (2020) who finds that full integration minimizes the strength of contagion as financial shocks are diversified and shared among countries. On the other extreme, when markets are fully segmented the potential magnitude of contagion is maximized and financial shocks are not shared among countries. Thus, markets have to be partially segmented for idiosyncratic spillovers to take place.

Generally speaking, financial market volatility increases during periods of stress so we would expect to find stronger spillover effects across markets in the crisis period than in the pre-crisis period. Alter and Beyer (2014) find increased spillovers before major news announcements and financial market events during the sovereign debt crisis in Europe. The literature has identified different patterns for return versus volatility spillovers during crisis periods. For instance, Diebold and Yilmaz (2009) find that return spillovers in global equity markets exhibit a mild increasing trend but no bursts, whereas volatility spillovers exhibit no discernible trend but intense outbreaks. Jørgensen and Valseth (2011) find that volatility spillovers are of less significance than return spillovers in both stock and bond markets. We have no reason to believe that these findings will not carry over to the case of the eurozone sovereign bond market. Unfortunately, there is lack of a theoretical framework that would provide new insights on the differences between return and volatility spillovers across financial markets.

Regarding the direction of return or volatility spillovers and the countries they originate from, we would expect periphery countries to act as transmitters of shocks within their region but also to core eurozone countries during the crisis period. We would also expect periphery countries to act as receivers of shocks transmitted from core countries, although such shocks would normally be of a lower magnitude than those originated from the periphery countries. Caceres, Guzzo, and Segoviano (2010) show that periphery countries, namely, Greece, Portugal, and Spain put pressure on euro-area government bonds during the crisis, as there was increased emphasis towards short-term refinancing risk and long-term fiscal sustainability. Kalbaska and Gątkowski (2012) show that with the exception of Greece, all periphery countries display a triggering capacity of a similar strength during the eurozone crisis. Antonakakis and Vergos (2013) find that bond yield spreads spillovers among eurozone countries run mainly from the periphery and to a smaller extent from the core eurozone countries. Alter and Beyer (2014) find that after the establishment of the European Financial Stability Facility (EFSF) in 2010, core countries are more sensitive to shocks from periphery countries.

Finally, we would expect to find increased spillovers prior to important macroeconomic events and policy interventions during the eurozone sovereign debt crisis in line with Alter and Beyer (2014). These spillover effects that contribute to systemic risk are expected to subside after the interventions. That is, the bailout packages and the liquidity injections that took place during the crisis, such as the European Central Bank's (ECB) Securities Market Programme (SMP), are expected to mitigate the risk of spillovers and financial contagion. We would also expect the market to react to those news releases in an asymmetric fashion. Andersen et al. (2003) find that bad news has greater impact than good news which relates to theoretical work on information processing (Conrad, Cornell, and Landsman 2002; Hautsch and Hess 2002). Beetsma et al. (2013) and Caporale, Spagnolo, and Spagnolo (2018) have also arrived at the same conclusion that markets react more strongly to negative news and such reaction intensifies during crises periods. Thus, we would expect the credit rating downgrades by Fitch, Moody's and Standard & Poor's, to have a greater impact than good news. Beetsma et al. (2013) find that spillovers of bad news from GIIPS countries onto non-GIIPS countries to be of a lower magnitude than those to other GIIPS countries. Along these lines we would expect spillovers to be larger within the GIIPS countries than between GIIPS and non-GIIPS countries.

We employ the Diebold and Yilmaz (2012) generalized VAR framework for measuring spillover effects between and within core and periphery eurozone countries over both tranquil and turbulent periods, in which forecast-error variance decompositions are invariant to the variable ordering. Our main findings are summarized as follows: (i) nearly 70% of return and volatility forecast error variance in both core and periphery economies and across all maturity segments is attributed to spillovers rather than idiosyncratic shocks; (ii) volatility spillovers are larger within the GIIPS and non-GIIPS regions than between those regions;[4] (iii) volatility spillovers from the periphery to the core region are quite pronounced during the crisis period; (iv) the non-GIIPS 10- and 30-year longer-term benchmarks are the largest net volatility transmitters, whereas the GIIPS 2- and 5-year shorter-term instruments are the major net receivers of volatility shocks, on average; *(v)* the short and the long end of the yield curve act as net receivers of return spillovers in both GIIPS and non-GIIPS regions, while medium-term benchmarks act as the sole net transmitters of return shocks; *(vi)* longer-term bonds are less sensitive to liquidity disturbances during the crisis than shorter-term bonds; *(vii)* GIIPS bonds of both short and long maturities become volatility spillover transmitters during serious liquidity events, such as the first and second set of credit rating downgrades.

The rest of the paper is organized as follows. Section 2 discusses the related literature. Section 3 presents the MTS market structure. Section 4 describes the econometric methodology and the dataset. Section 5 discusses the empirical results. Section 6 provides some concluding remarks.

2. Related literature

There is a large number of studies on cross-asset spillovers such as those of Steeley (2006) and Jørgensen and Valseth (2011) (stock-bond markets), Lucey (2013) (industrial metals), Antonakakis and Kizys (2015) (commodity and currency markets), and Wong (2019) (currency and stock markets), as well as studies on single-asset market linkages during both calm and crisis periods (Kim, Lucey, and Wu 2006; Skintzi and Refenes 2006; McMillan, Ruiz, and Speight 2010; Bekiros 2014; Li and Giles 2015). Studies on spillover effects in global bond markets and in particular in bond markets within the eurozone are scarce and mainly focus on lower frequency financial datasets.

Christiansen (2007) examines volatility spillovers from the U.S. and aggregate European bond markets into individual European bond markets using a GARCH volatility-spillover model and weekly data extracted from Datastream. The author finds that regional effects are more important than global effects in EMU countries while European effects are smaller than U.S. effects in non-EMU countries. EMU bond markets have become strongly integrated after euro's inception mainly due to convergence in interest rates. Arellano and Bai (2013) develop a multicountry default model in which domino effects occur among interlinked countries. The model predicts that interest rate spreads within Europe exhibit positive correlation to one another due to the fact that countries are prone to joint defaults.

De Bruyckere et al. (2013) investigate spillover effects and contagion between bank and sovereign default risk in the European debt crisis using CDS spreads at the bank and at the sovereign level. They find that banks with a weak capital position are particularly vulnerable to risk spillovers while at the country level, the debt ratio is the most important driver of contagion. Antonakakis and Vergos (2013) examine the linkages of government bond yield spreads between eurozone countries over the period 2007–2012 taking into account spillover effects during the global and the eurozone financial crises. They find that yield spread spillovers mainly originate from the periphery countries and to a lesser extent from the core eurozone countries. Alter and Beyer (2014) study the interlinkages between sovereigns and banks in the euro-area during the financial crisis using daily data of CDS spreads and propose a method to compute thresholds of excessive spillovers based on empirical distributions of CDS changes along with subjective preferences. Their findings reveal an upward pattern of growing interdependencies between banks and sovereigns that represents a source of systemic risk. Claeys and Vašiček (2014) analyse the bilateral linkages and spillover effects between European Union (EU) sovereign bond markets using factor-augmented VAR methods and daily data (2000–2012) on the sovereign bond yield spreads of 16 EU countries. Their results indicate the presence of significant spillovers across sovereign bond markets in Europe during the crisis which are also important for countries outside the eurozone, such as Czech Republic, Hungary and Poland.

Glover and Richards-Shubik (2014) develop a network sovereign default model in order to quantify the impact of spillover effects using data on sovereign credit default swap spreads from 13 European sovereigns from 2005 to 2011. The authors provide evidence that the magnitude of spillover effects as a result of sovereign defaults is small and commonalities in sovereign credit risk contribute little to market-wide financial linkages. Aït-Sahalia, Laeven, and Pelizzon (2014) study self- and cross-excitation of shocks in the eurozone sovereign credit default swap market. Using a multivariate model with credit default intensities, the authors find evidence for self-excitation and asymmetric cross-excitation. In a second step, the authors identify countries within the eurozone where policy interventions would be most effective and summarize the implications for practice. Garcia-de-Andoain and Kremer (2017) propose a composite indicator of sovereign bond market stress in the euro-area which combines bond yields, bond liquidity and volatility. Using daily and weekly data on risk spreads and volatilities the authors find that financial stress mainly originates from a few countries and spillover patterns are time-varying across euro-area markets. Sabkha, De Peretti, and Hmaied (2017) study volatility spillovers among 33 global sovereign CDS markets and their underlying bond markets, including the eurozone bond markets, and show that credit risk spillovers are amplified during crisis periods compared to non-crisis periods and exhibit varying levels of sensitivity to financial market turbulence. Schneider, Lillo, and Pelizzon (2018) model the time-series of illiquidity events in the Italian sovereign bond market as a multivariate Hawkes process. Using high-frequency data from the MTS markets they provide evidence for both illiquidity spillovers and illiquidity spirals which are more pronounced during the sovereign bond crisis.

Our study also relates to the literature on the microstructure of the European sovereign bond markets. The majority of studies focus on non-crisis periods and employ lower frequency datasets. Examples of studies that have used high-frequency data from the European MTS markets include those of Cheung, Rindi, and De Jong (2005), Dunne, Moore, and Portes (2007), Beber, Brandt, and Kavajecz (2009), Favero, Pagano, and Von Thadden (2010), Dufour and Nguyen (2012), Pelizzon et al. (2016), and O'Sullivan and Papavassiliou (2020).

3. The MTS market

MTS is a fixed-income market with over 500 unique counterparties and average daily volumes exceeding EUR 100 billion. MTS was launched in 1988 by the Italian Treasury and the Bank of Italy and since October 2007 is majority owned by the London Stock Exchange Group. A great variety of financial instruments are traded on the MTS platforms, such as government bonds, corporate bonds, and repo instruments across interdealer and dealer-to-client markets.

Apart from domestic MTS platforms, a market for trading benchmark securities – bonds with an outstanding value of at least 5 billion – was established in 1999 called EuroMTS. Although these two are separate trading platforms, bonds are allowed to trade on both simultaneously causing liquidity to fragment across benchmark and domestic markets. MTS operates as a central limit order book market in which trading is anonymous and order execution is based on the principle of price-time priority. MTS is linked to all major clearing houses in Europe and central securities depositories, either domestic or international.

Participants are split into primary dealers and dealers where the latter can only act as price takers as opposed to the former who enjoy a price maker-taker status (Dufour and Skinner 2004). Primary dealers apart from specifying prices have the obligation to specify *block* and *drip* quantities, i.e. overall proposal size and partial proposals to be made visible to the rest of the market, respectively.

4. Methodology and data

In this paper, we employ the Diebold and Yilmaz (2012) generalized VAR framework which builds on Koop, Pesaran, and Potter (1996) and Pesaran and Shin (1998), in which forecast-error variance decompositions are invariant to the variable ordering and directional volatility or return spillovers are explicitly included. This results in shocks to each variable that are not orthogonalized so that the sum of contributions to the variance of the forecast error does not necessarily equal one. This is particularly important in the present study as it would be hard to justify a particular ordering or rotate variables in a multivariate VAR setting.

Consider a covariance stationary N-variable VAR(p), $x_t = \sum_{i=1}^{p} \Phi_i x_{t-i} + \varepsilon_t$, where $\varepsilon \sim (0, \Sigma)$ is a vector of *iid* disturbances. The moving average representation is $x_t = \sum_{i=0}^{\infty} A_i \varepsilon_{t-i}$, where $A_i = \Phi_1 A_{i-1} + \Phi_2 A_{i-2} + \cdots + \Phi_p A_{i-p}$, with A_0 being an $N \times N$ identity matrix with $A_i = 0$ for $i < 0$. Variance decompositions provide the proportion of the movements in the dependent variables that are due to their own shocks versus shocks to the other variables and are sensitive to the ordering of the variables.

