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**VOLATILITY CONNECTEDNESS OF BANK STOCKS
ACROSS THE ATLANTIC**

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Volatility Connectedness of Bank Stocks Across the Atlantic

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Abstract: This paper presents an analysis of the dynamic measures of volatility connectedness of major bank stocks in the US and the EU member countries. The results show that in the early stages of the US financial crisis in 2007 and 2008, the direction of the volatility connectedness was from the US banks towards the EU banks. However, once the financial crisis became global in the last quarter of 2008, volatility connectedness became bi-directional. The surge in volatility connectedness from the EU banks to the US banks in June 2011 was unprecedented, reflecting the scale of deterioration in the state of the EU banks. Finally, the within-connectedness of the US banks fluctuated throughout our sample period, while the within-connectedness of the EU banks increased steadily since 2007, a reflection of the fact that the European debt and banking crisis has not ended yet.

Key Words: Risk measurement, systemic risk, connectedness, systemically important financial institutions, vector autoregression, variance decomposition

JEL codes: C3, G2

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1 Introduction

The global financial crisis of 2008-09 struck the modern capitalist system like no other crisis in recent history. It took several stages that lasted a year and a half, before the crisis that originated in the US subprime mortgage market was transformed into a crisis on a global scale in the last quarter of 2008. The crisis affected many countries and markets around the world, leading to global recession and the collapse of world trade in 2009.

That was not all. As the US financial crisis appeared to be in the ebbing in the second half of 2009, peripheral EU member countries started to face serious troubles in their financial systems. The European whirlwind involved more than just financial institutions with constantly worsening balance sheets: This time around the governments were caught in the eye of the storm as well.

Financial institutions played a key role in the evolution of the crisis and its spread around the world. Disproportionate risks taken by big financial institutions have over time caused serious trouble for the whole financial system. In the US, with the outbreak of the subprime crisis highly leveraged investments in mortgage based securities and other derivatives linked to mortgages led to the collapse of individual banks. In Europe, credits extended to troubled commercial and housing real estate sectors had turned into sizable non-performing loans. Many European banks that invested in the US subprime mortgage derivatives had also got their hands burned. When governments in several countries decided to bailout the banks, public sector finances were strained and sovereign debt stocks soared.¹

In this paper, my aim is to analyze how major American and European banks contributed to the evolution of the global financial crisis, and the banking and sovereign debt crisis in the EU periphery. In particular, I measure and analyze the dynamic volatility connectedness of major bank stocks on both sides of the Atlantic from January 2004 through June 2013. The paper is a sequel to Diebold and Yilmaz (2014) where a unified framework for conceptualizing and empirically measuring connectedness was developed at a variety of levels and applied to stocks of the major US financial institutions. Following that framework, Yilmaz (2011) analyzed the connectedness of the European banks and showed that as of September 2011, major European bank stocks were connected in a state of high volatility.

This study of the major bank stocks is motivated by the developments on the ground.

¹The bailout of five banks by the Irish government was a good example. The Irish government's September 2008 decision to guarantee deposits at six main Irish banks was followed by the complete bailout of these banks in 2009 at a cost of approximately €45 billion as of 2010. This led to a government budget deficit equivalent to 32% of GDP in 2010 and an increase in the government debt to GDP ratio from 65.5% in 2009 to 96.2% in 2010.

The news about the troubles of a major bank lead investors to flee the stocks of that bank first, followed by the stocks of other banks in the country. Furthermore, depending on the size of the banking system and its financial connectedness with other countries, the news about the troubles of the banking system in a single country force investors to flee the banking sector stocks not only in that country but in other countries as well. As a consequence, the banking stocks became connected not only in one country but across countries.

There are several important contributions to the literature on the measurement of connectedness of financial firms. Among these one can count the correlation-based measures. However, as they measure only pairwise association and are based on linear Gaussian distributions, they are of limited value in understanding connectedness of financial firms that lead to systemic risk. Recent contributions to the literature offer alternative approaches to study financial firm connectedness in a multivariate setting. The equi-correlation approach of Engle and Kelly (2012), for example, effectively focuses on average pairwise correlation. The CoVaR approach of Adrian and Brunnermeier (2008) and the marginal expected shortfall (MES) approach of Acharya et al. (2010) go beyond pairwise association, tracking association between individual-firm and overall-market movements, in one direction or the other.

There are other important contributions to the literature as well. Among those Barigozzi and Brownlees (2013) propose a two step lasso procedure which allows the decomposition of the long run linkages into the dynamic and contemporaneous dependence relations. Dungey et al. (2013), on the other hand, rely on Google's PageRank Algorithm to develop a measure of the systemic risk and rank systemically important financial institutions. In another contribution, Black et al. (2013) specifically focuses on the measurement of systemic risk in the European banking sector. It proposes a systemic risk measure, called "distress insurance premium," that can be used to identify a financial institution's contribution to the total capital shortfall of the financial system during a crisis. They show that the European banking systemic risk measure reached its highest level in late 2011.

All alternative approaches to the measurement of connectedness reviewed above are certainly of interest, but they measure different things, and a unified framework remains elusive. As argued by Diebold and Yilmaz (2014) and shown in the remainder of this paper, the Diebold-Yilmaz connectedness index approach provides such a framework.

