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Comovement and disintegration of EU sovereign bond markets during the crisis

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ABSTRACT

In this paper, we show that the comovement of bond yields in the EU before and during the European sovereign debt crisis is frequency-dependent. Using frequency cohesion and wavelet coherence, we demonstrate that the comovement is concentrated mainly at low frequencies. The comovement decreased in the eurozone during the crisis but remained high among countries with national currencies. Within the eurozone, we document a complex heterogeneity in the comovement that spans well beyond the traditional division between the core and the periphery. Overall, our results provide more credibility to the eurozone fragility hypothesis rather than to those who consider the fundamental factors to be the main driving force of the crisis.

1. Introduction

The 2008 financial crisis with the fall of Lehman Brothers shattered lenders' trust in both corporations and banks. The revelation that Greece underreported its fiscal deficits in the past and was forced to make a sharp downward revision of its budgetary projections had a similar effect on European Union member states. Suddenly, borrowing via government bonds became more expensive, especially for the EU periphery, because market participants began discriminating even among the euro area member states depending on their perceived ability to roll over their existing stock of debts when the no-bailout clause was not abandoned.

There are two main competing narratives of the European sovereign debt crisis, both of which lead to distinct policy recommendations. The fundamentalist viewpoint claims that the crisis emerged because of the deterioration of macroeconomic fundamentals. Those advocating this viewpoint note that the crisis mainly hit those countries that suffered from lack of fiscal discipline before the crisis, had a high debt-to-GDP ratio and limited growth prospects at best (Aizenman, Hutchison, & Jinjarak, 2013; Beirne & Fratzscher, 2013; Bernoth & Erdogan, 2012; Von Hagen, Schuknecht, & Wolswijk, 2011). Additionally, attempts to estimate the determinants of bond spreads in the eurozone often confirm their higher sensitivity to fundamentals in the years of the crisis (Afonso & Leal, 2017). According to the fundamentalist view, the countries in trouble should adopt austerity policies to improve their fiscal positions and to lower their expected debt.

The alternative perspective is presented by the eurozone fragility hypothesis proposed by De Grauwe and Ji (2013). This approach emphasizes deficiencies in the design of the eurozone and considers them as the main driving factor in fueling the crisis. Most

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importantly, the ECB does not serve as the lender of last resort for troubled sovereigns even with a temporary lack of cash needed to roll over their debts. Hence, De Grauwe and Ji (2013) consider the European sovereign debt crisis to be an example of a crisis driven by self-fulfilling prophecies and as evidence of multiple equilibria on bond markets at which austerity might be inefficient. The appropriate crisis resolution should address the flaws in the construction of the eurozone, and the mandate of the ECB should be extended to allow the provision of liquidity of the sovereigns. Proponents of the fragility hypothesis often point to the fact that the crisis also affected countries with a low pre-crisis debt-to-GDP ratio, and with a sound record of compliance with the EU fiscal rules, such as Spain or Ireland. Additionally, they stress the fact that many countries outside the eurozone experienced similar increases in the debt-to-GDP ratio without being punished by prohibitively high bond yields.

In this paper, we contribute to the debate between the proponents of the two alternative narratives. While the literature often estimates the determinants of sovereign bond yields or spreads (Afonso, Arghyrou, Gadea, & Kontonikas, 2018), we focus on comovements of sovereign bond yields across different frequencies and on the evolution of comovements over time. First, we investigate how the fall of Lehman Brothers and the revelation of Greece's false accounting affected the comovement dynamics of yields on sovereign bonds in the EU. Then, we assess whether some form of contagion or disintegration was present during the crisis.

De Grauwe and Ji (2013) propose several tests for the fragility of the eurozone hypothesis. First, large movements in bond spreads should occur over a short period of time. Second, changes in fundamentals cannot account for the total change in the spreads, although the evolution of fundamentals might function as a trigger of the fear factor that drives movements on bond markets. Third, changes in spreads should be clustered in time, i.e., changes in comovements should appear in more countries at similar points in time. De Grauwe and Ji (2013) show that indeed, changes in fundamentals are not enough to explain the variation of sovereign bond spreads in the European debt crisis because time-dummies in the crisis years remain significant even after controlling for all main variables that are supposed to drive the bond spreads.[1] In our paper, we provide an implicit test of the third aspect of the fragility hypothesis. We test whether the changes in spreads or yields are clustered over time and across countries.

We use the methods based on the frequency and the time-frequency domain: First, we employ frequency cohesion (Croux, Forni, & Reichlin, 2001) in order to compare the dominant frequencies in bond yields among the groups of the EU member states before and after the fall of Lehman Brothers. Second, we analyze comovement using wavelet cohesion and coherence to show how comovements on different frequencies changed over time, without imposing an explicit structural break to the analysis and without the risk of model misspecification and heteroscedasticity that complicate utilization of other methods, such as panel data analysis (Rigobon, 2016). We apply these methods on the 10-year sovereign bond yields of 11 EU member states over the period from January 2001 to December 2013.

Comovement analysis with frequency- and time-frequency-domain techniques is one of the novelties of this paper. The existing literature has commonly used time-domain techniques, for example, D'Ecclesia and Costantini (2006); Idier (2011). Recently, Ehrmann and Fratzscher (2017), Stamatopoulos, Arvanitis, and Terzakis (2017) and Buchholz and Tonzer (2016) address the problem of comovement and integration of euro area sovereign bond markets during the European debt crisis. These papers document significant fragmentation of the euro area bond market and contagion across countries. However, time-domain analysis omits the frequency dimension, which means that potential differences between the long-term and short-term comovements are not considered. Frequency-domain techniques make such a decomposition feasible. In particular, the frequency cohesion (Croux et al., 2001) compares correlations among multiple time series across different frequencies. Thus, this technique is well suited for evaluation of changes in the multivariate comovement among the sovereign bond yields before and after the fall of Lehman Brothers.

We then resort to the wavelet analysis that allows changes in comovements over time and over frequencies to be measured simultaneously, exploiting both the time and frequency domains. In principle, wavelet analysis decomposes a time series into frequency bands, called wavelet scales, that correspond to cyclical components. As wavelet filters have compact support,[2] the wavelet transform allows for good localization in time at which those cyclical components represent an important part of the original series.(Percival & Walden, 2000; Ftiti, Jawadi, & Louhichi, 2017).[3] Furthermore, in the multivariate setting, wavelets allow us to discriminate among short-term, medium-term and long-term comovement, which can be perceived as market dynamics at different investment horizons. The comovement analysis with wavelets is addressed, for example, in Rua (2010); Vacha and Barunik (2012), Nachane and Dubey (2013) and Hkiri, Hammoudeh, Aloui, and Shahbaz (2018) among others. In particular, wavelet cohesion (Rua & Lopes, 2015) and wavelet coherence (Aguiar-Conraria, Martins, & Soares, 2012) are used to detect dependencies at various frequency bands and to assess whether the change in comovement was gradual during the crisis, as was the change in fundamentals, or clustered in short periods of time.

Indeed, our results imply that the frequency decomposition of bond returns is crucial because their comovement is highly frequency dependent. Even before the start of the financial crisis in 2008, comovement was concentrated mainly at the low frequencies. During the European debt crisis, comovement in low frequencies dropped among the eurozone members but remained high among countries with their own currencies. Within the eurozone, the comovement decreased not just between the core and the periphery but within these groups as well. In particular, the weakening of cohesion among the core countries has not yet been emphasized in the literature. Interestingly, the largest comovement can be documented among Germany, the Netherlands, and Sweden and Denmark, two countries outside the eurozone. Overall, we demonstrate that the fall of Lehman Brothers and the Greek budget deficit announcement strongly influenced the dependence structures on European sovereign bond markets. From a policy perspective, our results seem to be consistent

[1] Similarly, Afonso and Leal (2017) report lower R^2 of their regressions used for estimation of determinants of bond spreads after 2008 in comparison to the previous period.

[2] Note that a function has compact support if it is zero outside of a compact set.

[3] The introduction to the continuous wavelet transform is provided in Appendix B.

with the eurozone fragility hypothesis rather than with the fundamental narrative, as the changes in the comovement correspond to a behavior of markets driven by a strong fear factor and flight to safety and liquidity, which has not been compensated by policy measures from the EU level.

The remainder of this paper is structured as follows. In Section 2, we describe the dataset and motivate the wavelet analysis. Next, in Section 3, we present the results of the comovement using cohesion and wavelet coherence. Section 4 is dedicated to the contagion analysis of the EU. Finally, Section 5 concludes.

2. Data

In our analysis, we use daily data on the bid yields of 10-year sovereign bonds. All data are from the Reuters Wealth Manager database. The dataset covers the period from January 1, 2001, to December 31, 2013. We chose the sovereign yields of 11 states that are being representative for all three main categories of the EU, the core and the periphery of the eurozone, and countries that kept their own currencies.

The core of the eurozone is represented by Germany, France, the Netherlands, and Belgium. From the periphery, we have chosen Greece, Spain, Portugal, and Italy, two large and two small economies. During the crisis, these countries were hit by increased bond yields at most, although for different reasons, and their governments were forced to adopt extensive austerity measures. Then, we have included the following EU member states outside the eurozone: the United Kingdom, Denmark, and Sweden. All three countries have opted to remain outside the eurozone, but Denmark decided to align its currency (the krone) to the euro via the ERM. Overall, our selection of countries contains those that were strongly affected by the crisis and countries that suffered less; the inclusion of the countries outside the euro area enables an explicit analysis of the effect of the eurozone membership on economic resilience.