The H-step-ahead forecast error variance decompositions, for $H = 1, 2, \ldots$, is given by

$$\theta_{ij}^{g}(H) = \frac{\sigma_{jj}^{-1} \sum_{h=0}^{H-1} \left(e_i' A_h \Sigma e_j\right)^2}{\sum_{h=0}^{H-1} \left(e_i' A_h \Sigma A_h' e_i\right)} \tag{1}$$

where Σ is the variance matrix for the error vector ε, σ_{jj} is the standard deviation of the error term for the jth equation and e_i is the selection vector. It should be noted that the sum of the elements in each row of the variance decomposition table does not equal 1, that is: $\sum_{j=1}^{N}\theta_{ij}^{g}(H) \neq 1$. The spillover index proposed is calculated by normalizing each entry of the variance decomposition matrix by the row sum as follows:

$$\widetilde{\theta_{ij}^{g}}(H) = \frac{\theta_{ij}^{g}(H)}{\sum_{j=1}^{N}\theta_{ij}^{g}(H)} \tag{2}$$

where $\sum_{j=1}^{N}\widetilde{\theta_{ij}^{g}}(H) = 1$ and $\sum_{i,j=1}^{N}\widetilde{\theta_{ij}^{g}}(H) = N$. The total volatility/return spillover index is given by:

$$S^{g}(H) = \frac{\sum_{\substack{i,j=1 \\ i\neq j}}^{N}\widetilde{\theta_{ij}^{g}}(H)}{\sum_{i,j=1}^{N}\widetilde{\theta_{ij}^{g}}(H)} \cdot 100 = \frac{\sum_{\substack{i,j=1 \\ i\neq j}}^{N}\widetilde{\theta_{ij}^{g}}(H)}{N} \cdot 100 \tag{3}$$

which is invariant to the ordering of the variables in the VAR. Diebold and Yilmaz (2012) argue that this is the analog of the Cholesky factor based measure used in Diebold and Yilmaz (2009). Actually, the total spillover index measures the contribution of spillovers of volatility/returns shocks across the four volatility/returns maturity segments included in the VAR to the total forecast error variance. Essentially, this total spillover index is derived from the summation of the cross-variance shares across all variables in the VAR at a certain forecast horizon H, expressed as a ratio of the total forecast error variation.

The directional return/volatility spillovers received by market i from all other markets j are measured as:

$$S_{i.}^{g}(H) = \frac{\sum_{\substack{j=1 \\ j\neq i}}^{N}\widetilde{\theta_{ij}^{g}}(H)}{\sum_{i,j=1}^{N}\widetilde{\theta_{ij}^{g}}(H)} \cdot 100 = \frac{\sum_{\substack{j=1 \\ j\neq i}}^{N}\widetilde{\theta_{ij}^{g}}(H)}{N} \cdot 100 \tag{4}$$

while the corresponding spillovers transmitted by market i to all other markets j are measured as:

$$S_{.i}^{g}(H) = \frac{\sum_{\substack{j=1 \\ j\neq i}}^{N}\widetilde{\theta_{ji}^{g}}(H)}{\sum_{i,j=1}^{N}\widetilde{\theta_{ji}^{g}}(H)} \cdot 100 = \frac{\sum_{\substack{j=1 \\ j\neq i}}^{N}\widetilde{\theta_{ji}^{g}}(H)}{N} \cdot 100 \tag{5}$$

The directional spillovers are estimated using the normalized elements of the generalized variance decomposition matrix, as variance decompositions are invariant to the ordering of variables. In other words, Equation (4) is the sum of the row-elements of a matrix which contains all bilateral linkages to and from different markets or assets, whereas Equation (5) is the sum of each column of the same matrix, not including the own contribution of each market or asset. That is, the column-elements of the matrix are simply the contribution from a volatility/return shock in market or asset i to those on other markets. The directional spillovers indicate the magnitude of the total spillover that comes from, or goes to, a particular market or asset class.

The net volatility/return spillover from market i to all other markets j is obtained as:

$$S_{i}^{g}(H) = S_{.i}^{g}(H) - S_{i.}^{g}(H) \tag{6}$$

which is the difference between the gross volatility/return shocks transmitted to and those received from all other markets.

Our high-frequency dataset spans the dates from January 2008 to December 2010 and includes both tranquil and crisis periods (we consider November 2009 as the beginning of the eurozone debt crisis following Greece's sovereign debt downgrade by Fitch). It consists of the following 11 countries: Austria, Belgium, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Portugal, and Spain, and contains the three best bid and ask quotations throughout the trading day time-stamped to the nearest second. We use four time-to-maturity segments, i.e. 2-, 5-, 10-, and 30-year as we intend to examine the magnitude of spillover effects across the yield curve. We assign bonds to different maturity segments based on residual maturity, i.e. days from the observed date until the maturity date of the bond. The same allocation method is used for all countries in our dataset. For each country and each maturity category, we select the most heavily traded benchmark security. If a benchmark drops out of a particular maturity segment over time it is replaced by a new benchmark, thus our results are robust to such changes.

We have selected to work with benchmark fixed coupon-bearing government bonds. We have properly filtered our dataset to consider quotes recorded during regular trading hours, i.e. from 8:15 am until 5:30 pm CET. We have also excluded pre-sessional and end-of-day quotations as well as quotes with zero and negative bid-ask spreads in order to mitigate microstructure effects, in line with McInish and Wood (1992) and O'Sullivan and Papavassiliou (2020).

We first construct 5 min returns from the linearly interpolated logarithmic midpoint of the continuously recorded bid and ask quotes as follows:

$$r_{it} = \log\left(m_{i,t}/m_{i,t-1}\right) \tag{7}$$

where $m_{i,t}$ represents the midpoint of the bid-ask spread for security i prevailing at the end of interval t. As discussed in the Introduction, the selection of 5 min returns as the optimal sampling frequency balances two competing factors: measurement error and microstructure biases. Daily bond returns are estimated as the summation of the 5 min returns for each security.

Daily realized variance measures for each benchmark security are constructed by the summation of squared 5 min intraday returns, following Andersen and Bollerslev (1998). Subsequently, we obtain daily realized volatility measures using the square-root of the variance series, i.e. for $N = 1, 2, 3, \ldots$ the realized variance for day t is defined as:

$$\widehat{\sigma}^2_{t,N} = \sum_{j=1}^{N} r^2_{t,j,N} \tag{8}$$

while realized volatility is defined as $\widehat{\sigma}_{t,N}$. All of our series are stationary at levels based on standard unit root tests (data not shown for the sake of brevity). Figure 1 depicts the time evolution of volatility at the index level from the non-GIIPS and GIIPS regions across the 2-, 5-, 10-, and 30-year maturity segments (VNG and VG denote the volatility of non-GIIPS and GIIPS countries, respectively), while Figure 2 depicts the time evolution of the 10-year benchmark volatility for individual eurozone countries. Daily realized volatility is higher for longer maturity benchmarks in both the non-GIIPS and GIIPS regions. We note that realized volatility has strengthened during the crisis for GIIPS countries but has lowered for non-GIIPS countries.[5]

Table 1 compares realized volatility and liquidity between non-GIIPS and GIIPS countries across all four maturity segments. The table confirms Figures 1 and 2 and clearly shows that volatility has strengthened for GIIPS countries during the crisis, with the exception of the 30-year bond which follows an autonomous path. On the contrary, realized volatility has lowered for non-GIIPS countries in the crisis across all maturity segments possibly due to lower trading intensity for non-GIIPS bonds as evidenced by the smaller quoted depths for those bonds across all maturities. A similar result has been documented by O'Sullivan and Papavassiliou (2019) who argue that hedge funds might have played an important role in reducing volatility of non-GIIPS countries. In terms of liquidity, the sovereign bond markets of non-GIIPS countries are more liquid than the GIIPS markets, as evidenced by higher quoted depth measures in both pre-crisis and crisis periods.

5. Empirical findings and discussion

Section 5.1 discusses the return and volatility spillover results across core and periphery eurozone countries. Section 5.2 analyzes return and volatility spillovers around major macroeconomic events.

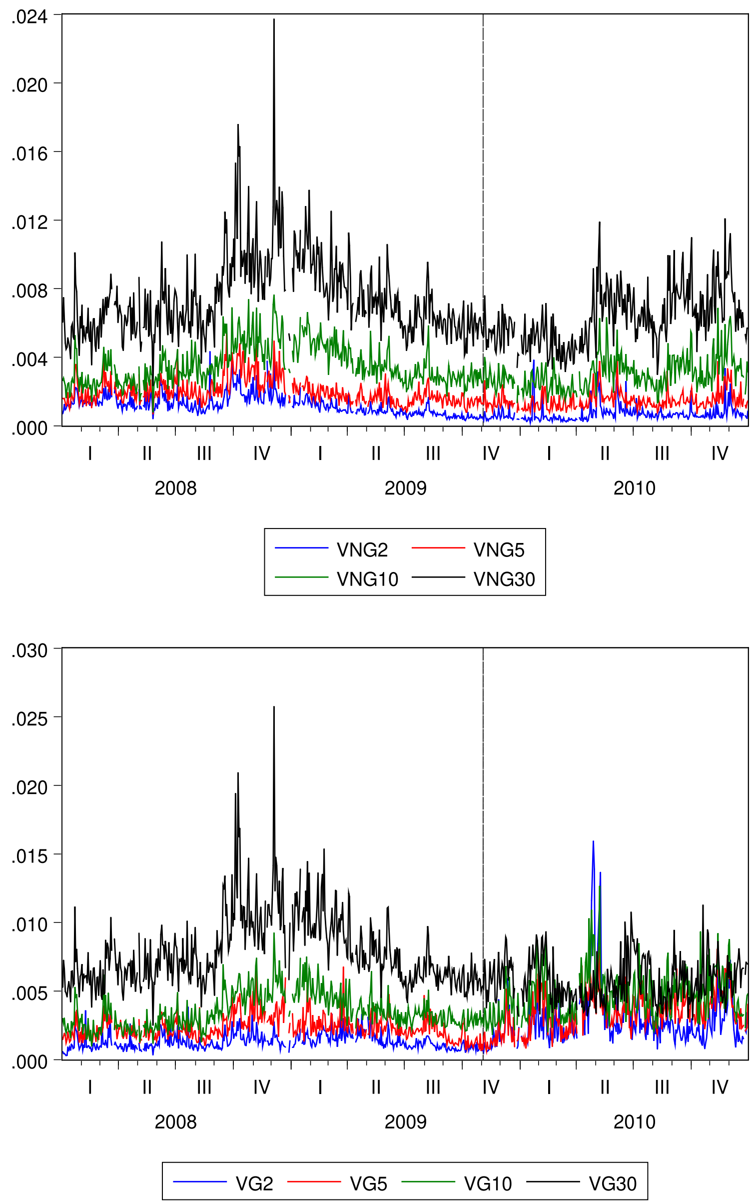

Figure 1. Daily realized volatility. The figure plots daily realized volatility series (V) for core non-GIIPS (NG) and periphery GIIPS (G) eurozone countries across the 2-, 5-, 10-, and 30-year maturity segments. The sample period spans the dates from January 2008 to December 2010. The vertical line corresponds to the beginning of the European sovereign debt crisis (November 2009). Pre-crisis period: January 2008–October 2009; Crisis-period: November 2009–December 2010.