In section 2, I briefly summarize the conceptual framework and measures. For more detailed exposition of the methodology, I refer the reader to Diebold and Yilmaz (2014) and Diebold and Yilmaz (2012). Finally, in section 3, I apply the Diebold-Yilmaz framework to study connectedness at all levels among a large set of return volatilities of US financial

institutions during the last decade, including during the financial crisis of 2007-2008. I conclude in section 6.

2 The Connectedness Index Methodology

This section provides a summary of the Diebold-Yilmaz connectedness index methodology, which was developed in a series of papers (Diebold and Yilmaz, 2009, 2011, 2012). As it's already been mentioned in the introduction, the connectedness index is built upon the variance decomposition matrix associated with an N -variable vector autoregression. The total connectedness index is the ratio of the sum of off-diagonal elements of the forecast error variance-covariance matrix to the sum of all elements of the same matrix.

Consider a covariance stationary N -variable VAR(p), $x_t = \sum_{i=1}^p \Phi_i x_{t-i} + \varepsilon_t$, where $\varepsilon_t \sim (0, \Sigma)$. The moving average representation is $x_t = \sum_{i=0}^{\infty} A_i \varepsilon_{t-i}$, where the $N \times N$, coefficient matrices A_i obey the recursion $A_i = \Phi_1 A_{i-1} + \Phi_2 A_{i-2} + \dots + \Phi_p A_{i-p}$, with A_0 an $N \times N$ identity matrix and $A_i = 0$ for $i < 0$. The moving average coefficients (or transformations such as impulse response functions or variance decompositions) are the key to understanding the dynamics. I rely on variance decompositions, which allows me to split the forecast error variances of each variable into parts attributable to the various system shocks. Variance decompositions also allow one to assess the fraction of the H -step-ahead error variance in forecasting x_i that is due to shocks to $x_j, \forall i \neq j$, for each i .

A study of the financial connectedness of major financial institutions is not complete without an analysis of directional connectedness across financial institutions. Calculation of variance decompositions requires orthogonal innovations, whereas the VAR innovations are generally correlated. Identification schemes such as that based on Cholesky factorization achieve orthogonality, but the variance decompositions then depend on the ordering of the variables. As a result, it is not possible to use the variance decompositions from the Cholesky factor orthogonalization to study the direction of connectedness. With this understanding, Diebold and Yilmaz (2012) propose to circumvent this problem by exploiting the generalized VAR framework of Koop et al. (1996) and Pesaran and Shin (1998), which produces variance decompositions invariant to ordering. Instead of attempting to orthogonalize shocks, the generalized approach allows correlated shocks but accounts for them appropriately using the historically observed distribution of the errors. As the shocks to each variable are not orthogonalized, the sum of contributions to the variance of forecast error (that is, the row sum of the elements of the variance decomposition table) is not necessarily equal to one.

Using the VAR framework introduced above, I define *own variance shares* to be the fractions of the H -step-ahead error variances in forecasting x_i due to shocks to x_i , for $i = 1, 2, \dots, N$, and *cross variance shares*, or *connectedness*, to be the fractions of the H -step-ahead error variances in forecasting x_i due to shocks to x_j , for $i, j = 1, 2, \dots, N$, such that $i \neq j$.

The generalized impulse response and variance decomposition analyses also rely on the MA representation of the N -variable VAR(p) equation above. Pesaran and Shin (1998) show that when the error term ε_t has a multivariate normal distribution, the h -step generalized impulse response function scaled by the variance of the variable is given by:

$$\gamma_j^g(h) = \frac{1}{\sqrt{\sigma_{jj}}} A_h \Sigma e_j, \quad h = 0, 1, 2, \dots \quad (1)$$

where Σ is the variance matrix for the error vector ε , σ_{jj} is the standard deviation of the error term for the j^{th} equation and e_i is the selection vector with one as the i^{th} element and zeros otherwise. Variable j 's contribution to variable i 's H -step-ahead generalized forecast error variance, $\theta_{ij}^g(H)$, for $H = 1, 2, \dots$, is defined as:

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

As explained above, the sum of the elements of each row of the variance decomposition table is not necessarily equal to 1: $\sum_{j=1}^N \theta_{ij}^g(H) \neq 1$. In order to use the information available in the variance decomposition matrix to calculate the connectedness index, Diebold and Yilmaz (2012) normalize each entry of the variance decomposition matrix (equation 2) by the row sum as²:

$$\tilde{\theta}_{ij}^g(H) = \frac{\theta_{ij}^g(H)}{\sum_{j=1}^N \theta_{ij}^g(H)} \quad (3)$$

Now, by construction $\sum_{j=1}^N \tilde{\theta}_{ij}^g(H) = 1$ and $\sum_{i,j=1}^N \tilde{\theta}_{ij}^g(H) = N$. Using the normalized entries of the generalized variance decomposition matrix (equation 3), Diebold and Yilmaz (2012) construct the total connectedness index as:

²Alternatively, one can normalize the elements of the variance decomposition matrix with the column sum of these elements and compare the resulting total connectedness index with the one obtained from the normalization with the row sum.