We analyze bond yields rather than spreads, which is not a particularly common approach. The use of spreads is more typical in larger panel data studies with multiple dependent variables. Much of the literature defines the yield spread as the difference between a country's yield and that on German sovereign bonds, but we aim to analyze Germany because it is arguably the most important economy in the EU. Furthermore, we would like to model “real” yields, which are those demanded by investors. A yield spread represents the risk premium of a bond and is thus a different variable in practice.

In general, a wavelet transform does not require stationarity; the process only needs to be locally stationary. However, to obtain reasonable confidence intervals for the wavelet correlation, we need data without nonstationary features (Gençay, Selçuk, & Whitcher, 2001). Hence, we use the log-differences of sovereign bond yields (Fig. 1). The descriptive statistics indicate that no time series of yields is normally distributed. This is not surprising, as excessive kurtosis is observable in all cases, especially for Greece, Spain and Portugal (Table 1).

3. Comovement in bond yields

To determine how the financial crisis changed perceptions of financial risk in the EU, we study comovements in sovereign bond

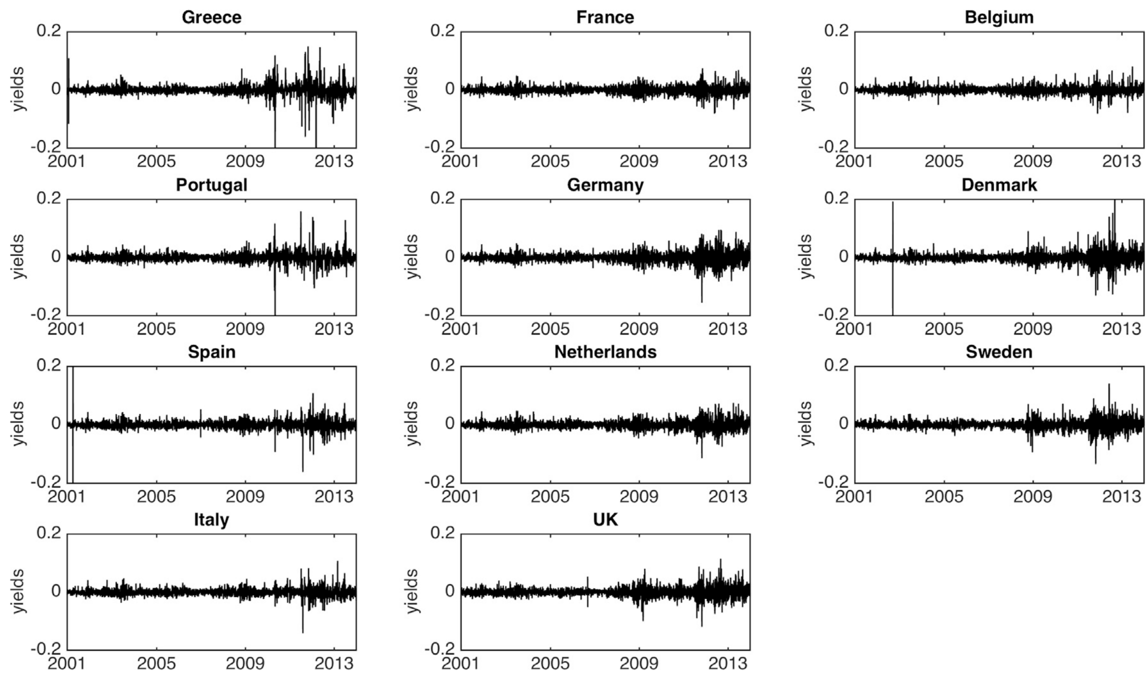

Fig. 1. Log-differences of 10-year sovereign bond yields.

Table 1
Descriptive statistics of sovereign bond yields.

Country	Mean	S.D.	Min.	Max.	Skew.	Kurtosis
Greece	0.00013	0.0223	−0.7155	0.1501	−12.214	371.7
Portugal	0.00004	0.0156	−0.3019	0.1590	−1.2580	48.9
Spain	−0.00006	0.0148	−0.2541	0.2578	−0.2881	59.5
Italy	−0.00007	0.0124	−0.1411	0.1081	0.0009	10.0
France	−0.00021	0.0131	−0.0816	0.0750	0.0210	3.9
Germany	−0.00027	0.0172	−0.1559	0.0958	−0.0058	5.7
Netherlands	−0.00024	0.0143	−0.1147	0.0748	0.1405	4.2
UK	−0.00014	0.0155	−0.0005	0.1152	0.1463	5.8
Belgium	−0.00021	0.0126	−0.0817	0.0810	0.2169	4.6
Denmark	−0.00028	0.0187	−0.2122	0.2913	1.1421	32.2
Sweden	−0.00019	0.0158	−0.1338	0.1407	0.2037	7.9

yields. Further, we aim to examine the influence of various investment horizons on these comovements; therefore, we test whether these comovements are frequency-dependent. To do so, we employ frequency cohesion, wavelet cohesion, and wavelet coherence to discover the time-frequency relationship among the states.[4]

We are primarily interested in two specific days crucial to the European debt crisis. The first is September 15, 2008 – the day that Lehman Brothers went bankrupt, which is considered the start of the 'hot' phase of the global financial crisis. The second date, October 20, 2009, is the day when the Greek minister of finance, Papakonstantinou, announced that the country's budget deficit would be much higher than previously expected. Both dates are marked on the coherence plots with red vertical lines.

3.1. Multivariate comovement

First, we examine the multivariate comovement using the frequency and wavelet cohesion. The frequency cohesion is a multivariate measure of dynamic correlation on frequency bands, and it can be understood as a correlation of band-pass-filtered series (Croux et al., 2001). For more details, see Appendix A.

Fig. 2 depicts frequency cohesion for the core, periphery, and outside the eurozone. We divide the sample into two time periods: the first one is before Lehman Brothers bankruptcy, and the second covers the period after. We can immediately see that the comovement is frequency dependent. In the first time period, before the crisis, the comovement is apparent on low frequencies but remains lower at high frequencies in all three groups of countries. Hence, the convergence of bond yields within the euro area suggesting evidence of an increased degree of financial market integration arises due to long-term developments, while the yields remained more dispersed in high frequencies, especially in the EU periphery.

Following the crisis, the pattern in the comovement changed significantly in all three groups of countries. In the euro area, regardless of whether in the core or in the periphery, the frequency cohesion at low frequencies dropped significantly but remained similar or somewhat higher at high frequencies. The decrease in cohesion at the low frequencies is more pronounced in the periphery than in the core. On the other hand, the developments in the countries outside the eurozone tell a different story. The comovements increased at high frequencies in particular, and a small but still significant increase appears at low frequencies as well.

Next, we focus on changes of the multivariate comovement over time, and we employ the wavelet cohesion methodology developed by Rua and Lopes (2015), as an extension of the frequency cohesion to the time-frequency space. Instead of relying on a prespecified structural break, the wavelet cohesion shows continuous changes in comovements also in the time domain. For further details on wavelet cohesion, see Appendix D.

The comovement of sovereign bond yields is depicted in the wavelet cohesion plots (Fig. 3), where the horizontal axes represent time and the vertical axes represent the frequency depicted as period measured in days. Short periods in the upper part represent high-frequency components, i.e., short-term comovement, which is related to short investment horizons of several days, while long periods located in the lower part of the graph represent low-frequency components, i.e., long-term comovement, which is related to long investment horizons of several months to one year.

We do not report cyclical components with periods longer than 256 days, as results after this period are difficult to interpret because the cone of influence would be excessively large. The intensity of the comovement is represented by a color scale, where yellow indicates the highest intensity and dark blue indicates no relationship. Further, there are hazy areas at the beginning and end of the graph. In these areas, the so-called edge effect is present, meaning that the wavelet filters analyze partly nonexistent data. As a consequence, these small parts of the wavelet cohesion estimates, called the cone of influence, are not fully reliable due to boundary effects (Torrence & Compo, 1998).

The wavelet cohesion graphs provide more detailed information about the dynamics of the comovement in all three groups. The fall of Lehman Brothers decreased the cohesion, notably in the euro area and at frequencies with periods between 3 and 6 months. However, while the cohesion of the core countries increased, at least temporarily, after the Greek deficit announcement of October 2009, the

[4] For the estimation of wavelet coherence, we use the MATLAB toolbox created by A. Grinsted, J.C. Moore and S. Jevrejeva, http://noc.ac.uk/using-science/crosswavelet-wavelet-coherence.