5.1. Return and volatility spillovers across core and periphery eurozone countries

Panel A of Table 2 presents the volatility spillover table over the full sample. The results are based on vector autoregressions of order 4 based on the Akaike information criterion (AIC) and generalized variance decompositions of 10-day-ahead volatility forecast errors. We denote the volatility measures as VNG and VG, where NG denotes non-GIIPS measures and G denotes GIIPS measures. These measures are constructed at the index level as equally-weighted daily averages from the GIIPS and non-GIIPS regions. The off-diagonal column sums and

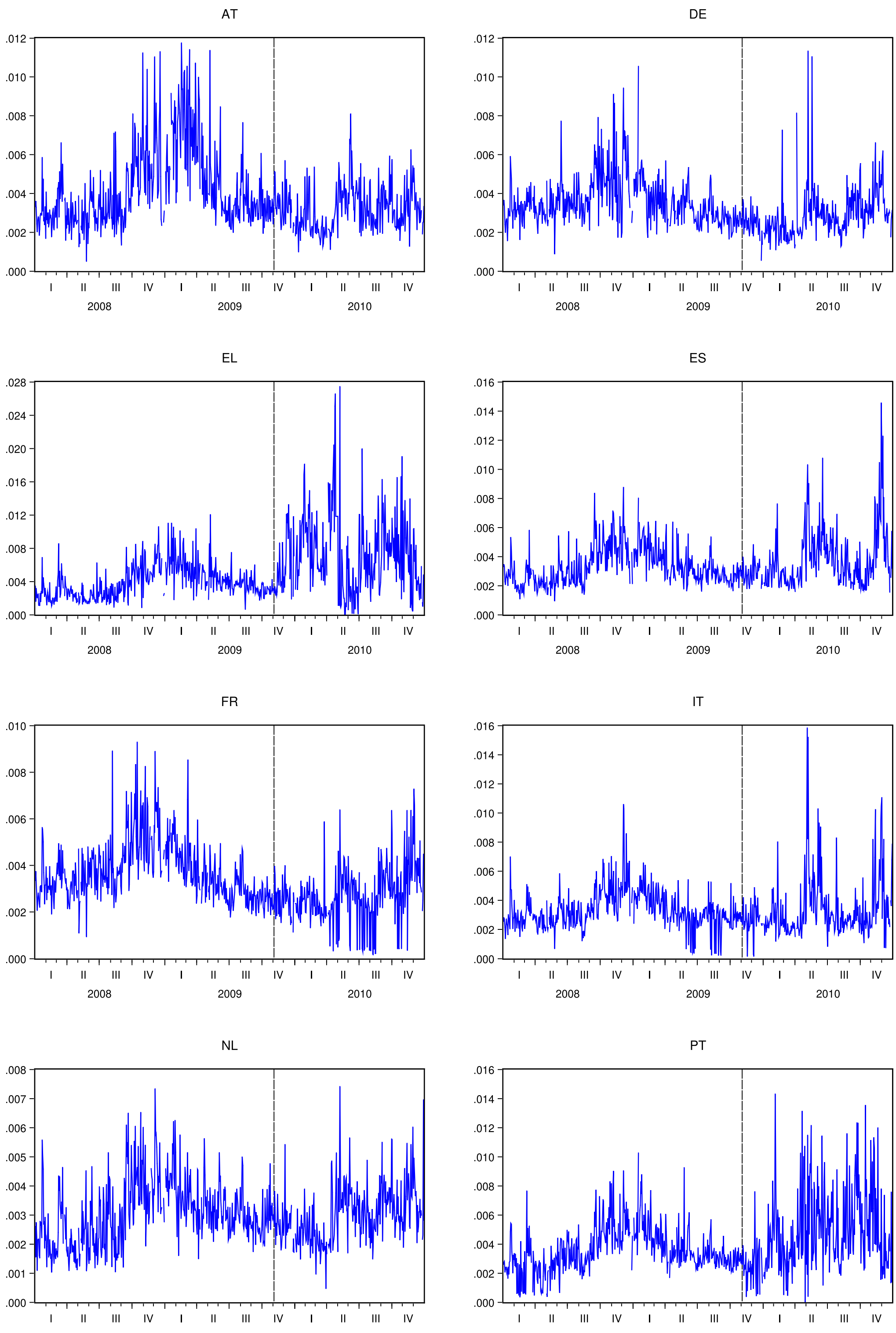

Figure 2. Daily realized volatility. The figure plots daily realized volatility series for the 10-year benchmark bond for Austria (AT), Germany (DE), Greece (EL), Spain (ES), France (FR), Italy (IT), the Netherlands (NL) and Portugal (PT) The sample period spans the dates from January 2008 to December 2010. The vertical line corresponds to the beginning of the European sovereign debt crisis (November 2009). Pre-crisis period: January 2008–October 2009; Crisis-period: November 2009–December 2010.

Table 1. Realized volatility and liquidity. The Mean values are shown for realized volatility and quoted depth measures across the 2-, 5-, 10-, and 30-year maturity segments.

		Pre-crisis		Crisis	
Measures	Maturity	Non-GIIPS	GIIPS	Non-GIIPS	GIIPS
Realized volatility	2-year	0.0012	0.0013	0.0007	0.0028
	5-year	0.0020	0.0023	0.0015	0.0034
	10-year	0.0036	0.0035	0.0030	0.0047
	30-year	0.0074	0.0079	0.0063	0.0058
Quoted depth (in millions)	2-year	27.29	23.16	25.97	18.39
	5-year	30.04	27.38	27.84	18.82
	10-year	28.64	25.35	25.70	18.56
	30-year	11.08	10.52	10.73	9.26

Notes: Daily realized volatility measures are constructed by the summation of squared 5 min intraday returns. Quoted depth is defined as the quantity of bonds bid or offered for sale at the posted bid and offer prices. non-GIIPS: Austria, Belgium, Finland, France, Germany, and the Netherlands; GIIPS: Greece, Ireland, Italy, Portugal, Spain. Pre-crisis period: January 2008–October2009; Crisis-period: November 2009–December 2010.

row sums depict the 'to' and 'from' directional spillovers, while the 'to minus from' differences are the net volatility spillovers. The total volatility spillover index is shown in the lower right corner of the table and indicates that, on average, across the entire sample 67.8% of the volatility forecast error variance in both GIIPS and non-GIIPS regions and across all maturity segments comes from spillovers whereas the remaining 32.2% is explained by idiosyncratic shocks.

The highest observed pairwise volatility spillover is from VNG30 to VG30 (19.49%), whereas the lowest is the one from VG2 to VG30 (1.51%). It is evident that volatility spillovers are larger within regions than between regions. For instance, innovations in VNG10 are responsible for 16.07% of the 10-day-ahead forecast error variance of realized volatility in VNG5, but only 9.06% in VG5. The same holds true for spillovers from the GIIPS region to the non-GIIPS region. Interestingly, the contribution to others is highest within regions at their own maturity and neighbouring maturities (with the exception of the VG30 which we discuss in more detail below). For instance, the contribution of VNG10 to VNG2 is 13.42%, increases to 16.07% and 24.57% for VNG5 and VNG10, respectively, and then falls to 18.06% for VNG30. Similarly, the contribution of VG10 to VG2 is 17.48%, remains flat at 17.21% for VG5, increases to 32.39% for VG10, and then falls to 7.49% for VG30. A similar pattern occurs in the transmission of volatility shocks from GIIPS to non-GIIPS bonds with cross-market volatility shocks exerting a larger effect on own and nearest maturity bonds.

Volatility shocks transmitted from non-GIIPS to GIIPS benchmarks have a larger effect on the GIIPS 30-year, regardless of the maturity of the transmitting non-GIIPS shock. For example, the contribution of VNG10 to VG2 is 5.29% and increases to 9.06%, 12.02% and 15.97% for VG5, VG10 and VG30, respectively. As previously mentioned, the 30-year GIIPS instrument exhibits a unique pattern in terms of volatility shock transmissions. Although shocks to VG30 have the largest effect on the VG30 forecast error variance, the cross-market effects of shocks in VG30 to the other maturity non-GIIPS bonds are larger than own-market effects on the other maturity bonds. Also, VG30 receives a lower contribution of volatility spillovers from its shorter-term counterparts. This result indicates that for long maturity bonds (so called buy-and-hold bonds) (a) the selling pressure was not as high as for benchmarks of shorter maturities, and (b) there has been a decline in investors' appetite towards longer-term bonds as they prefer to trade on more liquid bonds during liquidity dry-ups (O'Sullivan and Papavassiliou 2019).

In terms of directional spillovers to others throughout the full sample, results suggest that volatility of the VNG10 contributes the most to other maturities' forecast error variance (89.9%), followed by the VNG30 (89.7%), VNG5 (75.0%) and VG10 (73.5%). In terms of directional spillovers received from others, VNG30 receives the highest percentage of shocks from other benchmarks (75.5%), followed by VNG10 (75.4%) and VNG5 (74.4%), whereas the lowest percentage of shocks is received by VG2 (51.9%).

The last row of the table depicts the net directional volatility spillovers defined as the difference between the column-wise sum ('contribution to others') and the row-wise sum ('contribution from others'). Net volatility

Table 2. Full-sample volatility and returns spillover table.

Panel A – realized volatilities

	VNG2	VNG5	VNG10	VNG30	VG2	VG5	VG10	VG30	Contribution from others
VNG2	33.78	16.41	13.42	12.89	2.85	5.37	4.98	10.31	66.20
VNG5	15.35	25.64	16.07	15.37	2.83	5.50	7.89	11.35	74.40
VNG10	11.26	14.22	24.57	18.40	2.91	5.82	9.67	13.15	75.40
VNG30	11.30	13.28	18.06	24.47	2.02	5.78	8.79	16.32	75.50
VG2	5.65	4.06	5.29	3.40	48.15	13.28	17.48	2.68	51.90
VG5	7.04	7.64	9.06	9.15	5.11	37.82	17.21	6.96	62.20
VG10	5.88	8.44	12.02	10.99	7.29	13.74	32.39	9.24	67.60
VG30	10.32	11.00	15.97	19.49	1.51	3.75	7.49	30.47	69.50
Contribution to others	66.80	75.00	89.90	89.70	24.50	53.20	73.50	70.00	542.70
Contribution including own	100.60	100.70	114.50	114.20	72.70	91.10	105.90	100.50	67.80%
Net spillovers	0.60	0.60	14.50	14.20	−27.40	−9.00	5.90	0.50	

Panel B – returns

	RNG2	RNG5	RNG10	RNG30	RG2	RG5	RG10	RG30	Contribution from others
RNG2	31.71	23.51	16.11	6.18	4.34	8.11	5.90	4.14	68.30
RNG5	19.52	26.28	20.90	10.18	2.99	7.49	6.81	5.83	73.70
RNG10	13.37	20.85	26.29	15.31	2.13	5.81	7.88	8.37	73.70
RNG30	6.27	12.48	19.06	32.56	0.71	3.02	5.81	20.08	67.40
RG2	5.67	4.87	3.57	1.01	41.84	20.20	18.24	4.60	58.20
RG5	7.50	8.50	6.63	2.96	15.03	30.65	20.79	7.94	69.30
RG10	5.49	7.66	8.79	5.39	12.32	19.40	29.46	11.49	70.50
RG30	4.33	7.24	10.35	19.84	3.53	8.59	13.38	32.73	67.30
Contribution to others	62.10	85.10	85.40	60.90	41.00	72.60	78.80	62.50	548.50
Contribution including own	93.90	111.40	111.70	93.40	82.90	103.30	108.30	95.20	68.6%
Net spillovers	−6.20	11.40	11.70	−6.50	−17.20	3.30	8.30	−4.80	

Notes: Panel A depicts the volatility spillover table which is based on the Diebold and Yilmaz (2012) VAR framework over the period January 2008 until December 2010. Results are based on vector autoregressions of order 4 based on the Akaike information criterion and generalized variance decompositions of 10-day-ahead volatility forecast errors. Volatility measures are denoted as VNG and VG, where NG and G correspond to non-GIIPS and GIIPS measures, respectively. Panel B depicts the corresponding spillover table for returns. We denote the returns measures as RNG and RG, where NG denotes non-GIIPS measures and G denotes GIIPS measures. The off-diagonal column sums and row sums depict the 'to' and 'from' directional spillovers, whilst the 'to minus from' differences refer to the net volatility or return spillovers.

spillovers provide information on whether a market is a receiver or a transmitter of volatility in net terms. The largest net positive spillovers are those of VNG10 (14.5%) and VNG30 (14.2%), showing that the longer-term benchmarks of the non-GIIPS region are the largest net volatility transmitters in the system. On the other hand, the largest net negative spillovers are those of VG2 (-27.4%) and VG5 (-9.0%), showing that the most liquid shorter-term instruments of the GIIPS region are the leading net receivers of volatility shocks, on average.