$$C(H) = \frac{\sum_{\substack{i,j=1 \\ i \neq j}}^N \tilde{\theta}_{ij}^g(H)}{\sum_{i,j=1}^N \tilde{\theta}_{ij}^g(H)} = \frac{\sum_{\substack{i,j=1 \\ i \neq j}}^N \tilde{\theta}_{ij}^g(H)}{N} \quad (4)$$

Next considering directional connectedness, Diebold and Yilmaz (2012) define gross directional connectedness received by firm i from all other firms j as:

$$C_{i \leftarrow \bullet} = \frac{\sum_{\substack{j=1 \\ j \neq i}}^N \tilde{\theta}_{ij}^g(H)}{\sum_{i,j=1}^N \tilde{\theta}_{ij}^g(H)} \times 100 = \frac{\sum_{\substack{j=1 \\ j \neq i}}^N \tilde{\theta}_{ij}^g(H)}{N} \times 100 \quad (5)$$

In similar fashion, directional volatility connectedness transmitted by firm i to all other firms j is measured as:

$$C_{\bullet \leftarrow i} = \frac{\sum_{\substack{j=1 \\ j \neq i}}^N \tilde{\theta}_{ji}^g(H)}{\sum_{i,j=1}^N \tilde{\theta}_{ji}^g(H)} \times 100 = \frac{\sum_{\substack{j=1 \\ j \neq i}}^N \tilde{\theta}_{ji}^g(H)}{N} \times 100 \quad (6)$$

One can think of the set of directional connectedness as providing a decomposition of total connectedness into those transmitted by each firm in the sample. Obviously, once the financial shocks transmitted and received by firm i are calculated, the difference between the two will result in a measure of the net directional connectedness transmitted from firm i to all other firms as:

$$C_i(H) = C_{\bullet \leftarrow i}(H) - C_{i \leftarrow \bullet}(H) \quad (7)$$

The net directional connectedness index (equation 7) provides information about how much each firm's stock return volatility contributes in net terms to other firms' stock return volatilities.

Diebold and Yilmaz (2014) showed that the connectedness framework was closely linked with the modern network theory. To start with, they showed that the total connectedness measure corresponds to the mean degree of a weighted, directed network. They also showed that the connectedness framework was closely linked to the modern measures of systemic risk. For example, the from-connectedness degree measures exposures of individual firms to systemic shocks from the network, in a way very much similar to the marginal expected shortfall of these firms (Acharya et al. (2010)). The to-connectedness degree, on the other hand, measures the contribution of individual firms to systemic network events, in a fashion very similar to CoVaR of the firm (Adrian and Brunnermeier (2008)).

3 US and EU Bank Stock Return Volatilities, 2004-2012

Thus far I have reviewed the tools for connectedness measurement. I now use those tools to characterize the evolution of volatility connectedness among major US and EU financial institutions in the age of financial crises. The empirical analysis proceeds in four steps. First, in the remainder of this section, I describe the data that I use to measure financial institution connectedness. Next, in section 4, I perform a full-sample (static) analysis, in which I effectively characterize average, or unconditional, connectedness across the banks of 8 countries. This is of intrinsic interest, and it also sets the stage for section 5, where I perform a rolling-sample (dynamic) analysis of conditional connectedness. As my ultimate interest lies there, I monitor high-frequency (daily) connectedness as conditions evolve, sometimes gradually and sometimes abruptly.

Financial institutions are connected directly through counter-party linkages associated with positions in various assets, through contractual obligations associated with services provided to clients and other institutions, and through deals recorded in their balance sheets. High-frequency analysis of financial institution connectedness therefore might seem to require high-frequency balance sheet and related information, which is generally unavailable.

Fortunately, however, the data on stock returns and return volatilities are available, which reflect forward-looking assessments of many thousands of smart, strategic and often privately-informed agents as regards precisely the relevant sorts of connections. I, therefore, use the available stock returns and return volatilities data to measure connectedness and its evolution. It is important to note that I remain agnostic as to how connectedness arises; rather, I take it as given and seek to measure it correctly for a wide range of possible underlying causal structures.

In this paper, I study *volatility* connectedness, for at least two reasons. First, if volatility tracks investor fear (e.g., the VIX is often touted as an “investor fear gauge”), then volatility connectedness is the “fear connectedness” expressed by market participants as they trade. I am interested in the level, variation, paths, patterns and clustering in precisely that fear connectedness. Second, volatility connectedness is of special interest because I am particularly interested in crises, and volatility is particularly crisis-sensitive.

Volatility is latent and hence must be estimated. In this paper I use range volatility, which has received significant attention in recent years.³ For a given bank on a given day, I

³For surveys see Andersen et al. (2006), Andersen et al. (2010) and Andersen et al. (2011).

construct daily range volatility estimate using high-low-open-close prices of the stock.