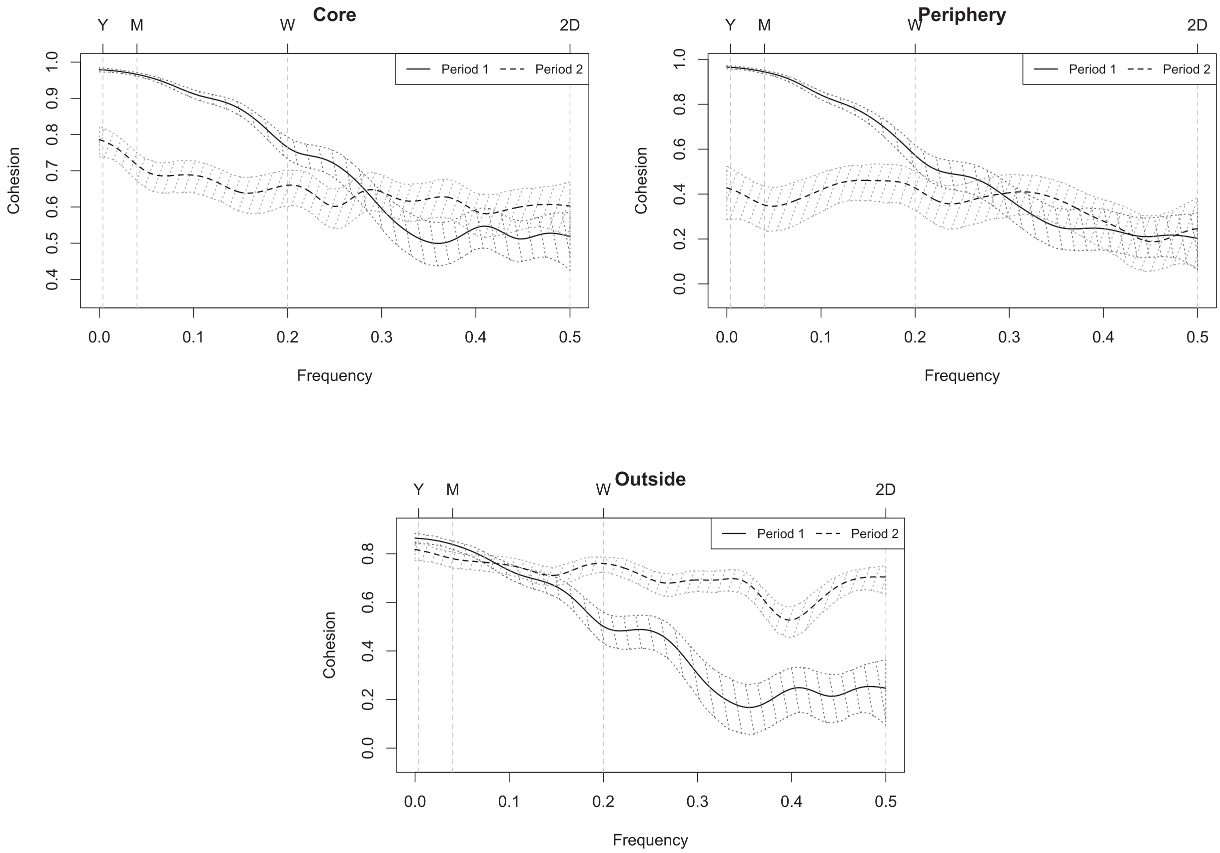

Fig. 2. Frequency cohesion for core, periphery and the states outside of the eurozone. Frequency on the x-axis has resolution from approx. a year (Y) over month (M) and week (W) to two days (2D). The y-axis depicts the multivariate cohesion. Period 1 (2) covers the sample before (after) the fall of Lehman Brothers. Shadow regions around the estimates represents 95% confidence interval.

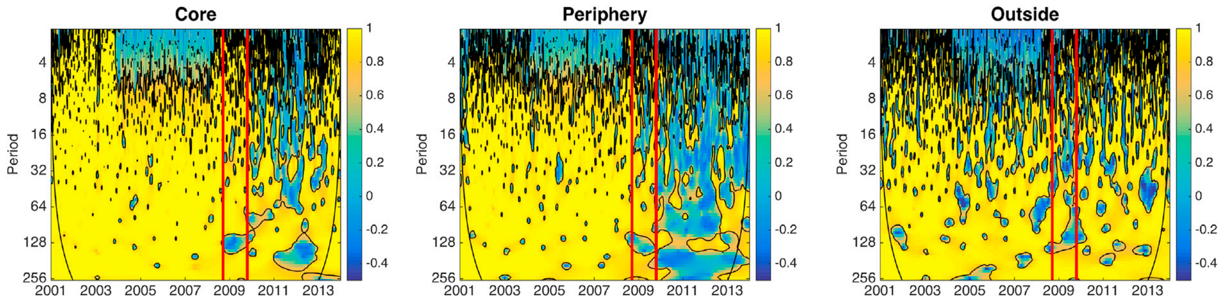

Fig. 3. Wavelet cohesion for core, periphery and the states outside of eurozone. Horizontal axis: years. Vertical axis: frequency, represented by the length of the period (in days). The color scale in the right bar shows the intensity of the cohesion used in the graph. The red lines represent the dates of the fall of Lehman Brothers and the Greek deficit announcement. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

disintegration of the periphery itself accelerated and quickly appeared at all frequencies. Then, the core partially disintegrated in the most acute phase of the European sovereign debt crisis in 2011 and 2012. The countries outside the eurozone are different, with rather similar patterns of comovement at low frequencies before and during the crisis.

Overall, our analysis of the cohesion using the frequency and time-frequency methods confirms the divergence of bond yields across eurozone members and extends the evidence in two directions: comovement was concentrated in low frequencies before the crisis, while some dispersion has remained at high frequencies. After the crisis, even the developments at low frequencies became dispersed, not only between the core and periphery but within those country groups as well. Hence, the prevailing division of the euro area to the core and periphery masks potentially important within-group differences.

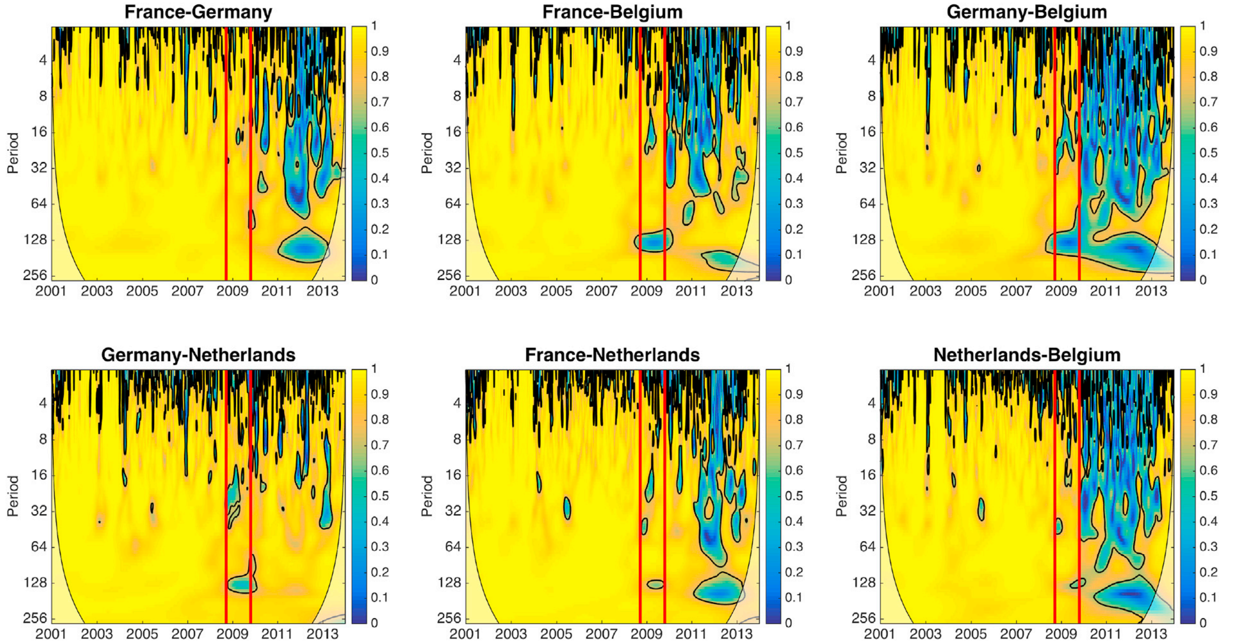

Fig. 4. Intragroup coherence: the core. Horizontal axis: years. Vertical axis: frequency, represented by the length of the period (in days). The color scale in the right bar shows the intensity of the cohesion used in the graph. The red lines represent the dates of the fall of Lehman Brothers and the Greek deficit announcement. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.2. Intragroup analysis

We analyze comovement of bond yields within each group of countries to show whether some clusters of countries evolve differently from others. For the bivariate analysis of intragroup comovements we employ the wavelet coherence analysis (Torrence & Compo, 1998). The method is equivalent to wavelet cohesion but intended for a comparison of two time-series. In principle, the wavelet coherence measures dynamic evolution of correlation between two time series both in time and frequency. The coherence plots can be read in exactly the same way as the cohesion plots introduced in the previous section. The description of the method is provided in Appendix C.