Gurkaynak, Sack, and Swanson (2005) show that long-run Treasury bond yields respond excessively to macroeconomic announcements relative to established new Keynesian DSGE models. Giglio and Kelly (2018) find excessive volatility of long maturity prices relative to short maturity prices across a range of asset classes including Treasury yields, sovereign and corporate credit default swaps, equity and currency derivatives, commodities futures, and inflation swaps. This excessive volatility cannot be explained by many standard asset pricing models including, in the fixed income setting, a series of affine term structure models (Duffie, Pan, and Singleton 2000). However, a model that accounts for investor extrapolative/over-reactive beliefs where investors treat cash flows as more persistent than they actually are can account for these findings. Consistent with the research on excess volatility of long maturity securities, we find that long-term bonds are considerably more volatile than short-term bonds across both non-GIIPS and GIIPS bonds and over the pre-crisis and crisis periods (see Table 1). Furthermore, the fact that long-term bonds are the largest net volatility transmitters is consistent with the fact that these bonds are more sensitive to volatility shocks, and thus are more likely to be transmitters of shocks from the long end to the short end of the yield curve. The fact that volatility transmission tends to flow from non-GIIPS to GIIPS is explained by the fact that the non-GIIPS bonds are more liquid in terms of quoted depths, as shown in Table 1, where the quoted depths of non-GIIPS bonds are higher than those of GIIPS bonds over the pre-crisis and crisis periods.

Panel B of Table 2 depicts the spillover table for returns. We denote the returns measures as RNG and RG, where NG denotes non-GIIPS measures and G denotes GIIPS measures. We find that almost 69% of forecast error variance comes from spillovers, hence spillovers are equally important in both returns and volatilities and, on average, are of the same magnitude. The eight bond indices are driven by common risk factors such as European interest rates and macroeconomic conditions. However, each index will also be impacted by idiosyncratic risk due to differences in liquidity and credit risk profiles and due to the segmentation of investors that invest in certain maturity ranges and sovereigns. Our findings that the majority (approximately 70%) of the forecast error variance of each bond index is attributable to spillovers with the remainder attributable to idiosyncratic shocks means that common factors account for the majority of spillovers. The fact that there is a high degree of commonality in the returns and volatility of these bond indices, as found in other markets (Hasbrouck and Seppi 2001; Chordia, Sarkar, and Subrahmanyam 2005), and that this high degree of commonality is associated with a high degree of spillovers is consistent with the results of Alter and Beyer (2014).

It is clear from Table 2 that volatility and return spillovers are larger within regions than between regions. It seems that financial shocks propagate more strongly within the core and periphery regions as the constituent countries share common macroeconomic and credit risk characteristics. These results are in line with those of Beetsma et al. (2013) who find that spillovers, especially those of bad news, from GIIPS countries onto non-GIIPS countries to be of a lower magnitude than those to other GIIPS countries.

The gross directional return spillovers from others to RNG5 and RNG10 are the largest standing at 73.7%, followed by RG10 and RG5 (70.5% and 69.3%, respectively). The 2- and 30-year instruments in both regions appear to be the sole net receivers of return spillovers, with negative values that can exceed 17%. This finding is in contrast to the evidence provided by the volatility spillover table, especially for the 30-year non-GIIPS bond which is a key net transmitter of volatility shocks across both regions. The 5- and 10-year benchmarks take on large and positive values and are the sole net transmitters of return shocks in the system. Medium-term benchmarks are the most liquid bonds in terms of quoted depths as shown in Table 1, where the quoted depth of 5- and 10-year bonds is higher than that of 2- and 30-year bonds across non-GIIPS and GIIPS bonds and over the pre-crisis and crisis periods. As a result, medium maturity bonds will, on average, embed information faster than bonds with shorter and longer maturities thus, returns shocks to the medium maturities will tend to transmit to the short and long maturity spectrums. Brandt and Kavajecz (2004) show that the 2-5-year maturity range in the U.S. Treasury market is the most prominent segment of the yield curve in terms of influencing other maturity segments. For example, they show that yield changes in all maturity ranges have a strong reaction to their own order flow imbalance, relative to adjacent maturity ranges, but an even stronger reaction to the order flow imbalance at the 2- to 5-year maturity range. Possible reasons include that institutional investors are more likely to hold middle duration bonds and that futures trading is concentrated in bonds with maturities in the middle maturity range. In our paper, the 2-year maturity range represents the shorter end of the yield curve, the 5- and 10-year represent the middle maturity range and the 30-year represents the long maturity range. Consistent with Brandt and Kavajecz (2004), we find that the middle maturity range of bonds exerts the most influence on the other maturity ranges in terms of returns spillovers as the 5- and 10-year maturity bonds are, on average, net transmitters of returns spillovers whereas, the 2- and 30-year maturity bonds are, on average, net receivers of returns spillovers.

The full-sample spillover index provides an average of spillover behaviour but is not designed to detect time-varying cyclical movements in spillovers. Along these lines, we also estimate volatility spillovers using 100-day rolling samples in order to assess the extent of the spillover variation over time, which we visually illustrate in total spillover plots in Figure 3. There is a declining trend for the full year in 2008 and half of 2009, where the total volatility spillover plot fluctuates between 65% and 85%. However, a new cycle is identifiable after June 2009 where spillovers exceed 75% at the onset of the crisis. This finding is in line with that of Claeys and Vašiček (2014) who show that spillovers increased significantly since the start of the financial crisis. It is also consistent with evidence provided by Diebold and Yilmaz (2012) who find increased directional spillovers during turbulent times. A second cycle that lasts until the end of 2010 involves movements of the index between 70% and 50%,

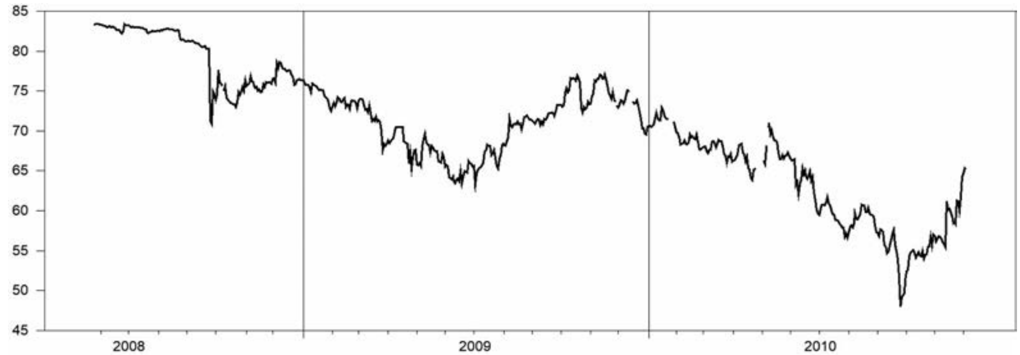

Figure 3. Total volatility spillovers. The figure illustrates volatility spillovers using 100-day rolling samples. The sample period spans the dates from January 2008 to December 2010. Vertical lines correspond to the first time period within a year. The Diebold and Yilmaz (2012) generalized VAR framework is employed using high-frequency bond data from the following countries: Austria, Belgium, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Portugal, and Spain. Pre-crisis period: January 2008–October 2009; Crisis-period: November 2009–December 2010.

showing that volatility spillovers gradually smooth out, most likely due to Greece's bailout that occurs in May 2010.

The net directional volatility spillover plot is shown in Figure 4 where each point in the figure corresponds to $S_i^g(H)$ in Equation (6). The net volatility spillovers from the non-GIIPS benchmarks stayed at positive levels throughout the crisis period, especially those that emanated from the 10- and 30-year instrument, showing that non-GIIPS countries are net transmitters of volatility to the GIIPS markets. Non-GIIPS markets also exercised greater influence on GIIPS markets during the pre-crisis period, confirming the results of Conefrey and Cronin (2015). In contrast, volatility spillovers from the GIIPS 2-year and 5-year bonds have dipped into negative territory (net recipients of volatility shocks), while the ones corresponding to the 30-year benchmark are at both the transmitting and receiving ends of net volatility diffusions, implying that longer maturity benchmarks have been less vulnerable to liquidity dry-ups during the crisis than shorter maturity ones. As mentioned previously, long maturity bonds are buy-and-hold bonds and the selling pressure for those bonds was not as high as for shorter maturity bonds as evidenced by the quoted depths in Table 1. The 10-year benchmark of the GIIPS region follows an autonomous path as the majority of its net spillovers are more pronounced and have stayed positive during the crisis, reaching levels as high as 15%.

We also calculate net pairwise volatility spillovers between and within GIIPS and non-GIIPS regions for a selection of countries focusing on the 10-year benchmark. Figure 5 shows the net pairwise spillovers for Germany (DE), France (FR), the Netherlands (NL), and Austria (AT). The volatility from the German market is transmitted to all three markets but mainly to Austria, with volatility levels nearly reaching 15% during the crisis period. France is also a net transmitter of volatility shocks within the non-GIIPS countries and especially to Austria which seems to be the major net recipient of spillovers from other countries. Figure 6 displays the net pairwise volatility spillovers for Greece (EL), Portugal (PT), Italy (IT), and Spain (ES). Clearly, net volatility spillovers within the GIIPS countries are smaller than those of the non-GIIPS countries, with Greece being the major net recipient of modest levels of volatility shocks from its counterparts. This result demonstrates that Italy and Spain being the largest economies within the GIIPS region act as major transmitters of shocks to smaller economies like Greece and is consistent with the findings of Kalbaska and Gątkowski (2012). However, the result that net spillovers within the GIIPS countries are smaller in magnitude than those in the non-GIIPS region contradicts the findings by Antonakakis and Vergos (2013) who show that within-effects spillovers are stronger within the periphery than within the core region. A possible explanation for this difference in results can be the fact that Antonakakis and Vergos (2013) study bond yield spread spillovers whilst we focus on volatility spillovers.