Volatilities tend to be strongly serially correlated – much more so than returns, particularly when observed at relatively high frequency. I will capture that serial correlation using vector-autoregressive approximating models, as described earlier. Volatilities also tend to be distributed asymmetrically, with a right skew, and approximate normality is often obtained by taking natural logarithms. Hence I work throughout with log volatilities. This is helpful not only generally, as normality-inducing transformations take us into familiar territory, but also specifically as I use generalized variance decompositions (Koop et al. (1996), Pesaran and Shin (1998)), which invoke normality.

I study stock return volatilities for 10 major US and 16 major EU banks. The sample covers the period from January 2004 to June 2013. Tables 1 and 2 present lists of the US and the EU financial institutions, respectively, along with their stock tickers, stock market capitalization in the pre- (as of the end of 2006) and post-crisis period (June 2013), and total assets as of March 2013. The US sample includes 7 commercial banks, 2 investment banks, one credit card company. All financial institutions in the EU sample are commercial banks. These are the largest financial institutions such that their stocks are included in the major stock market indices in their respective countries. An overwhelming majority of the banks included in the analysis are classified as Global Systemically Important Banks (G-SIBs).⁴

Market capitalization of all US banks declined substantially during the global financial crisis. Since the end of the global financial crisis in 2009, their stock prices recovered some of the lost ground. As a result, market capitalization of 7 out of 10 US banks on June 30, 2013 were either above or very close to their corresponding market capitalizations on December 29, 2006. The exceptions are Bank of America, Citigroup and Morgan Stanley, all of which suffered substantially during the crisis. While the US sample covers almost all financial institutions that are important for the US financial system, the EU sample is not complete. As I decided to include only financial institutions from the EU member countries, I did not include two major systemically important Swiss banks (UBS and Credit Suisse) in my sample.

Institution	Ticker	Market Cap.		Assets
		12/29/06	6/30/13	3/31/13
J. P. Morgan Chase	JPM	169	199	2,389
Bank of America	BAC	241	138	2,176
Citigroup	C	274	145	1,881
Wells Fargo	WFC	121	218	1,436
Goldman Sachs	GS	86	69	959
Morgan Stanley	MS	85	48	801
US Bancorp	USB	64	67	355
Bank NY Mellon	BK	30	32	355
PNC Financial	PNC	22	38	309
American Express	AXP	74	82	156

Table 1: EU Financial Institution DetailMarket capitalizations are in billions of US dollars.

4 Static (Full-Sample, Unconditional) Analysis

Table 3 is the full-sample connectedness table. There are 26 banks in the sample. However, it is impossible to present the 26x26 matrix on a single page. For that reason, I aggregate the connectedness measures at the national level, which allows me to diminish the size of the connectedness matrix to 8x8. This table is still informative about how volatility shocks to one or more bank stocks in a country spread to bank stocks in other countries. The diagonal elements (own connectednesses) tend to be the highest individual elements of the table. Obviously, the diagonal elements are higher than non-diagonal ones, because they capture not only the own-connectedness of each bank, but also connectedness of banks within the same country. For example, the diagonal element for the US, 724 %, measures both the own-connectedness of each American bank as well as its connectedness with other American banks.

With the exception of the US, total directional connectedness (“from others” or “to others”) tends to be larger than the corresponding own-connectedness. Total connectedness across all banks (not across countries) obtained from the average of the “from others” column (or, for that matter, the average of the “to others” row) is a very high 81.1%.

Let’s discuss some of the features of the connectedness table at greater length, beginning with the pairwise directional connectedness measures, $\tilde{C}_{i \leftarrow j}^H$, which are the off-diagonal

⁴Out of 26 banks in the sample only six (three from the US, three from the EU) are not included in the G-SIBs list announced by the Financial Stability Board on November 1, 2012 on its website.

Institution	Ticker	Country	Market Cap.		Assets
			12/29/06	6/30/13	3/31/13
Dexia	DEX	Belgium	31	0.05	473
KBC	KBC		45	16	331
Deutsche Bank	DBK	Germany	70	43	2,605
Commerzbank	CBK		25	10	829
BNP Paribas	BNP	France	101	68	2,551
Societe Generale	GLE		79	27	1,597
Credit Agricole	ACA		63	21	2,582
Unicredito	UCG	Italy	91	27	1,170
Intesa San Paolo	ISP		46	25	854
ING Bank	ING	Netherlands	98	35	1,513
Bank Santander	SAN	Spain	117	69	1,643
BBVA	BBVA		85	46	855
HSBC	HSBA	UK	211	193	2,681
Barclays	BARC		93	54	2,426
Royal B. Scotland	RBS		123	25	1,988
Lloyds Bank	LLOY		63	68	1,346

Table 2: EU Financial Institution DetailMarket capitalizations are in billions of US dollars.

elements of the 8x8 matrix. A quick inspection of Table 3 shows that the highest pairwise connectedness measure observed is from the US to the UK ($\tilde{C}_{UK \leftarrow US}^H = 108.6\%$). In return, the pairwise connectedness from the UK to US ($\tilde{C}_{US \leftarrow UK}^H = 106.8\%$) is ranked second. There is very little difference between the two pairwise directional connectedness measures, implying that the net pairwise connectedness from the US to the UK banks was quite small: $\tilde{C}_{US,UK}^H = 1.8\%$. Therefore, in the static framework of the full sample analysis, volatility of the bank stocks in the two countries affected each other almost equally.