Coherence analysis reveals that the core states have been highly integrated since 2001; see Fig. 4. We observe significant coherence (yellow-colored regions) and, thus, strong comovement in all non-crisis time periods. During the crisis, the previously high coherence within the core group vanished. From a policy perspective, the most important is the gradually decreasing coherence between France and Germany that, since 2011, appears at almost all frequencies, except the very low ones. Presumably, the divergence in economic developments between the two largest economies, and by far most powerful countries of the European Union, contributed to the difficulties in negotiating joint policy actions to mitigate the debt crisis. Regarding the two smaller countries, the Netherlands remained strongly interconnected with Germany, while the coherence of Belgium with Germany and the Netherlands almost disappeared. Therefore, bivariate analysis corroborates that even the core countries became partially disintegrated during the crisis.

The dynamics of the periphery countries has been even more dramatic. At first glance, the periphery countries are far from being homogenous (Fig. 5). The only two countries that retained somewhat higher co-dependence on lower frequencies were Spain and Italy, despite the large difference in their pre-crisis debt-to-GDP ratio. Interestingly, in 2011 and 2012, there appear higher coherences at lower frequencies in country pairs with Greece, which might indicate a contagion, i.e., intensification of the comovement, in the EU periphery in the most acute part of the European debt crisis.[5]

The coherence of the states outside the eurozone shows a different story (Fig. 6). We observe that the non-eurozone states were less integrated than the core and the periphery states before the crisis, but during the crisis period, comovement among the former appears to be stronger than that observed among the periphery countries. This finding is in line with Claeys and Vašíček (2014). The intensity of short-term comovement varies, especially between Sweden and the United Kingdom.[6] Even over the medium term (8–32-day periods),

[5] We report a similar increase in coherence between Italy, Spain and France in the next section, in which we show the results of intergroup coherence analysis.

[6] We have to interpret this result with caution because quantitative easing (QE), introduced by the Bank of England in 2009, may have played a significant role in the loss of comovement; see Christensen and Rudebusch (2012).

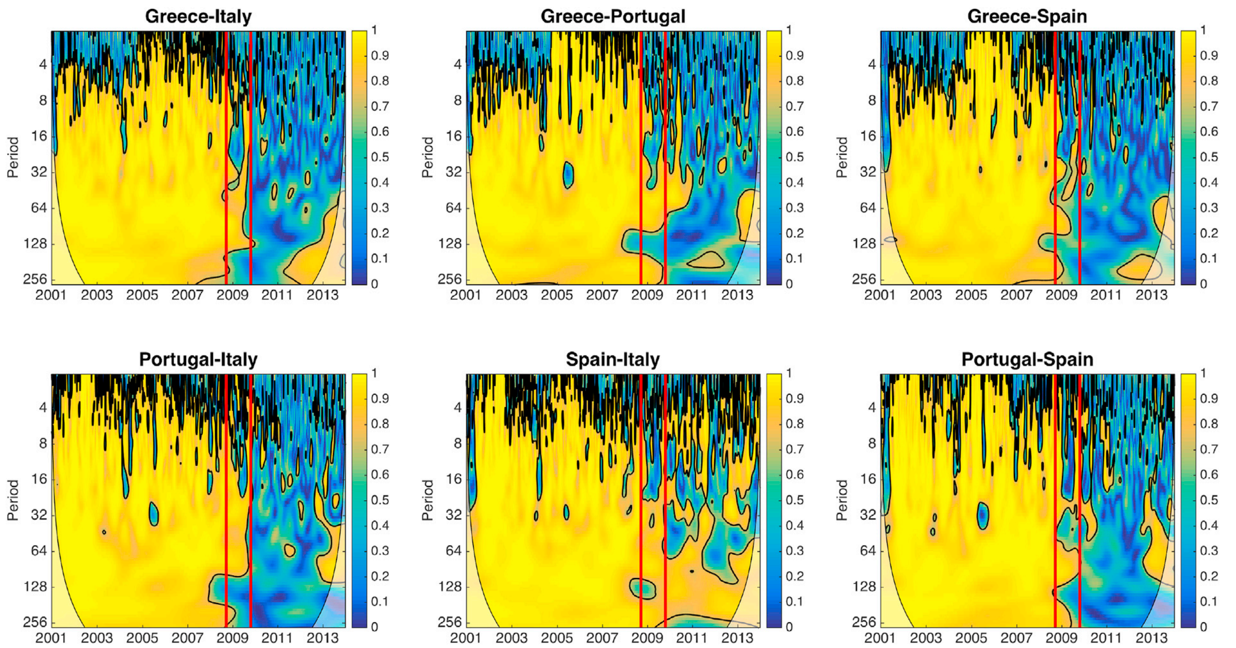

Fig. 5. Intragroup coherence: the periphery. Horizontal axis: years. Vertical axis: frequency, represented by the length of the period (in days). The color scale in the right bar shows the intensity of the cohesion used in the graph. The red lines represent the dates of the fall of Lehman Brothers and the Greek deficit announcement. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

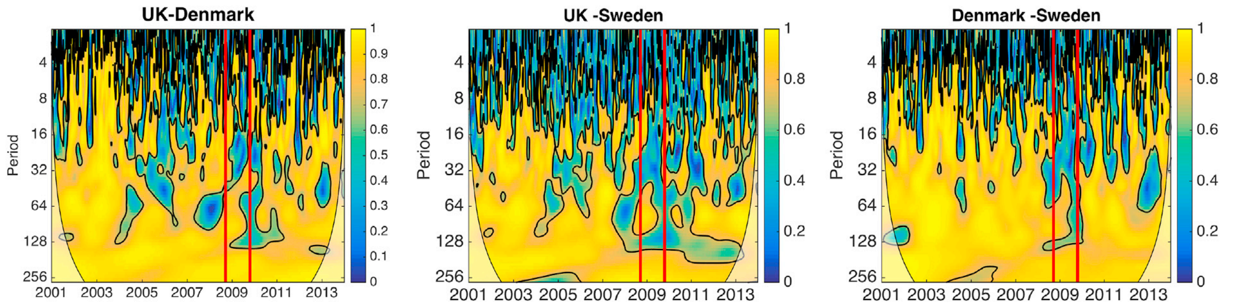

Fig. 6. Intragroup coherence: the states outside the eurozone. The horizontal axis: years. The vertical axis: frequency, represented by the length of the period (in days). The color scale in the right bar shows the intensity of the cohesion used in the graph. The red lines represent the dates of the fall of Lehman Brothers and the Greek deficit announcement. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

comovement does not appear to be consistently strong.[7] The most interesting is the Sweden-Denmark pair. There is a clear decrease in comovement after the fall of Lehman Brothers and an increase immediately after October 20, 2009.

3.3. Intergroup analysis

Now, let us focus on the intergroup analysis to see whether the division into the core, periphery and outside the eurozone does not mask interesting comovements of countries of distinct groups. First, we present the estimates of comovement with the peripheral states in Figs. 7–9.

Let us start with Greece. comovement with Germany, France, Belgium, the Netherlands, Denmark and Sweden was gradually increasing across all frequencies until 2007/2008, indicating that Greece became more integrated (Fig. 7). However, after the fall of Lehman Brothers, the comovement almost disappeared. Surprisingly, the revelation about the Greek deficit did not play an important

[7] The presence of exchange rate risk is a possible reason why comovement at high frequencies is relatively low and volatile.

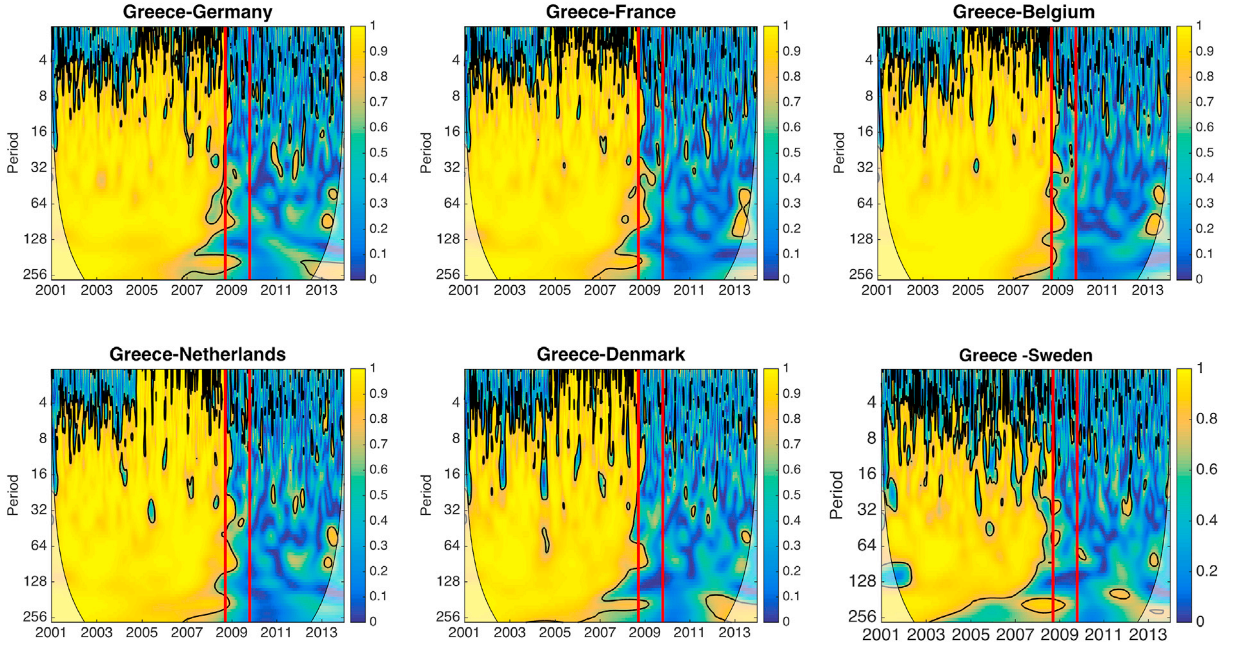

Fig. 7. Intergroup coherence with Greece.