Figure 7 shows the net paiwise volatility spillovers for a selection of GIIPS and non-GIIPS countries, namely Greece (EL), Italy (IT), Germany (DE), and France (FR). The criteria for selecting those countries are their systemic importance and the level of liquidity of their bond markets. Greece is the main net recipient of volatility

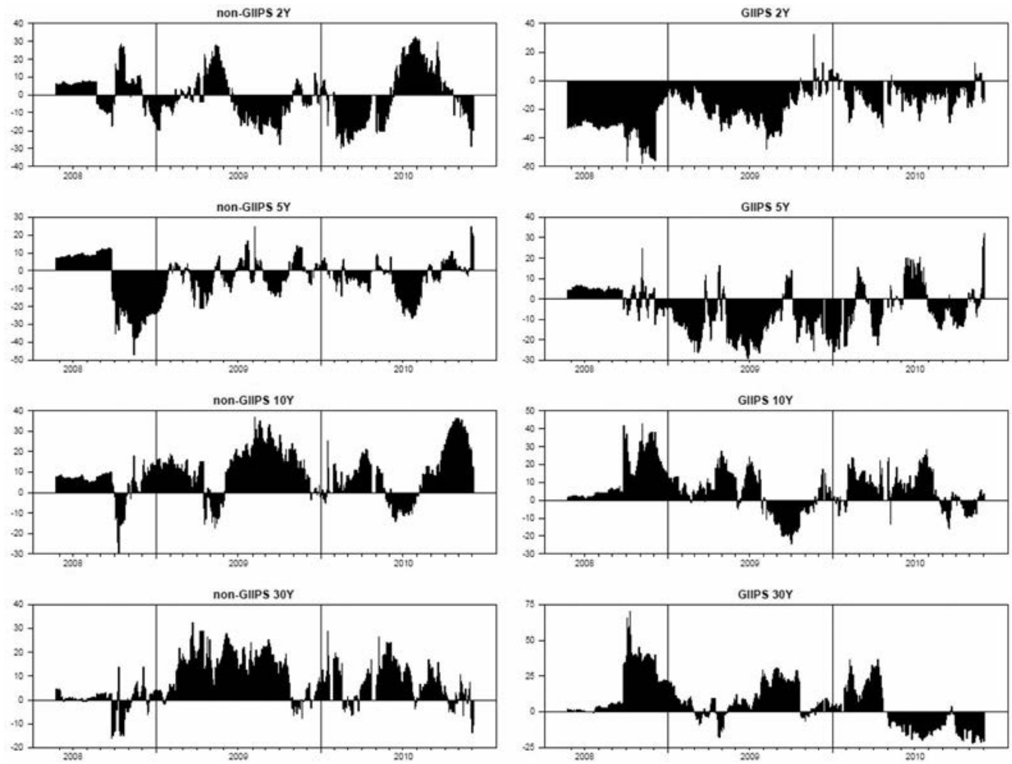

Figure 4. Net directional volatility spillovers across regions. The figure illustrates net directional volatility spillovers across the GIIPS and non-GIIPS regions. The sample period spans the dates from January 2008 to December 2010. Vertical lines correspond to the first time period within a year. Diebold and Yilmaz (2012) generalized VAR framework is employed using high-frequency bond data from GIIPS and non-GIIPS countries across 2-, 5-, 10-, and 30-year maturity segments. GIIPS: Greece, Ireland, Italy, Portugal, Spain; non-GIIPS: Austria, Belgium, Finland, France, Germany, and the Netherlands. Pre-crisis period: January 2008–October 2009; Crisis-period: November 2009–December 2010.

shocks from Italy, Germany and France during the crisis period, whereas it transmits a higher percentage of volatility shocks to its European counterparts during the pre-crisis period. This result reflects the importance of the larger economies of Italy, Germany, and France in driving the euro crash risk during the sovereign debt crisis. Italy proves to be a significant net volatility transmitter during the crisis mainly to France and Greece, confirming previous findings by Broto and Pérez-Quirós (2011), Ang and Longstaff (2013), Antonakakis and Vergos (2013), and Fernández-Rodríguez, Gómez-Puig, and Sosvilla-Rivero (2015) who highlight the fact that spillovers from the periphery to the core region are quite pronounced during market turmoil, especially those that emanate from Italy and Spain.

During systemic outbreaks financial contagion gains significance and the markets with the higher contribution to spillover effects are those mostly affected by the crisis (Caceres, Guzzo, and Segoviano 2010). In other words, the eurozone core countries have become exposed to those with higher sovereign risk, especially after the launch of EFSF in 2010 (Kalbaska and Gątkowski 2012; Alter and Beyer 2014). It must be noted that banking institutions of core countries were holders of GIIPS sovereign bonds of substantial amounts, especially Greek bonds. Volatility spillovers coming from GIIPS countries exert destabilizing effects over non-GIIPS countries of a higher magnitude than the other way around. GIIPS countries exhibit a high probability of a credit event which leads to a rise in sovereign bond yields amid global risk aversion. The selling pressure on sovereign bonds of GIIPS econonies as a result of flight-to-quality episodes deteriorates their long-term sustainability prospects and elevates their funding needs. Fernández-Rodríguez, Gómez-Puig, and Sosvilla-Rivero (2015) argue that variables that gauge market participants' perceptions as well as macroeconomic fundamentals seem to be equally relevant in the determination of volatility spillovers between core and periphery countries.

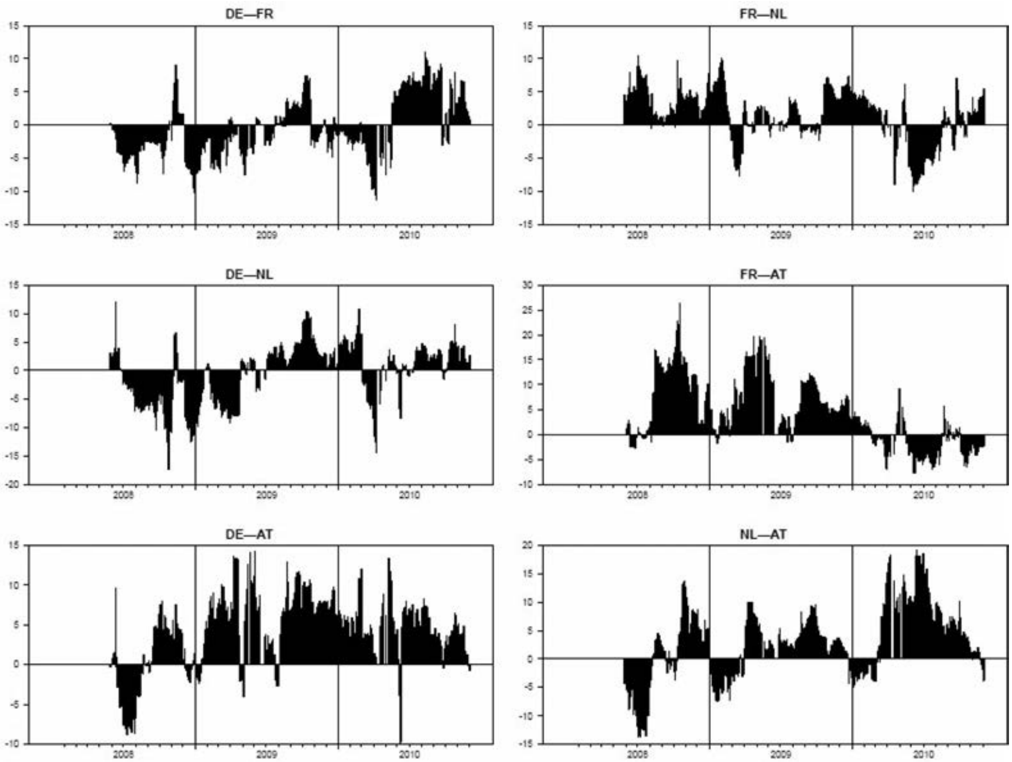

Figure 5. Net pairwise volatility spillovers (non-GIIPS). The figure illustrates net pairwise volatility spillovers on the 10-year benchmark bond across Germany (DE), France (FR), the Netherlands (NL), and Austria (AT). The sample period spans the dates from January 2008 to December 2010. Vertical lines correspond to the first time period within a year. The Diebold and Yilmaz (2012) generalized VAR framework is employed using high-frequency bond data from MTS markets. Pre-crisis period: January 2008–October 2009; Crisis-period: November 2009–December 2010.

Figures 8–10 display the corresponding net return spillovers within and between the two regions. Figure 8 shows that Austria is clearly the dominant net receiver of return spillovers from France, Germany, and the Netherlands, especially during the crisis period. France appears to be a net transmitter of return shocks to Germany and the Netherlands during the pre-crisis period, but its role weakens during the crisis period as it becomes a net receiver of shocks. The dominant net transmitter of return spillovers during the crisis is Netherlands followed by Germany.

Figure 9 shows that the largest net returns transmitter in the system is Spain with very pronounced peaks during the crisis period that reach up to 10% in 2010. Greece's role is also important as from a net receiver of shocks during the pre-crisis period it becomes an important transmitter, mainly to Italy (up to 11% in May 2010) and Portugal (up to 13% also in May 2010). These results are consistent with the findings of Metiu (2012), De Santis (2012), Claeys and Vašiček (2014), and Blatt, Candelon, and Manner (2015) who show that Greece is a positive and significant net transmitter to other countries. Moreover the rest of GIIPS countries also appear to exert positive net transmissions within the bond market.

Figure 10 displays the corresponding net return spillovers within and between the two regions for Greece (EL), Italy (IT), Germany (DE), and France (FR), confirming Greece's and Italy's role as net receivers of return shocks from Germany and France during the crisis. These results partially differ from those of net volatility spillovers. Although Greece appears to be a major recipient of both volatility and return shocks, Italy's role is ambiguous as it is a net transmitter of volatility shocks and a net receiver of return shocks from other countries. These results confirm the findings of Diebold and Yilmaz (2009) who show that return spillovers follow different patterns than volatility spillovers during periods of stress. These negative spillover effects in returns between

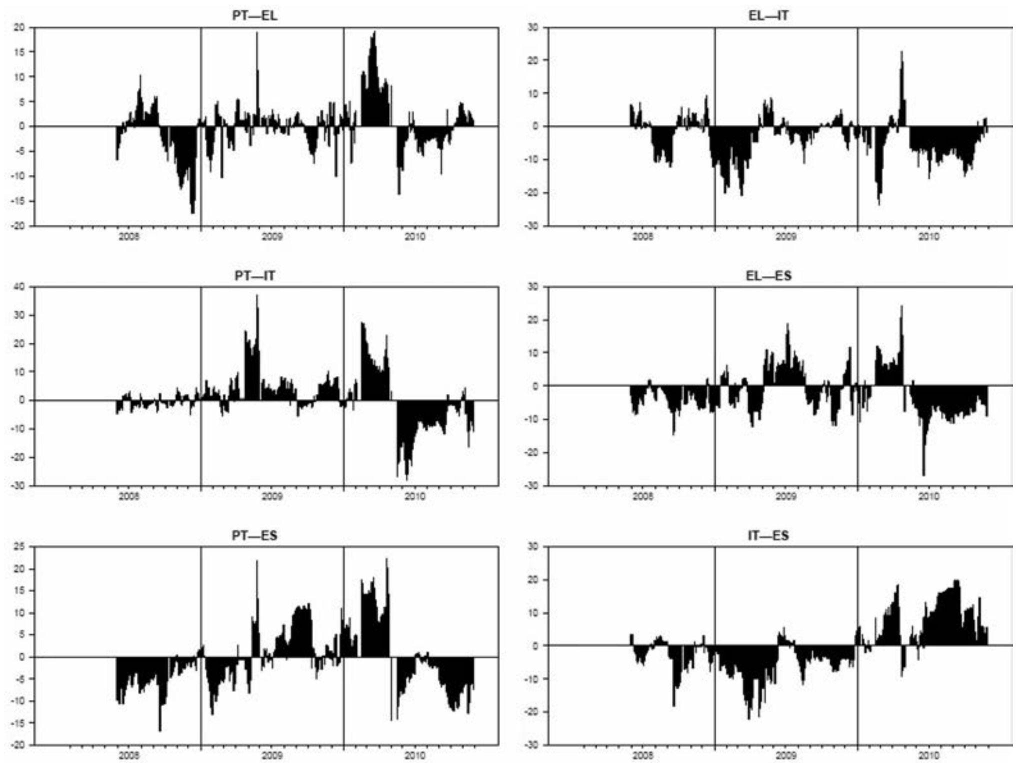

Figure 6. Net pairwise volatility spillovers (GIIPS). The figure illustrates net pairwise volatility spillovers on the 10-year benchmark bond across Greece (EL), Portugal (PT), Italy (IT), and Spain (ES). The sample period spans the dates from January 2008 to December 2010. Vertical lines correspond to the first time period within a year. The Diebold and Yilmaz (2012) generalized VAR framework is employed using high-frequency bond data from MTS markets. Pre-crisis period: January 2008–October 2009; Crisis-period: November 2009–December 2010.