One factor behind the high pairwise directional connectedness between the US and the UK is the high number of banks from the two countries included in the analysis. Yet, this cannot be the only reason. The connectedness from the US to France (which has 3 banks in the analysis) is 50.2% and from France to the US 48.4%, less than half of the respective pairwise connectedness measures between the US and the UK. High pairwise connectedness measures between the two countries therefore highlight the strong ties between the two countries' financial sectors. The high pairwise connectedness between the two countries

	BEL	GER	FRA	ITA	NLD	SPA	UK	USA	FROM
Belgium (2)	63.4	14.1	27.4	15.4	8.5	14.0	29.0	28.1	136.6
Germany (2)	11.2	49.4	28.5	18.1	10.5	15.7	30.3	36.3	150.6
France (3)	17.5	25.6	87.3	29.6	15.4	29.7	44.6	50.2	212.7
Italy (2)	13.2	16.9	33.1	54.7	9.1	22.0	27.2	23.7	145.3
Netherlands (1)	5.4	9.5	14.9	8.8	16.4	9.3	16.7	18.9	83.6
Spain (2)	11.2	15.3	33.2	21.0	10.0	56.2	26.5	26.8	143.8
UK (4)	17.3	28.2	44.0	24.5	17.4	25.5	134.4	108.6	265.6
USA (10)	14.9	38.4	48.4	22.7	20.8	23.9	106.8	724.0	276.0
TO	90.7	148.0	229.5	140.1	91.7	140.3	281.1	292.7	
FROM	136.6	150.6	212.7	145.3	83.6	143.8	265.6	276.0	81.1
NET	-45.8	-2.6	16.8	-5.2	8.1	-3.5	15.5	16.7	

Table 3: Full-Sample Connectedness Table

The sample is Jan 2, 2004 through June 28, 2013. The ij -th entry of the upper-left 8x8 country submatrix gives the ij -th pairwise directional connectedness; i.e., the percent of 12-day-ahead forecast error variance of all firms located in country i due to shocks from firms located in country j . The last column (FROM) is equal to the row sum excluding the diagonal elements, and gives the total directional connectedness *from* all others to country i . The TO row at the bottom is equal to the column sum excluding the diagonal elements, and gives the total directional connectedness from country j to others. The last row (NET) is equal to the difference between the “to” and “from” total directional connectedness. The bottom-right element (in boldface) is total connectedness (mean from-connectedness, or equivalently, mean to-connectedness) among 26 financial institutions. Finally, the number in parenthesis next to each country name indicates the number of financial institutions included in the analysis from the respective country.

could also be due to the fact that both countries are home to two most important centers in the global financial system. An increase in the volatility of bank stocks in one of the global financial centers has more important implications for the banks in the other global financial center compared to banks in other countries.

The row sum of the pairwise connectedness measures results in the total directional connectedness from others to each of the eight countries. In other words, the “FROM” column measures the share of volatility shocks received from bank stocks in other countries in the total variance of the forecast error for all bank stocks in each country. By definition, it is equal to the number of banks times 100% minus the own share of the total forecast error variance. As the own-effects (diagonal elements of the matrix) range between 16.4 and 724%, the total directional connectedness in the “FROM” column ranges between 83.6 and 276%.

Similarly, the column sum of all pairwise connectedness measures results in the total directional connectedness to others of the corresponding country’s major banks. As each

stock's contribution to others' forecast error variances is not constrained to add up to 100%, entries in the "TO" row can exceed 100% times the number of major bank stocks from the country included in the analysis. While the financial stocks are largely similar in terms of receiving volatility shocks from others, they are highly differentiated as transmitters of volatility shocks to others.

For some of the eight countries, the "to-" and "from-connectedness" measures are not too far apart. For example, in the case of German banks, the to-connectedness is only 2.6 % less than their from-connectedness. The net-connectedness of Germany is therefore negligible. In the case of Spain and Italy, the from-connectedness exceeds the to-connectedness by 3.5 and 5.2 percentage points, respectively. Even though, this difference is small it indicates that both countries, on average, received more volatility shocks from others than transmitting volatility shocks to others. This is an interesting result, given that the two countries face serious problems in terms of the sustainability of their sovereign debt and problems with some of their regional banks. It turns out that their largest banks are not necessarily the ones that had troubles when considered over the full sample. Over the full static sample, they are net recipients of volatility shocks from others.

Belgium has a negative net-connectedness, -45.8%, indicating that it is a net-recipient of volatility shocks from others. It is the highest net-connectedness figure in absolute value. Among the banking systems that have positive net-connectedness, France has the highest value (16.8%), followed by the US (16.7%), the UK (15.5%), and Netherlands, (8.1%). Three French banks, BNP Paribas, Societe Generale and Credit Agricole, generate slightly higher net volatility connectedness compared to 10 American banks and 4 British banks. One can try to explain this fact by referring to the share of sovereign debt stocks of Greece, Italy and Spain held by the French banks in their portfolio. There is definitely some truth to this. However, it is too early to reach this conclusion because there has been significant variation in the volatility of bank stocks throughout the 2004-2013 sample. Therefore, one has to wait a detailed analysis of the dynamic measures of directional connectedness in order to reach a conclusion about the exposition of banks to sovereign debt stocks that created serious trouble for the region's banks.