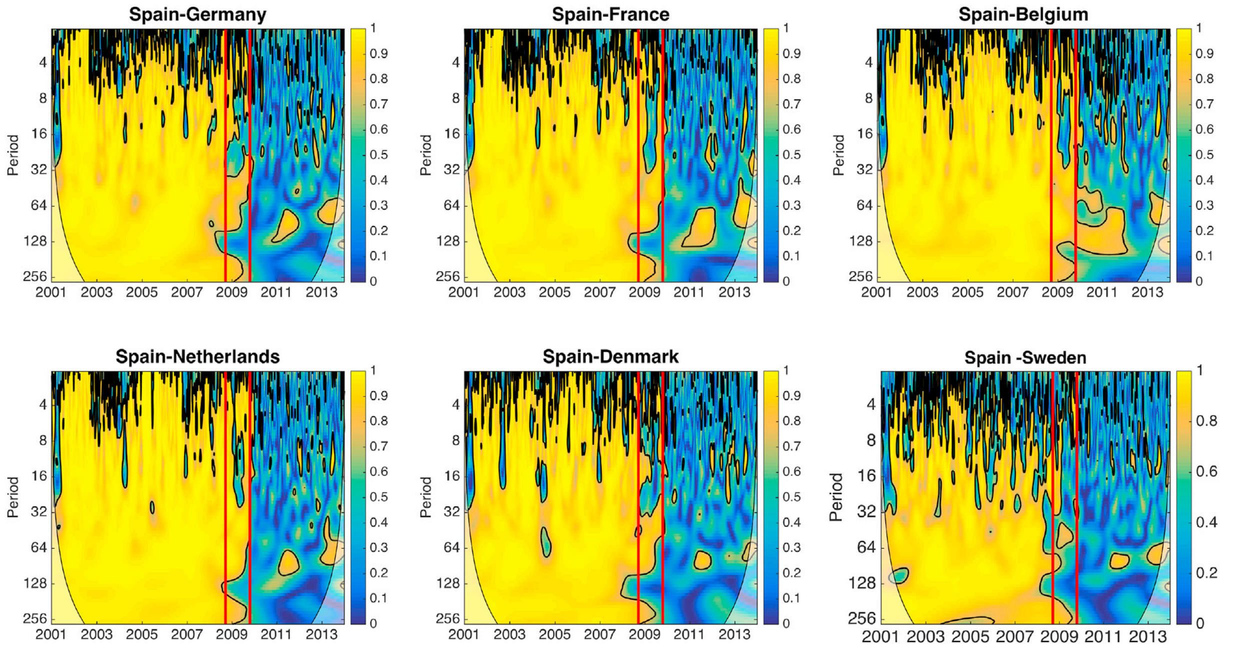

Fig. 8. Intergroup coherence with Spain.

role in the disintegration of Greek government bonds with those of other states. Hence, the disintegration started immediately with the financial crisis, well before the information about the state of the Greek public finance was revealed.[8]

Interestingly, the announcement of the higher-than-expected deficit of Greece had profound effects on bond yields of other countries, especially for Spain and Italy. As seen in Figs. 8 and 9, the comovement vanished at the 8–32- and 128-day periods, and another significant drop followed after October 20, 2009, for all periods.

[8] In fact, the dynamics of Greek bond yields started to diverge well before the fundamentals actually changed, which is at odds with the "fundamentalist perspective" on the European sovereign debt crisis.

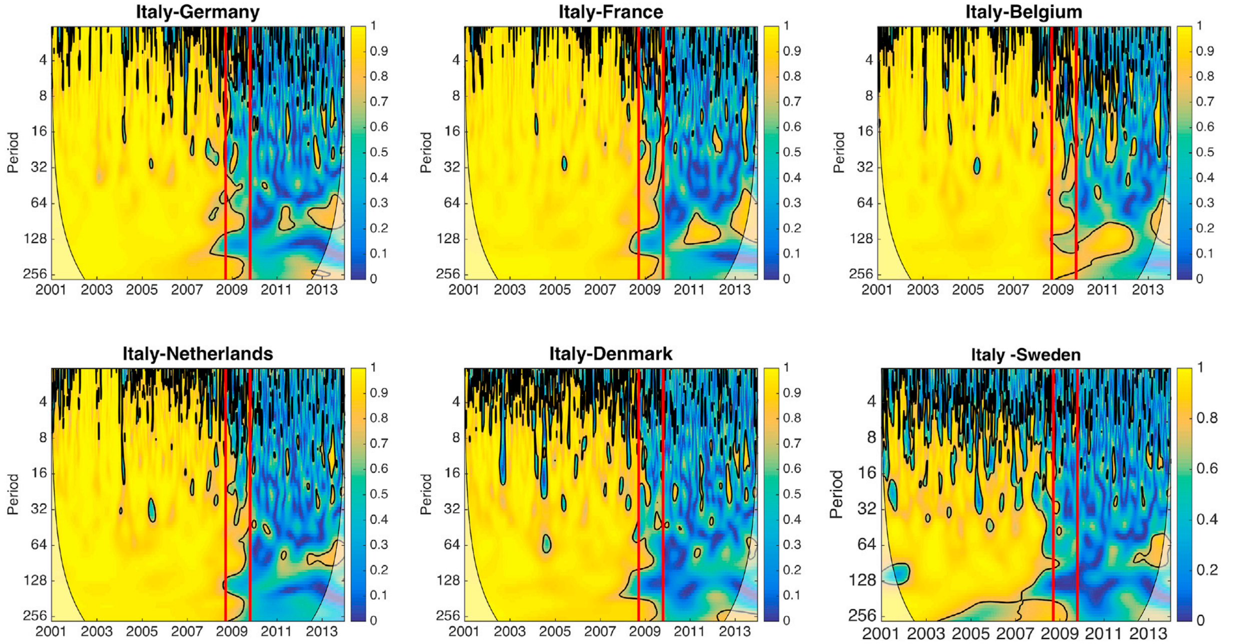

Fig. 9. Intergroup coherence with Italy.

We have already noted that the comovement of the core also decreased during the European sovereign debt crisis. The analysis of comovement of Spain and Italy with the core countries completes the story: It is evident that the intensity of comovement between Spain and Italy and France and Belgium actually increased on low frequencies corresponding to periods of approximately 128 days in 2011 and 2012, when the crisis reached its peak.

Finally, we provide estimates of the wavelet coherence between the countries outside the euro area and the core countries. Figs. 10

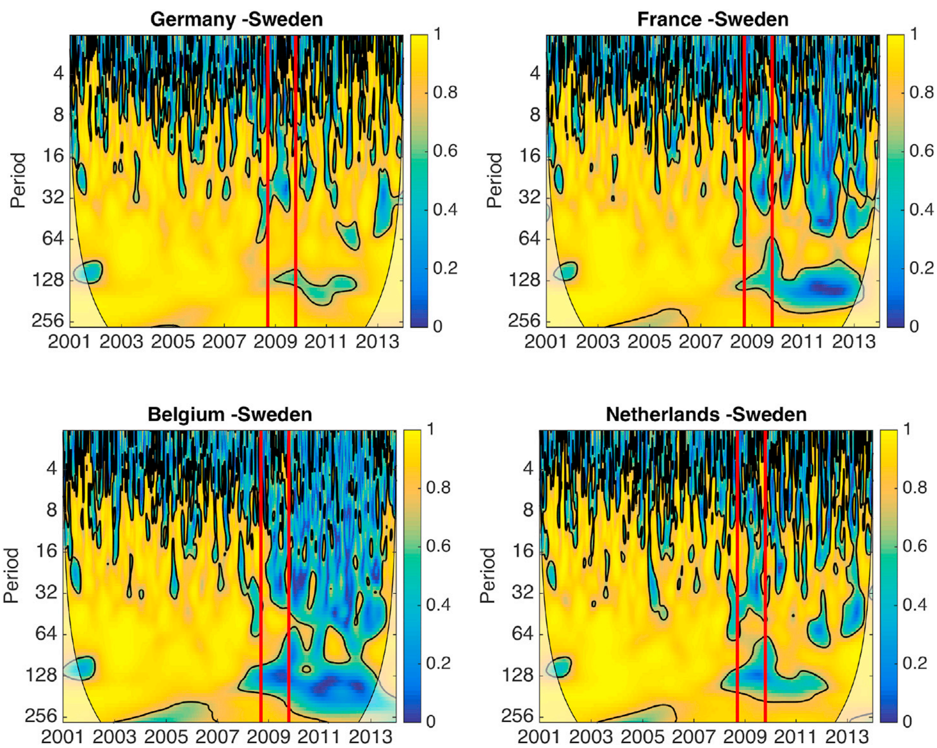

Fig. 10. Intergroup coherence with Sweden.