GIIPS and non-GIIPS countries can be interpreted as evidence of flight-to-quality episodes that have taken place during the European sovereign debt crisis. Global investors usually rebalance their portfolios by liquidating their investments in highly risky assets and buying safer ones. That is exactly what happened during the eurozone debt crisis where investors shifted their preferences towards benchmarks with higher credit ratings, such as those of Germany and France. These results are in line with those of Antonakakis and Vergos (2013) and O'Sullivan and Papavassiliou (2019). They are also consistent with the theoretical predictions of Shalen (1993) who argues that during periods of high uncertainty there is a dispersion of beliefs in relation to asset values among investors, mainly due to asymmetric information.

There are a number of policy implications from our research. First, we document an increase in spillovers during the crisis showing that sovereign bond market linkages are amplified in times of stress. The strengthening of spillover effects may lead to contagion effects within the eurozone and can create substantial systemic risk in the financial system. The contagion effects across eurozone bond markets could have a further impact on the banking sector as banks are the main holders of sovereign debt. Moreover, institutional investors and pension funds could be impacted who are obliged by law to invest in sovereign bonds of certain credit ratings. Second, we note that the strengthening of return and volatility spillovers can be seen as the result of eurozone's economic and financial integration since the inception of the euro, something that can challenge the arguments in favour of a single currency. Third, the documented spillover effects can propagate through flight-to-quality and flight-to-liquidity channels. This is important not only for global investors who rebalance their portfolios but also for regulators who monitor the allocation of investment funds across different investments. Fourth, the magnitude of spillovers is larger within core and periphery countries than between core and periphery countries. This finding provides useful information to regulators and policy makers who design and implement fiscal and monetary policies.

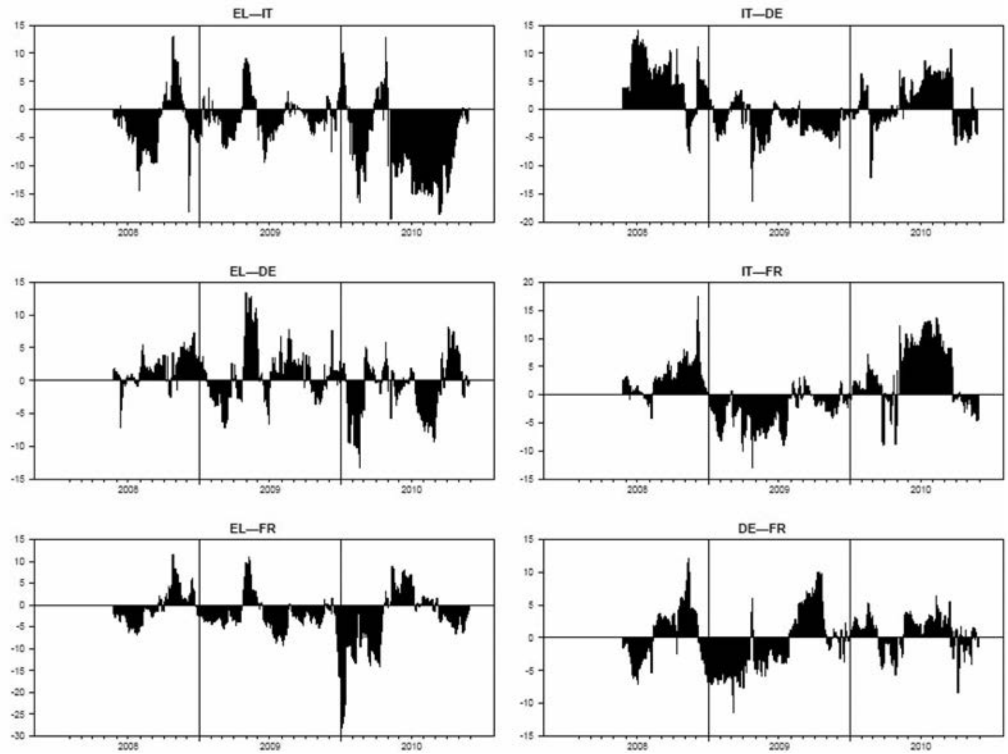

Figure 7. Net pairwise volatility spillovers (GIIPS and non-GIIPS). The figure illustrates net pairwise volatility spillovers on the 10-year benchmark bond across Greece (EL), Italy (IT), Germany (DE), and France (FR). The sample period spans the dates from January 2008 to December 2010. Vertical lines correspond to the first time period within a year. The Diebold and Yilmaz (2012) generalized VAR framework is employed using high-frequency bond data from MTS markets. Pre-crisis period: January 2008–October 2009; Crisis-period: November 2009–December 2010.

5.2. Spillovers around major macroeconomic events

In this section, we study spillovers around major macroeconomic events that took place during the sample period. Figures 11 and 12 depict net volatility spillover estimates for, respectively, non-GIIPS and GIIPS bonds along with a series of important macroeconomic events. Net spillovers are estimated as the transmission of volatility spillovers to minus the receipt from other non-GIIPS and GIIPS bonds (excluding spillovers to themselves). That is, we are considering spillovers to all seven bond volatility indices other than the index under consideration, but we separate the plots into non-GIIPS and GIIPS plots to make the plots easier to interpret. We also depict a number of important macroeconomic events that impact returns and volatilities in both regions. The events selected include the Lehman Brothers collapse, Greece's disclosure of the 2009 revised budget deficit, Dubai World's six-month debt moratorium, various downgrades on Greece's credit rating by Fitch, Moody's and Standard & Poor's, Greece's €110 billion bailout package, the launch of ECB's Securities Market Programme (SMP) and EU finance ministers agreeing on an additional €750 billion in financial assistance available to vulnerable European countries, and Ireland's €85 billion bailout. We refer to the series of announcements from Greece's disclosure of the 2009 revised budget deficit to the credit rating downgrade announcements, that occur between the 20th of October 2009 and the 22nd of December 2009, as the first set of downgrade announcements. We refer to the series of credit rating downgrade announcements that occur from the 9th of April 2010 to the 14th of June 2010 as the second set of ratings downgrades.

The volatility spillover plots are more volatile than the return spillover plots. Focusing on Figure 11 we see that in the run-up to the Lehman Brothers collapse the 2-, 5-, and 10-year non-GIIPS bonds were minor

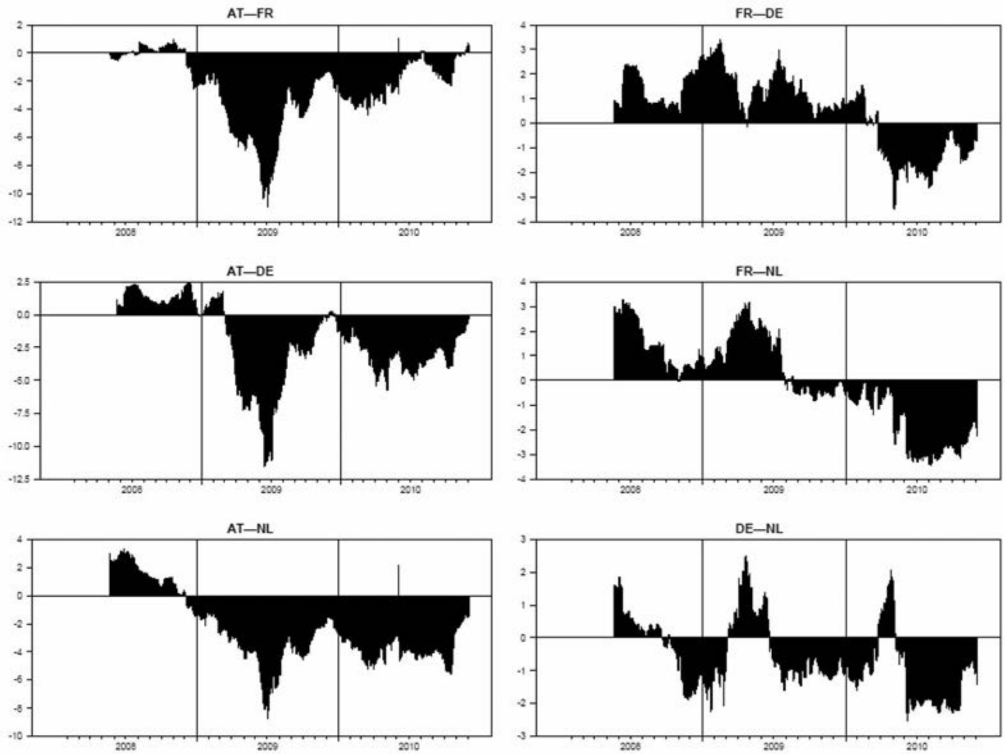

Figure 8. Net pairwise return spillovers (non-GIIPS). The figure illustrates net pairwise return spillovers on the 10-year benchmark bond across Germany (DE), France (FR), the Netherlands (NL), and Austria (AT). The sample period spans the dates from January 2008 to December 2010. Vertical lines correspond to the first time period within a year. The Diebold and Yilmaz (2012) generalized VAR framework is employed using high-frequency bond data from MTS markets. Pre-crisis period: January 2008–October 2009; Crisis-period: November 2009–December 2010.

net volatility transmitters with values of approximately 10% whereas, the 30-year non-GIIPS bond was neither a transmitter nor a receiver of volatility spillovers, suggesting that before the Lehman Brothers collapse the 30-year non-GIIPS bond follows an autonomous path and is less affected by the other bonds in terms of volatility spillovers. After the Lehman Brothers collapse, the 2-year becomes a net transmitter, and the 5-, 10- and 30-year bonds become net receivers of return volatilities. The 2-year bond will be the least impacted bond, among the four maturity ranges considered, by sudden changes in interest rates. As a result, the 2-year bond will often be the first bond sold if liquidity is needed or the first bond purchased if a safer asset is required, so it is to be expected that this bond will act as a net transmitter of volatility spillovers during extreme liquidity dry-ups. In the run-up to the beginning of the crisis, the 10- and 30-year non-GIIPS bonds become transmitters of volatility spillovers whereas, the 2- and 5-year become receivers of volatility spillovers. After the first set of credit rating downgrades we see that the 2-year non-GIIPS bond, and to a lesser extent the 10-year non-GIIPS bond, become net volatility spillover transmitters before fading away to receivers and then become transmitters again after the second set of credit rating downgrades. Thus, the 2-year non-GIIPS bond becomes a net volatility transmitter after serious liquidity events hit the market as a result of investors rebalancing their portfolios using the most liquid 2-year bond.