Finally, with a value of 81.1%, the total connectedness among 26 bank stocks is higher than the total connectedness measures I obtained in other settings, such as the connectedness among different asset classes, or among international stock markets. Given the large number of stocks included in the sample, there is a high degree of connectedness for the full sample. As can be seen below, there is always a high degree of connectedness even during tranquil

times. There is another reason for the total connectedness for a set of financial stocks to be higher than for a set of major national stock markets around the world or for a set of asset classes in a country. As the institutions included in the analysis are all operating in the finance industry, albeit in different countries, both industry-wide and macroeconomic shocks affect each one of these stocks one way or the other. As some of these institutions and their stocks are more vulnerable to external and/or industry-wide shocks than others, they are likely to be transmitting these shocks to other financial stocks, generating a higher degree of connectedness to others. Obviously, to the extent that they have important implications for the rest of the industry, idiosyncratic volatility shocks are also transmitted to other stocks. For that reason, compared to a similar number of stocks from different industries, the connectedness for a group of stocks in the finance industry is likely to be higher. It is also likely to be higher compared to the connectedness for a group of global markets, as these markets are not subject to common shocks as frequently as the stocks from the finance industry.⁵

5 Dynamic (Rolling-Sample, Conditional) Analysis

The full-sample connectedness analysis provides a good characterization of “unconditional” aspects of the connectedness measures. However, it does not help us understand the connectedness *dynamics*. The appeal of the connectedness methodology lies with its use as a measure of how quickly return or volatility shocks spread across countries as well as within a country. This section presents the dynamic connectedness analysis which relies on rolling estimation windows. The dynamic connectedness analysis uses daily range volatilities for 26 financial institutions that were used in the static, unconditional, full-sample analysis.

The dynamic connectedness analysis starts with the total connectedness, and then moves to various levels of disaggregation (total directional and pairwise directional). Finally, a brief assessment of the robustness of the results to choices of tuning parameters and alternative identification methods will be included at the end of the section.

5.1 Total Connectedness

Figure 1 plots total volatility connectedness over 200-day rolling-sample windows. I prefer to work with a 200-day rather than a 100-day window size because of the high number

⁵I have in mind a comparison with the total connectedness indexes reported in Diebold and Yilmaz (2009) and Diebold and Yilmaz (2012).



Figure 1: Rolling Total Volatility Connectedness. The rolling estimation window width is 200 days, and the predictive horizon for the underlying variance decomposition is 12 days.

of variables (26) included in the VAR analysis. From a bird’s-eye perspective, the total connectedness plot in Figure 1 has some revealing patterns.

After staying at a low of 65% throughout 2005 and the first four months of 2006, the total connectedness index jumped to 68% in May 2006 and increased gradually afterwards, to reach 73% in the following several months. The jump in May 2006 was a reaction to the Federal Open Market Committee’s (FOMC) decision to increase the federal funds rate target in May by 25 basis points as well as the announcement that there was room for another increase in its June meeting. The Fed’s decision led to the unraveling of carry trade positions of many developed country investors in emerging market assets. Apparently, this led to an increase in volatility connectedness across the European and American bank stocks.

Putting the 2006 episode aside, one can discern three major cycles in the total connectedness plot. The first one lasted longer than the others. It started in June 2007 and followed the stages of the global financial crisis, all the way to the end of 2009. The initial tremors of the subprime mortgage crisis were first felt at the end of February 2007. Once the initial tremors of the subprime crisis led the way to the liquidity crisis in the summer of 2007, the total volatility connectedness index increased from 70% in June to reach close to 80% in mid-August. This first jump was followed by another jump (from 81 to 86%) in January 2008 as the piling up of losses in major EU and US banks led to the intervention of their

respective central banks, by way of lowering policy rates significantly. Finally, following the collapse of Lehman Brothers in September 2008 led to a global financial crisis and the index jumped for six percentage points to reach 91%, the maximum ever.

The second major cycle started with the outbreak of the Greek sovereign debt crisis in late-2009 and early-2010, followed by the inability of the EU to come up with a workable solution for close to 5 months. The index climbed up from 77% to 81% in the first four months of 2010, before jumping up on May 6, 2010 by another five percentage points to reach 86%, days before the meeting of EU member countries' leaders. As the meeting produced only a half-hearted solution, the index continued to climb in the next two and a half months to reach 87%. The connectedness index stayed high, between 85 and 87%, until January 2011 before dropping down to 74 % by May 2011.

The index did not stay low for too long, thanks to the increased worries about the sovereign debt and banking problems in Italy and Spain, two EU members with sizable economies compared to the members that had problems before. As the pressure on the two countries increased, the index went up gradually to reach 77% by late-July, before experiencing a jump to 86% in the first week of August. The problems of the European banks continued through the last quarter of 2011, until the new President of the European Central Bank Mario Draghi announced the long-term refinancing operation (LTRO) plan to provide 1 trillion euros liquidity to Eurozone banks in two installments. The cycle in the connectedness index finally came to an end in the summer of 2012, as the data for the period is left out of the sample window and the ECB declared in August its willingness to support the troubled countries' austerity programs through purchases of their government bonds through an operation called outright monetary transactions (OMT). As of the end of September 2012, the total volatility connectedness across the 26 banks in Europe and the US stood at 75%.