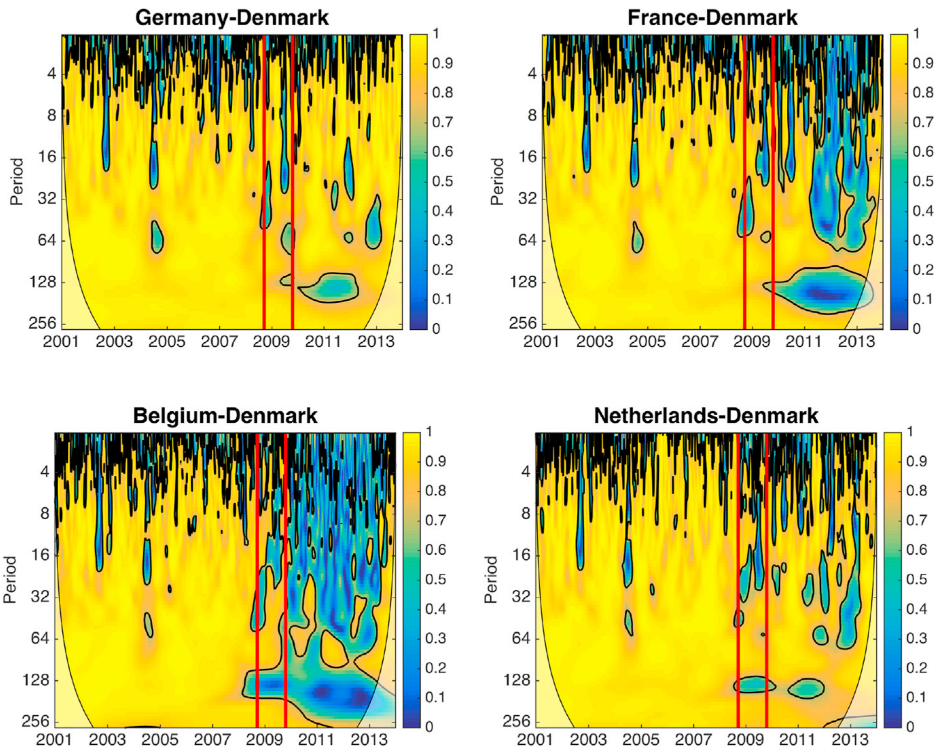

Fig. 11. Intergroup coherence with Denmark.

and 11 provide additional evidence for divergent trajectories of bond yields within the core. While Germany, the Netherlands, Denmark, and Sweden remained tightly connected even during the crisis of 2011/2012, the coherence between Belgium and France with Denmark and Sweden decreased, and it almost disappeared at low frequencies after the Greek deficit announcement. Further, France and Belgium became more closely interrelated with Italy and Spain from the periphery than to the core itself. Clearly, these results show that during the crisis, a new core consisting of Germany, the Netherlands, Denmark, and Sweden had been formed, from countries within and outside the eurozone rather than from its member states.

4. Contagion and disintegration in sovereign bond markets

The European sovereign bond crisis lead to disintegration of financial markets in the EU and in euro area in particular, mostly reflected by lower correlation in bond yields in comparison to the times before the crisis (Al-Eyd & Berkmen, 2013; ECB, 2012).[9] This market disintegration has had profound policy implications for monetary policy and financial stability because the dispersion in financing conditions for the non-financial sector impeded the transmission mechanisms of the ECB's monetary policy.

The disintegration did not occur at once in all countries in the periphery or in the core; rather, it spread through the euro area as a contagion, with some countries being more resilient than others.[10] To test for the presence of market disintegration, we use the wavelet correlation, as in Gallegati (2012), who uses this methodology to test for the presence of contagion on financial markets. This method provides us with a formal statistical test that can confirm significant change in correlation structure across different frequencies. Studies using time-frequency domain to test for the shifts in the correlation structure include, for example, Ftiti, Tiwari, Belanès, and Guesmi

[9] Baele, Ferrando, Hördahl, Krylova, and Monnet (2004) define markets as integrated when all agents face identical rules, have equal access to financial instruments or services, and market participants are treated equally, irrespective of their country of origin. As a consequence, the law of one price implies that in fully-integrated markets, assets with identical risks shall have the same expected returns regardless their origin. Hence, the most straightforward test of market integration is to check whether returns of assets of the same class are correlated across countries as the law of one price would predict. To this unconditional correlation, Ehrmann, Fratzscher, Gürkaynak, and Swanson (2011) add the dimension of the conditional behavior of bond yields in euro area countries. With integrated markets, bonds of different countries but with the same maturity should respond similarly to the common shock even when there is some country-specific noise. The authors document significant progress in market integration on the bond market until 2007, despite different habits and history in regulation inherited from history.

[10] We are aware of the fact that the definitions of contagion and its distinction from normal comovement is rather tenuous (Rigobon, 2016). Broadly, contagion is usually defined as a broad change in correlation structure in response to some shock, so-called shift contagion. In our paper, we use the term contagion as a description of a crisis spreading from one country to another. On the identification of contagion in the euro area during the crisis, see in particular (Mink & De Haan, 2013) and (Silvapulle, Fenech, Thomas, & Brooks, 2016).

(2015) and Dewandaru, Masih, and Masih (2016).

In contrast to previous sections, we focus on frequency components related to short-term investment horizons, covering periods from 2 to 16 days, as these high frequencies are usually related to contagion or market disintegration. Hence, we do not study the low frequencies that indicate rather long-term changes in comovements.

To test for changes in wavelet correlation[11] around the fall of Lehman Brothers and the announcement of the Greek budget deficit, we define $\rho_{XY}^{(I)}(j)$ as the correlation at a specific wavelet scale j before the respective date of structural break and define $\rho_{XY}^{(II)}(j)$ as the correlation after the structural break. Then, we test the null hypothesis that the two values are the same:

$$H_0 : \rho_{XY}^{(I)}(j) = \rho_{XY}^{(II)}(j) \tag{1}$$

$$H_A : \rho_{XY}^{(I)}(j) \neq \rho_{XY}^{(II)}(j). \tag{2}$$

An advantage of this wavelet-based method is its robustness to non-Gaussianity (Gallegati, 2012). The null hypothesis is rejected, and thus, a change in correlation at these scales is detected if the confidence intervals of pre-crisis and post-crisis correlation do not overlap. Gallegati's approach closely follows methods proposed by Bodart and Candelon (2009) and Orlov (2009) in which they decompose time series into different frequency components. We slightly modify Gallegati's approach to account not only for a contagion, i.e., an increase in wavelet correlations, but also for market disintegration characterized by lower intermarket linkages.[12] The contagion is identified when:

$$H_C : \rho_{XY}^{(I)}(j) < \rho_{XY}^{(II)}(j). \tag{3}$$

In the case when the correlation declines during the second period examined, we consider a change in correlation to be disintegration; thus,

$$H_D : \rho_{XY}^{(I)}(j) > \rho_{XY}^{(II)}(j). \tag{4}$$

We estimate the wavelet correlation on wavelet scales corresponding to 2–4 days, 4–8 days and 8–16 days over three time periods of length equal approximately to one trading year (282 observations). The first one is before September 15, 2008, the second is between September 15, 2008, and October 20, 2009, and the last one is after October 20, 2009. To detect change in wavelet correlation after October 20, 2009, we compare the second time period covering the post-Lehman Brothers bankruptcy with the third time period representing the sovereign debt crisis in the EU. Hence, this approach allows us to decompose a potential jump or decline in correlation between two events.[13] The results of the test for these two dates is summarized in Table 2. Additionally, we depict changes in wavelet correlations corresponding to the Lehman Brothers bankruptcy and the Greek budget deficit announcement in Fig. 12.

We observe that before the fall of Lehman Brothers, the correlation between Greece and Netherlands, Spain, Portugal, and Denmark was high and relatively homogeneous. On the other hand, we report lower wavelet correlation with Germany, France, Belgium, Italy, and the United Kingdom, especially at very high frequencies. These results are interesting, as the pre-crisis wavelet correlation does not depend on the division to the core, periphery and states outside the eurozone.

After the collapse of Lehman Brothers, we observe contagion, i.e., significant increases in the correlations at the lowest scale (2–4 days) for Italy, Germany, Belgium and France, but the correlations at the two remaining scales are almost similar. France is a good example of scale-dependence – a significant decrease on the 8–16 days scale parallels a significant increase on the 2–4 days scale. Thus, for these four states, we detect contagion only at the shortest investment horizon. At the same time, the previously high wavelet correlations between the Netherlands, Spain, Portugal, and Denmark with Greece decreased.

After the announcement that the Greek budget deficit was much higher than expected, we detect significant market disintegration of Greece from the rest of the eurozone. The wavelet correlation with the core countries, as well as with the countries outside the eurozone, became negative, which indicates high intensity of capital flows from the periphery to the core. The correlation of Greece with Spain, Portugal, and Italy remained positive, although lower than in the previous period. Perhaps the most interesting is the development of the wavelet correlation between Greece and Italy. While before the deficit announcement, the correlation was quite similar to the core countries; afterwards, the yields of Italy retained some degree of comovement with Greece at these high frequencies on a level similar to Spain. We consider this development as evidence for a shift in market perception of Italy during the crisis.