On the other hand, as can be seen in Figure 12, the 2-year GIIPS bond is a net volatility receiver for most of the sample with the exception of the first and second set of downgrades where the 2-year GIIPS bond becomes, for a short time, a net volatility transmitter. This suggests that the 2-year GIIPS bond becomes a volatility transmitter during very serious liquidity events such as the first and second set of ratings downgrades. The 10- and 30-year GIIPS bonds are generally net volatility spillover transmitters with their transmission rates generally increasing

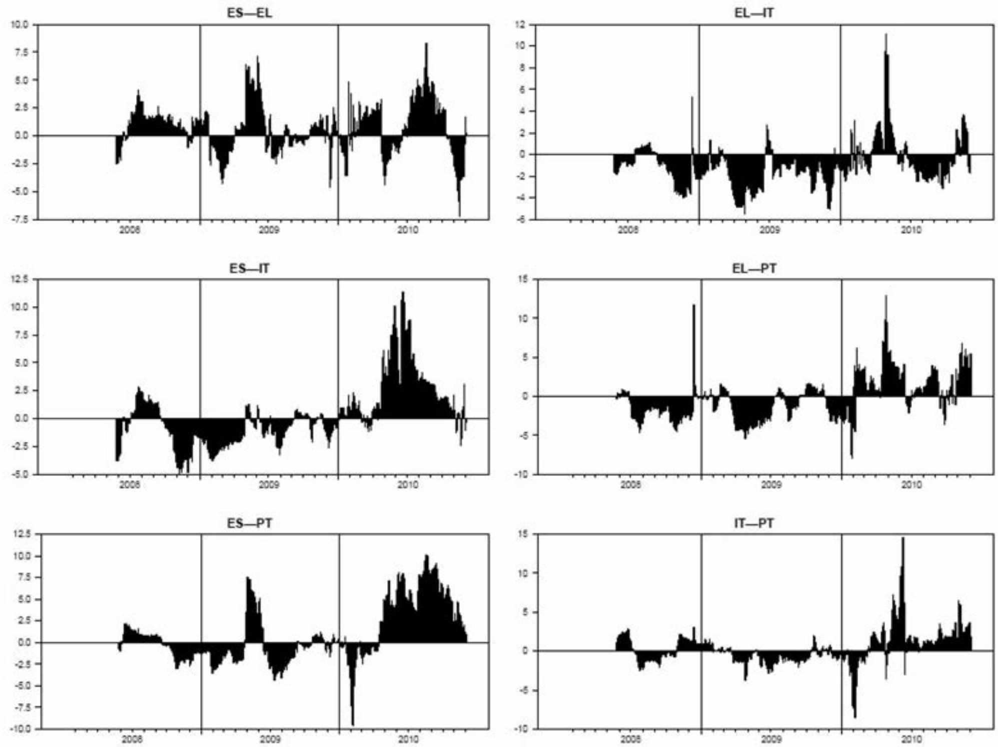

Figure 9. Net pairwise return spillovers (GIIPS). The figure illustrates net pairwise return spillovers on the 10-year benchmark bond across Greece (EL), Portugal (PT), Italy (IT), and Spain (ES). The sample period spans the dates from January 2008 to December 2010. Vertical lines correspond to the first time period within a year. The Diebold and Yilmaz (2012) generalized VAR framework is employed using high-frequency bond data from MTS markets. Pre-crisis period: January 2008–October 2009; Crisis-period: November 2009–December 2010.

after major liquidity events such as the Lehman Brothers collapse and the first set of credit rating downgrades for both bonds and the second set of downgrades for the 10-year bond.

Figures 13 and 14 depict net return spillover estimates for, respectively, non-GIIPS and GIIPS bonds. Net spillovers are estimated as the transmission of return spillovers to minus the receipt from other non-GIIPS and GIIPS bonds (excluding spillovers to themselves). Focusing on Figure 13 we see that 2-year non-GIIPS bond changes from being a net transmitter of return spillovers to a net receiver of return spillovers after the Lehman Brothers collapse. We also observe that the net return spillover estimate for the 2-year non-GIIPS bond decreases from −10% to −20% after the first set of credit rating downgrade announcements and remains a significant net receiver of return spillovers during the second set of downgrade announcements. The 30-year bond is initially a receiver of net return spillovers but increases to become a net transmitter of return spillovers in the months that follow the Lehman Brothers collapse but then becomes a net receiver in the aftermath of the first and second set of downgrade announcements. The 5- and 10-year non-GIIPS bonds are consistent net transmitters of return spillovers over the full sample remaining so around the major economic announcements we consider. Thus, 2- and 30-year non-GIIPS bonds tend to receive more return spillovers than transmit around the major macroeconomic events we consider with the 5- and 10-year non-GIIPS benchmarks remaining consistent transmitters. This is consistent with the 5- and 10-year non-GIIPS benchmarks being the most influential maturity range in terms of influencing other maturity ranges.

Turning our attention to Figure 14, we see that the net return spillovers for 5- and 10-year GIIPS bonds are positive up until early 2009 but then, some months after the Lehman Brothers collapse, the net return spillovers for 5- and 10-year GIIPS bonds become negative. Once the crisis begins in late 2009 however, the GIIPS 10-year bond net return spillover estimate becomes positive again and remains positive for the most of the rest of

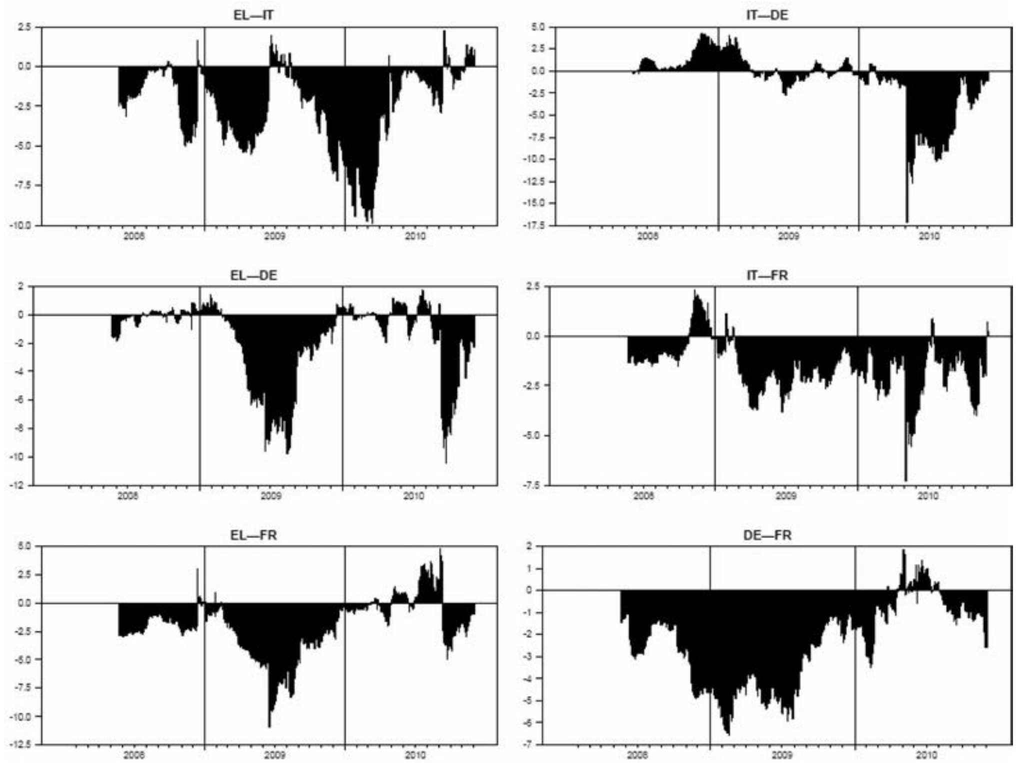

Figure 10. Net pairwise return spillovers (GIIPS and non-GIIPS). The figure illustrates net pairwise return spillovers on the 10-year benchmark bond across Greece (EL), Italy (IT), Germany (DE), and France (FR). The sample period spans the dates from January 2008 to December 2010. Vertical lines correspond to the first time period within a year. The Diebold and Yilmaz (2012) generalized VAR framework is employed using high-frequency bond data from MTS markets. Pre-crisis period: January 2008–October 2009; Crisis-period: November 2009–December 2010.

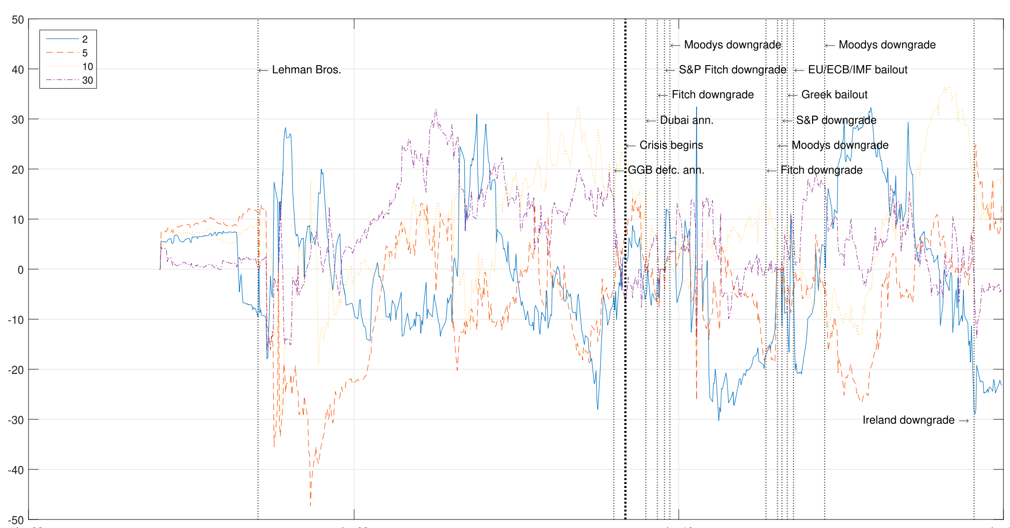

Figure 11. This plot depicts net volatility spillover estimates for non-GIIPS bonds where the net spillovers are estimated as the transmission of volatility spillovers to minus the receipt from other non-GIIPS and GIIPS bonds (excluding spillovers to themselves). The plot also depicts a number of important macroeconomic events that impact returns and volatilities in both regions. The sample period spans the dates from January 2008 to December 2010. Pre-crisis period: January 2008–October 2009; Crisis-period: November 2009–December 2010.

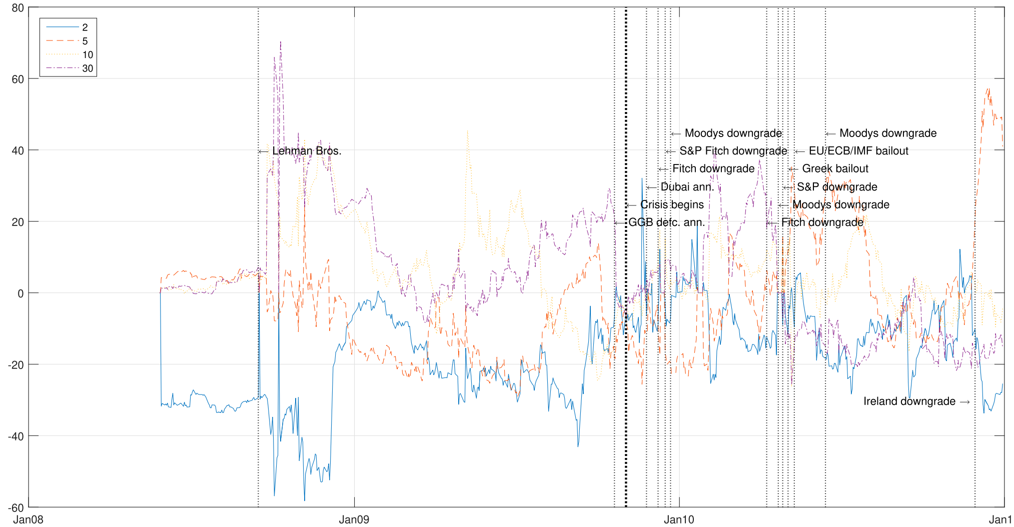

Figure 12. This plot depicts net volatility spillover estimates for GIIPS bonds where the net spillovers are estimated as the transmission of volatility spillovers to minus the receipt from other non-GIIPS and GIIPS bonds (excluding spillovers to themselves). The plot also depicts a number of important macroeconomic events that impact returns and volatilities in both regions. The sample period spans the dates from January 2008 to December 2010. Pre-crisis period: January 2008–October 2009; Crisis-period: November 2009–December 2010.