Towards the end of 2012, the heated political debate about the US fiscal policy flared up again. While Republicans proposed spending cuts to control the budget deficit, Democrats wanted to increase taxes. As the two sides couldn't find a compromise solution, the automatic spending cuts were expected to take place by the year's turn. The so-called "fiscal cliff" unnerved the markets. In this atmosphere the connectedness index increased gradually by four percentage points. However, a last-minute deal was struck to provide a temporary solution before the end of the year, and the volatility in the stock market did not necessarily go up any further. The index stayed around 79% until March 2013, after which it started coming down again. Ben Bernanke's warnings about the eventual stopping of QE policies in

late 2013 and/or early 2014 led to capital outflows from many emerging market economies in late-May and June. However, the impact of this announcement on the US and EU banks' stock return volatility was quite limited, with a two percentage point increase, part of which was later corrected at the end of June.

As of the end of the sample, June 2013, the connectedness index is approximately 10 percentage points higher than what it used to be in 2005 and early 2006; five percentage points higher than its value before the subprime crisis. The index shows that the markets are calmer in June 2013 compared to the stormy period of 2007-2011. However, the tranquility of the pre-2006 period is still some distance away from the US and EU bank stocks.

So far I have relied on the 200-day rolling sample window estimation to obtain the connectedness index. However, as emphasized before, the shape of the total connectedness plot in Figure 1 is sensitive to the size of sample window. I now reduce the window size to 150 days and plot the connectedness index in Figure 2. In Figure 2, the impact of the Fed's decision in May 2006 is clearly visible. Furthermore, the first tremors of the subprime crisis are shown to have an impact on the connectedness index when the 150-day window is used. The index jumps by six points in late February 2007. Other major developments in the US financial crisis are also well captured by the connectedness index based on 150-day sample window. Furthermore, the other two major cycles in the index are also consistent with the ones obtained with 200-day sample window. Finally, two minor cycles of mid-2009 and mid-2012 are also visible in the connectedness plot.

The total connectedness indices based on 200- and 150-day rolling sample windows provide us with valuable information about the timing of events that affected the major US and EU bank stock return volatilities. They prove the usefulness of the dynamic connectedness plots.

5.2 Total Directional Connectedness

The dynamics of total connectedness provides one with a clear understanding of the financial market developments influencing the volatility connectedness across major US and EU financial stocks. Keeping this analysis in the back of one's mind, it is now possible to focus on the dynamics of directional connectedness of the European and American banks over time.

I conduct the dynamic analysis of the total directional connectedness in three steps. First, I group the banks on each side of the Atlantic and analyze the volatility connectedness of the banks on the American side with the ones on the European side. Then, I analyze the volatility connectedness of a country's financial sector vis-a-vis the financial sectors of



Figure 2: Rolling Total Volatility Connectedness with 150-day sample window. The rolling estimation window width is 150 days, and the predictive horizon for the underlying variance decomposition is 12 days.

all other countries. Finally, in the third step I analyze the total volatility connectedness of some of the individual financial institutions vis-a-vis others. Since there are 26 institutions included in the analysis, at the final stage I will be focusing on the largest and the most connected among these institutions.

5.2.1 Connectedness Across the Atlantic

Figure 3 presents plots of total directional connectedness on two sides of the Atlantic. The upper panels (a) and (b) present the plots of volatility connectedness originating from the US and the EU, respectively. The lower panel, on the other hand, brings together the directional connectedness from the US and EU that appeared as dotted lines in the upper panels.

Let me start with the lower panel. There are three important observations one can make. First of all, the total directional connectedness across the Atlantic was rather low to begin with: the connectedness across the Atlantic fluctuated between 8 and 13% before the 2007 subprime crisis. The Fed’s decision in May and June 2006 to increase its policy rate triggered the unwinding of carry trades around the world. The Fed’s decision led the connectedness from the EU banks to the US banks to increase gradually to reach 14% by early 2007.

During the subprime crisis the connectedness of the US banks to the EU banks increased