5. Conclusion

The aim of this paper has been to explore the dynamics of comovement, contagion, and contagion among the sovereign bond yields of EU members. At the center of our attention were changes around two significant events – the collapse of Lehman Brothers and the

[11] For brief introductions to discrete wavelet transform and wavelet correlation, see Appendix E and Appendix F.

[12] The definition of contagion follows Forbes and Rigobon (2002), whose definition of contagion is a "significant increase in cross-market linkages". However, both, contagion and market disintegration, are caused by some form of contagion or panic in financial markets, so the distinction between both alternatives H_C and H_D is rather technical.

[13] The analysis is performed using the R package waveslim created by B. Whitcher. We use the maximal overlap discrete wavelet transform with the least asymmetric (LA8) wavelet filter.

Table 2
Contagion and market disintegration test for the dates of the Lehman Brothers bankruptcy and the Greek deficit announcement. NO = null hypothesis accepted, DIS = disintegration statistically significant, CONT = contagion statistically significant.

Countries	PT	ES	IT	FR	GE	NL	BE	DK	SW	UK
2–4 day horizon										
LB	DIS	DIS	CONT	CONT	CONT	DIS	CONT	DIS	DIS	CONT
Gr. def	CONT	NO	NO	DIS	DIS	DIS	DIS	DIS	DIS	DIS
4–8 day horizon										
LB	DIS	DIS	NO	NO	NO	DIS	NO	DIS	NO	NO
Gr. def	NO	NO	DIS	DIS	DIS	DIS	DIS	DIS	DIS	DIS
8–16 day horizon										
LB	DIS	DIS	NO	DIS	DIS	DIS	NO	DIS	DIS	DIS
Gr. def	NO	NO	NO	DIS	DIS	DIS	DIS	DIS	DIS	NO

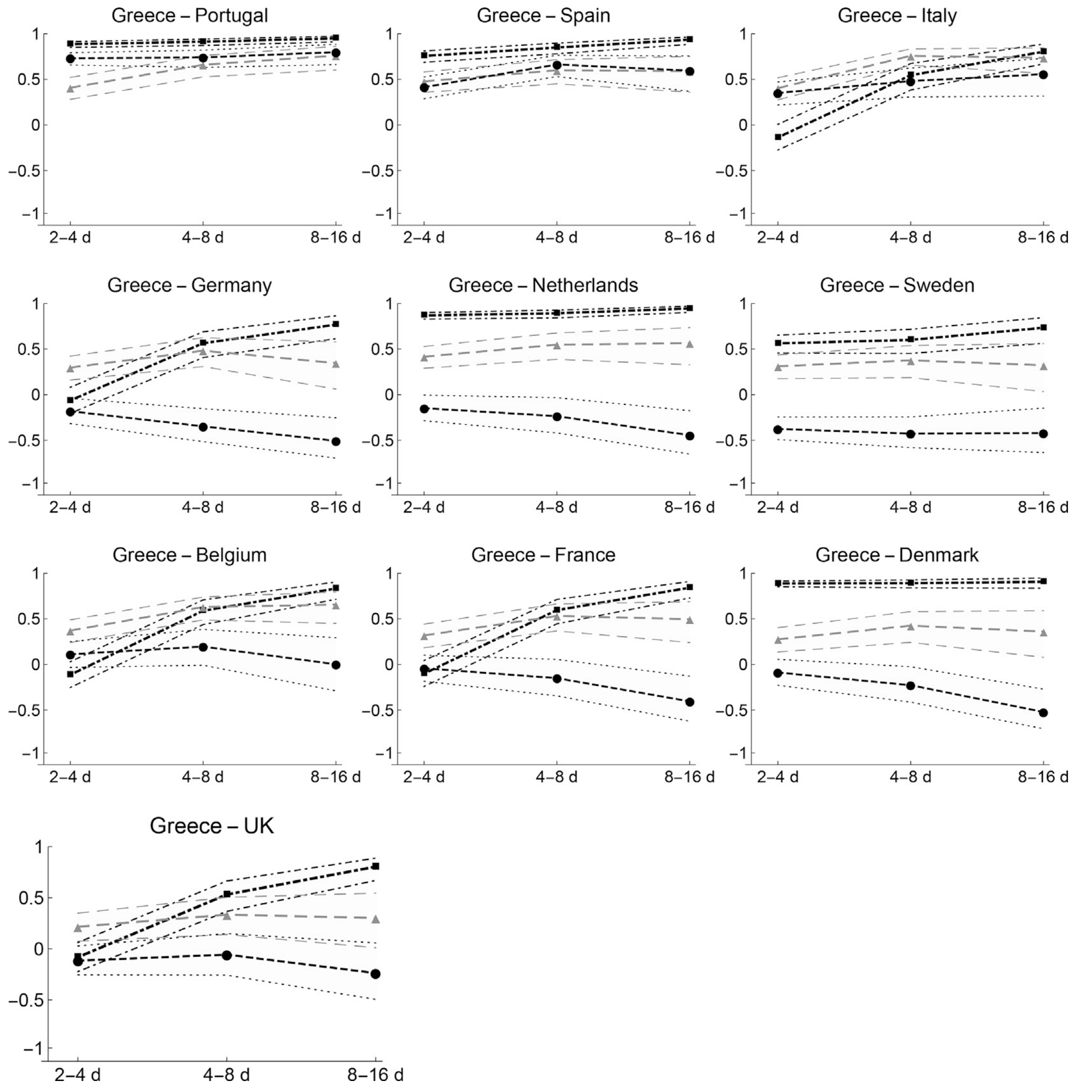

Fig. 12. Wavelet correlation (y-axis) of the 10-year sovereign bond yields between Greece and other states. The first time period before fall of Lehman Brothers - black dot-dashed line with squares. The second time period between the fall of Lehman Brothers and the Greek deficit announcement - gray dashed line with triangles. Period after the Greek deficit announcement - black dashed line with circles. Corresponding 90% confidence interval are depicted with lines.

announcement of the Greek deficit. We have demonstrated that comovement and contagion are frequency dependent, and thus, time-frequency techniques are needed to reveal all of the dynamic relationships in sovereign bond markets.

Comovement was significant at the majority of frequencies before the crisis, but after the crisis began, the formerly strong comovement among sovereign debt yields nearly disappeared, especially for the periphery countries and across groups. Additionally, even the core split: Our analysis has shown that after 2011, the comovement between Germany and the Netherlands, and France and Belgium, decreased, and a new set of "core" countries has emerged consisting of Germany, the Netherlands, Denmark and Sweden. From a policy perspective, the divergence between bond yields of France and Germany can be associated with different policy stances towards the resolution of the European sovereign debt crisis, since both countries faced different financial market conditions.

By the end of 2013, the bond yields of the core group had resumed their high degree of comovement, but the integration of the yields on the periphery was shattered and not re-established. Thus, it seems that, in general, the integration of sovereign bonds in the eurozone suffered a severe blow in the crisis, which impeded transmission of the common monetary policy especially in the EU periphery that suffered from a credit crunch, while Germany enjoyed a rapid and robust recovery.

We have further demonstrated that the application of correlation change tests around two critical dates during the crisis reveals important results. After the fall of Lehman Brothers, the disintegration of debt markets occurred for all groups, as we have observed significant declines in the correlations between Greece and other countries, such as Spain, Portugal, Denmark and the Netherlands. A subsequent decrease in correlation was observed after the announcement of the Greek deficit, leading to negative correlation in five pairs and resulting in the total disintegration of the Greek debt market with those of other eurozone countries.

Finally, our analysis has revealed series of facts that are hard to reconcile with the fundamental view on the European sovereign debt crisis, without excessive intellectual gymnastics. First, the disintegration of Greece from others started already with the fall of Lehman Brothers, a year before the actual state of the Greek public finances were announced. Hence, the markets did not react to the announcements of the changes in fundamentals but preceded them. Second, the Greek deficit announcement affected the comovement of Spain and Italy with the other countries of the euro area, regardless of the differences in the debt-to-GDP ratios and records of their ability to comply with European fiscal rules was. Third, the division of the core countries emerged as well, and Belgium and France became more correlated with Italy and Spain in 2011 at medium to long frequencies. However, the United Kingdom enjoyed favorable conditions on financial markets despite its banking crisis and the large increase in its debt-to-GDP ratio. At the same time, the eurozone fragility hypothesis, which relies on self-fulfilling prophecies of panic-driven crises, provides an intuition that makes these developments plausible. Hence, we conclude that the policy implications of the eurozone fragility hypothesis indicating deficiencies in the design of the monetary union should be taken seriously by EU policymakers in the future.