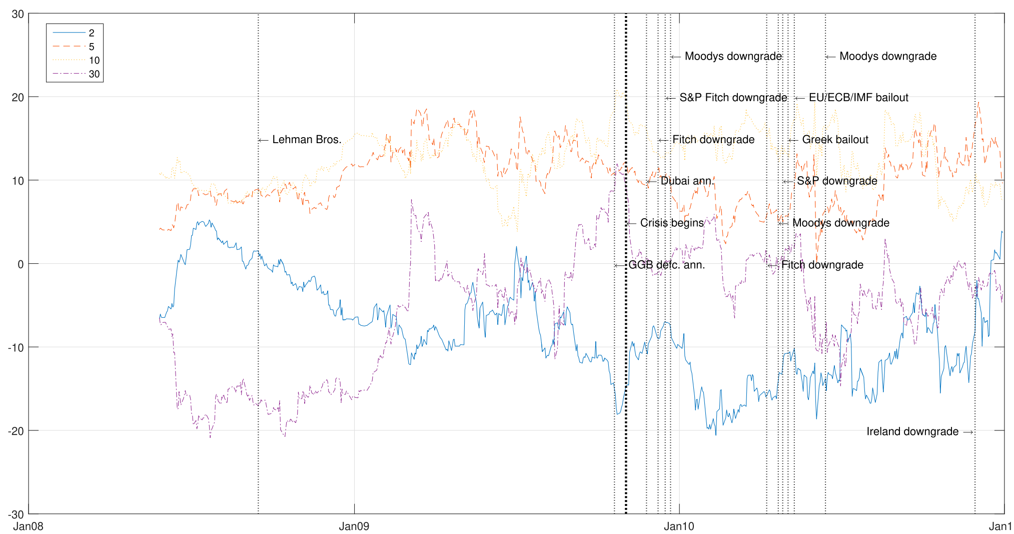

Figure 13. This plot depicts net return spillover estimates for non-GIIPS bonds where the net spillovers are estimated as the transmission of return spillovers to minus the receipt from other non-GIIPS and GIIPS bonds (excluding spillovers to themselves). The plot also depicts a number of important macroeconomic events that impact returns and volatilities in both regions. The sample period spans the dates from January 2008 to December 2010. Pre-crisis period: January 2008–October 2009; Crisis-period: November 2009–December 2010.

the sample. Thus, the 10-year GIIPS is the main channel for return spillover transmission from GIIPS bonds to the other GIIPS and non-GIIPS bonds for the crisis period. For the majority of the crisis period, the 2- and the 30-year GIIPS bonds are usually net receivers of return spillovers. However, the 2-year bond's net return spillover index increases after the first set of downgrade announcements and even becomes a net transmitter of return spillovers for a short time after the second set of downgrade announcements. The 10-year maturity GIIPS bond is often considered the main benchmark GIIPS bond so it is to be expected that this maturity bond leads the way as the main contributor of return spillovers from the GIIPS bonds to the other GIIPS and non-GIIPS bonds.

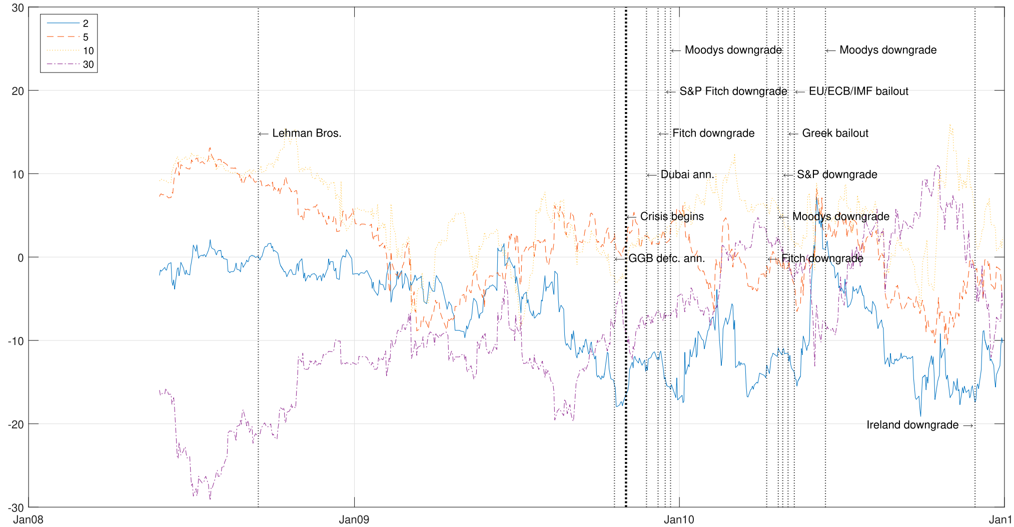

Figure 14. This plot depicts net return spillover estimates for GIIPS bonds where the net spillovers are estimated as the transmission of return spillovers to minus the receipt from other non-GIIPS and GIIPS bonds (excluding spillovers to themselves). The plot also depicts a number of important macroeconomic events that impact returns and volatilities in both regions. The sample period spans the dates from January 2008 to December 2010. Pre-crisis period: January 2008–October 2009; Crisis-period: November 2009–December 2010.

We note that return and volatility spillovers are quite strong prior to important events, such as credit rating downgrades by Fitch, Moody's and Standard & Poor's, and the bailout packages for Greece and Ireland, whilst their magnitude lowers after those announcements and policy interventions. This finding is in line with that of Alter and Beyer (2014) and highlights the fact that the risk of financial contagion is mitigated when appropriate measures are implemented to resolve the crisis. Another point to mention is the huge increase in spillovers after Lehman's announcement, in particular for GIIPS bonds, where the Fed actions that followed over the subsequent months reduced the magnitude of those spillovers, as clearly shown in Figures 12 and 14. On a different note, we document asymmetric reactions to news releases with bad news impacting more strongly than good news in both GIIPS and non-GIIPS markets and across all maturity segments. For instance, in Figures 11 and 12, it is shown that the impact of credit rating downgrades that took place at the time outweighs the impact of the Greek and Irish bailout and the launch of ECB's Securities Market Programme (SMP), confirming previous findings by Andersen et al. (2003), Beetsma et al. (2013), and Caporale, Spagnolo, and Spagnolo (2018).

There are a number of takeaways for policy makers and practitioners from this analysis. First, we show that country-specific credit ratings play an important role in the propagation of spillovers among countries. Clearly, the deterioration of credit risk for countries like Greece and Ireland has played an important role in the unfolding of the crisis. Policy makers should strive to reduce the credit risk of those countries in order to protect eurozone in its entirety. Credit rating downgrades can generate portfolio shifts which can affect sovereign bond yields. Moreover, as credit ratings are used to estimate the capital requirements of banks in a country, any credit rating downgrade can have a negative impact on bond portfolios held by banks and can affect the allocation of credit from central banks when these bond holdings are placed as collateral (a relevant discussion is provided in De Santis 2012). Second, news announcements associated to financial assistance packages to financially distressed countries generate large spillover effects to other countries. The sovereign debt of those countries is very sensitive to liquidity shortages and credit rating downgrades and can become a transmitter of financial shocks to other countries.

6. Conclusions

The European sovereign debt crisis has had a significant impact that extends beyond EU borders to the world as a whole. Sir Mervyn King, Governor of the Bank of England at the time referred to it as *the most serious financial* *crisis at least since the 1930s, if not ever*. Several eurozone member countries – with Greece at the epicentre – having potentially unsustainable levels of public debt and/or problems with their banking sector borrowed money from their European counterparts and the International Monetary Fund (IMF) in order to avoid default. Fear of contagion effects and turmoil in the banking sector drove major coordinated policy responses to avert a potential disaster. The crisis has exposed the problems of a single regional currency along with differing national fiscal policies. Additionally, it has raised concerns about necessary reforms to EU economic governance, has heightened concerns about the health of the European banking sector and has revealed significant conflicts among EU member states in relation to a closer EU integration.

Following the crisis, there is an urgent need for reliable tools and empirical evidence on the proper measurement of spillover effects across markets. Such information could help regulators and policy makers to design efficient policies for measuring systemic risk. Our study is the first to employ a rich and comprehensive high-frequency dataset from the MTS markets. The limitations of volatilities computed with the use of lower-frequency data along with statistical considerations suggest to use data at high frequencies in order to obtain reliable volatility estimates. Moreover, our study examines return and volatility spillover effects across the maturity spectrum, thus it provides more robust evidence regarding the sources, direction and the magnitude of those spillovers across short-, medium- and long-term benchmark securities.

Our methodological framework facilitates the study of both tranquil and crisis periods taking into account trends and bursts in spillovers. In our analysis of 11 eurozone bond markets from both core and periphery economies, we find consistent behaviour in the dynamics of total return spillovers versus volatility spillovers, however, we document differences in the net pairwise volatility versus return spillovers across core and periphery eurozone countries. We highlight the importance of longer-term bonds of the non-GIIPS region in the propagation of shocks as they prove to be the largest net volatility transmitters, whilst short-term securities in the GIIPS region are the major net receivers of volatility shocks. Moreover, we show that spillovers are of a higher magnitude within regions than between regions. Finally, we show that return and volatility spillovers, especially those of the GIIPS countries, are quite sensitive to major macroeconomic events, such as credit rating downgrades and liquidity injections to financially troubled countries.

Notes

1. More information on the main channels of contagion is provided by Pritsker (2001) and Longstaff (2010).
2. The reduction in noise when realized volatility measures are used is not clear-cut. As Dacorogna et al. (2001) mention, realized volatility has a considerable statistical error which can be reduced if asset returns are computed over short time intervals. However, using short return intervals leads to a bias caused by microstructure noise effects. According to the theory of quadratic variation of special semimartingales sampling at very high frequencies is the correct approach to take. On the other hand, the presence of microstructure noise suggests a lower sampling frequency would be preferable, thus an effective sampling frequency must balance the two competing factors. Aït-Sahalia and Yu (2009) argue that market microstructure noise is due to various market frictions inherent in the trading process such as bid-ask bounces, infrequent trading, price change discreteness, and inventory control effects. Andersen (2000), Andersen, Bollerslev, Diebold, and Ebens (2001), and Andersen, Bollerslev, Diebold, and Labys (2001) argue that the 5 min interval is short enough that the accuracy of the continuous record asymptotics work satisfactorily, and long enough that the effects of microstructure frictions are not overwhelming. The selection of 5 min returns as the optimal sampling frequency is probably the most popular choice and has been used extensively in the realized volatility literature.
3. Forbes and Rigobon (2002) show that the likelihood of contagion and spillover effects increases as cross-market comovements increase. The authors actually measure the correlation in returns between two markets during a calm period and subsequently test for a statistically significant increase in this correlation coefficient after a financial shock. Contagion occurs only when there is a statistically significant increase in the correlation coefficient which suggests that the transmission channel between two markets has strengthened.
4. We use the acronym GIIPS to refer to the distressed economies of Greece, Italy, Ireland, Portugal and Spain which was popularized during the European sovereign debt crisis of the late 2000s.
5. One of the main features of volatility is long memory, i.e. the slow decline of the autocorrelation function which denotes persistence in volatility. We measured the degree of fractional integration using the Geweke and Porter-Hudak (1983) semi-parametric procedure and found that there is mixed evidence of fractional dynamics with long memory features for our realized volatility series. A possible extension of this study could be the use of a multivariate extension of the Heterogenous Autoregressive Model (HAR) developed by Corsi (2009) which is able to capture different stylized facts associated with volatility and its

dynamics. See Fengler and Gisler (2015) for an analysis of U.S. stock, bond, and gold financial markets and Caloia, Cipollini, and Muzzioli (2018) for an analysis of European stock markets.

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