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Appendix A. Frequency cohesion

We define the frequency cohesion following (Croux et al., 2001): Let us define a vector of time series $\mathbf{x}_t = (x_{1t}, \cdots, x_{nt})'$, $n > 2$. The cohesion of variables in $\mathbf{x}_t$ at frequency λ is defined as:

$$coh(\lambda) = \frac{\sum_{i \neq j} w_i w_j \rho_{x_i x_j}(\lambda)}{\sum_{i \neq j} w_i w_j}, -\pi \leq \lambda \leq \pi, \tag{A.1}$$

where w_i and w_j are weights and $\rho_{x_i x_j}(\lambda)$ is a dynamic pairwise correlation associated with time series x_i and x_j, respectively.[14] The cohesion uses the dynamic pairwise correlation in frequency domain measuring comovement dynamics between times series at a frequency λ. The dynamic pairwise correlation is defined as:

$$\rho_{x_i x_j}(\lambda) = \frac{C_{x_i x_j}(\lambda)}{\sqrt{S_{x_i}(\lambda) S_{x_j}(\lambda)}}, -\pi \leq \lambda \leq \pi, \tag{A.2}$$

where $S_{x_i}(\lambda)$ and $S_{x_j}(\lambda)$ are the spectral density functions of x_i and x_j, respectively. $C_{x_i x_j}(\lambda)$ denotes the cospectrum. For more details, see (Croux et al., 2001).

Appendix B. The Continuous Wavelet Transform

This section introduces an important tool used in our work – continuous wavelet transformation. First, we describe a wavelet

[14] There are several possibilities for how to define the weights; see, for example, Ftiti (2010) and Hanus and Vacha (2018). In our analysis, we use equal weights.

function $\psi(t)$, which is called the mother wavelet. A function can be considered a wavelet if it has several properties. The first and most important is called the admissibility condition:

$$0 < C_\psi = \int_{-\infty}^{+\infty} \frac{|\widehat{\psi}(f)|^2}{f} df < \infty, \tag{B.1}$$

where $\widehat{\psi}(f)$ is a Fourier transformation of the function. If $f \to 0$, then $C_\psi \to 0$ (Percival & Walden, 2000). The second necessary condition is a consequence of the admissibility condition. This condition holds that the integral of a wavelet function must be equal to zero; thus, $\int_{-\infty}^{+\infty} \psi(t)dt = 0$. Further, we assume the wavelet to be a square integrable function having unit energy, i.e., $\int_{-\infty}^{+\infty} \psi^2(t)dt = 1 < \infty$.

Let us define the continuous wavelet transform (CWT) as:

$$W_x(\tau, s) = \int_{-\infty}^{+\infty} x(t) \frac{1}{\sqrt{s}} \psi^* \left(\frac{t-\tau}{s}\right) dt, \tag{B.2}$$

where $\psi^*\left(\frac{t-\tau}{s}\right)$ denotes a modified wavelet function with complex conjugate, and τ and s are the location and scaling parameters. As the CWT is an inner product of a time series and modified mother wavelet function, the CWT can be interpreted as the degree of similarity between the series and the mother wavelet in a time-frequency space.

Appendix C. Wavelet Coherence

Wavelet coherence allows us to express comovement between the time series in a time-frequency space. We will use standard notation, as in, e.g., Torrence and Compo (1998) or Grinsted, Moore, and Jevrejeva (2004). Let us assume that both time series $x(t)$ and $y(t)$ are square integrable and locally stationary. First, we have to define the cross-wavelet transformation (XWT) as a product of two wavelet transformations:

$$W_{xy} = W_x(\tau, s) W_y^*(\tau, s), \tag{C.1}$$

where $W_x(\tau, s)$ and $W_y(\tau, s)$ are continuous wavelet transformations of both time series, and $*$ denotes a complex conjugate. The cross-wavelet power spectrum is defined as:

$$CWS_{xy} = |W_{x,y}(\tau, s)|. \tag{C.2}$$

This is the wavelet equivalent of covariance, i.e., the covariance at wavelet scale τ. Following Torrence and Compo (1998), we define the squared wavelet coherence as:

$$R^2(\tau, s) = \frac{|(S(s^{-1}W_{xy}(\tau, s))|^2}{S(s^{-1}|W_x(\tau, s)|^2)S(s^{-1}|W_y(\tau, s)|^2)}, \tag{C.3}$$

where S denotes the smoothing operator. In our estimates of wavelet coherence, we use the Morlet wavelet[15](Goupillaud, Grossmann, & Morlet, 1984). For more detailed treatments, see Torrence and Compo (1998) and Grinsted et al. (2004).

The squared coherence is defined in the interval $0 \le R^2 \le 1$. A high level of coherence implies that there is strong comovement between the time series, whereas low values mean that the series are linearly independent at a particular wavelet scale.

An important question is whether our results are statistically significant. Although some formal significance tests have been developed for such applications (see Ge (2008)), according to Aguiar-Conraria et al. (2012), their null hypotheses are overly restrictive, and hence, they are not suitable for wavelet analysis in economics. For our purposes, we use Monte Carlo simulations.[16] The significant regions of the wavelet coherence estimates are within the bold black lines.

Appendix D. Wavelet cohesion

Wavelet cohesion is a measure of comovement of multiple time series in time and frequency simultaneously. Wavelet cohesion uncovers common cyclical behavior of studied time series. For the multivariate time series $\mathbf{x}_t$ where x_{it} is the i-th component, the wavelet cohesion is defined as (Rua & Lopes, 2015):

$$coh(\tau, s) = \frac{\sum_{i \neq j} \omega_{ij} \rho_{x_i x_j}(\tau, s)}{\sum_{i \neq j} \varpi_{ij}}, coh(\tau, s) \in [-1, 1], \tag{D.1}$$

where $\rho_{x_i x_j}(\tau, s)$ is a real wavelet-based measure of comovement for a specific time position τ and a scale s (Rua, 2010), defined as:

[15] The morel wavelet is ideal for the coherence analysis as it offers optimal balance between time and frequency localization.

[16] Following the testing procedure of Grinsted et al. (2004), we use 5% significance levels.

$$\rho_{x_i x_j}(\tau, s) = \frac{\Re\left(W_{x_i x_j}(\tau, s)\right)}{\sqrt{\left|W_{x_i}(\tau, s)\right|^2 \left|W_{x_j}(\tau, s)\right|^2}}, \rho_{x_i, x_j}(\tau, s) \in [-1, 1]. \tag{D.2}$$

The $\Re(W_{x_i x_j}(\tau, s))$ denotes the real part of the wavelet cross-spectrum of two time series. Using the real part, the measure can capture positive as well as negative comovement of the processes. The wavelet cross-spectrum is further normalized by the squared roots of two wavelet power spectra. The wavelet cohesion uses fixed weights ω_{ij}, which specifies a share of each pair.

Appendix E. Maximal overlap discrete wavelet transform

For the computation of wavelet correlation, we use a special form of discrete wavelet transform called maximal overlap discrete wavelet transformation (MODWT). In this section, we briefly demonstrate an application of the pyramid algorithm to obtain the MODWT wavelet and scaling coefficients that are used for wavelet correlation. In practice, the pyramid algorithm proposed by Mallat (1989) is based on filtering time series with MODWT wavelet filters; the output after filtering is then filtered again in a subsequent stage to obtain wavelet coefficients at other wavelet scales. In our analysis we use the Daubechies least asymmetric wavelet (LA8).[17] For detailed information on MODWT, see Percival and Walden (2000).

Appendix F. Wavelet Correlation

Let X_t and Y_t be two stationary stochastic time series. Following Percival and Walden (2000), we define the MODWT wavelet variance at the wavelet scale λ_j as:

$$\sigma_X^2(\lambda_j) = \frac{1}{\tilde{N}_j} \sum_{t=L_j-1} \tilde{w}_{X,j,t}, \tag{F.1}$$

where $\tilde{w}_{X,j,t}$ denotes the MODWT wavelet coefficient at scale λ_j, and L_j denotes the length of a wavelet filter of scale λ_j. The number of wavelet coefficients unaffected by the boundary conditions is $\tilde{N}_j = N - L_j + 1$[18] Further, we define the scale-by-scale covariance of the two series:

$$\gamma_{XY}(\lambda_j) = \frac{1}{\tilde{N}_j} \sum_{t=L_j-1}^{N-1} \tilde{w}_{X,j,t} \tilde{w}_{Y,j,t}. \tag{F.2}$$

Then, we can compute the scale-by-scale correlation between the two series:

$$\rho_{XY}(\lambda_j) = \frac{\gamma_{XY}(\lambda_j)}{\sqrt{\sigma_X^2(\lambda_j)\sigma_Y^2(\lambda_j)}}. \tag{F.3}$$

According to Whitcher, Guttorp, and Percival (2000), the estimator is unbiased, consistent and asymptotically normal. The confidence intervals of the MODWT wavelet correlation are computed via the following formula (Gençay et al., 2001):

$$\left[\tanh\left(\tanh^{-1}(\rho_{XY}(\lambda_j)) \mp \frac{\Phi^{-1}(1-p)}{\sqrt{N_j - 3}}\right)\right], \tag{F.4}$$

where $\Phi^{-1}(1-p)$ is a quantile of the standard normal distribution.

Appendix G. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.iref.2019.09.004.

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[17] The LA8 filter is popular in the literature for this type of analysis. We have also tried the D4 and the Haar, but the results were not significantly different.
[18] For a discussion of the boundary, see Gençay et al. (2001), Chapter 4.6.3.

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