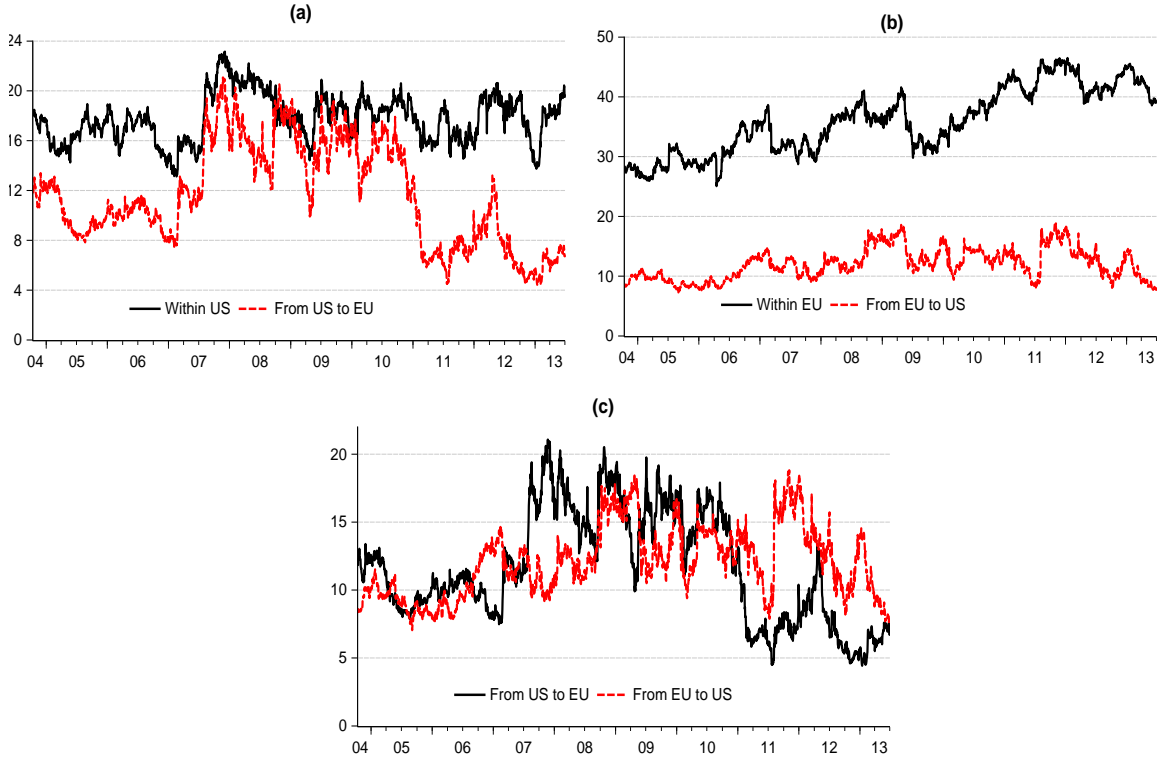


Figure 3: Directional Volatility Connectedness Across the Atlantic

The rolling estimation window width is 200 days, and the predictive horizon for the underlying variance decomposition is 12 days.

in three steps. First, at the end of February 2007, the connectedness from the US banks to the EU banks jumped up by more than 5 percentage points. Second, during the liquidity crisis of late-July, early-August days, the connectedness from the banks US to the EU banks jumped by another 7 points to reach 20%. Third, after a brief drop the connectedness from the banks US to the EU banks increased by another 4 points in October 2007 following the announcements by Citibank and other major banks, disclosing huge losses incurred from their investments in mortgage based securities (MBS). After reaching the peak in December 2007, the connectedness of the US banks to the EU banks declined temporarily, to increase again in January 2008.

Interestingly, the connectedness of the US banks to the EU banks increased by a total of 13 percentage points over the period from February 2007 to the first quarter of 2008. Over the same period, there was no significant increase in the connectedness of the EU banks to the US banks. It is therefore not wrong to claim that in the build-up stages of the US financial crisis volatility shocks that originated from the US financial system were transferred

across the Atlantic to the EU banks.

Following J. P. Morgan Chase's takeover of Bear and Sterns in March 2008, the volatility connectedness from the US banks to the EU banks gradually declined to 12% in the second and third quarter of 2008. The difference between the two lines in panel (c) narrowed down towards the end of the summer of 2008. They both jumped up by 6-8% immediately after the Lehman's collapse. Even though, the net-connectedness from the US banks to the EU banks was positive at the end of 2008, it was much smaller compared to the earlier phases of the financial crisis. The high bi-directional volatility connectedness across the Atlantic following the Lehman's collapse was a clear sign of the US financial crisis going global. Once the financial crisis turned into a global one, the troubles of the EU banks were magnified. As a result, following the collapse of Lehman Brothers until the early 2009 the directional connectedness measures across the Atlantic stayed high, within the 15-20% band.

As a coordinated policy response to the crisis took shape around the world, both connectedness measures declined to around 10% in early 2009, but the markets were not out of the woods yet. In order to gauge the soundness of the US financial institutions US Federal Reserve conducted bank stress tests in early 2009. Before the Fed announced the stress test results in early May 2009, the directional connectedness of the US banks to the EU banks increased to reach closer to 20%. While the test results were in general good for the whole US financial system, the Fed asked some major banks to raise additional capital to satisfy capital adequacy requirements. With small fluctuations, the connectedness of the US banks to the EU banks stayed high within the 15-20% band throughout 2009.

After staying in the 10-15% band in the second and third quarters of 2009, the EU banks' connectedness to the US banks increased by more than five points in late 2009, following the news about sovereign debt problems in Greece. Even though, the connectedness of the EU banks to the US banks declined back to 10% in a couple of months time, it increased again in the second quarter of 2010 following the EU's inability to put together a financial aid package that would help contain the Greek sovereign debt crisis. Six months after the public learned that the Greek debt was actually much higher than previously known, the EU finally announced a financial rescue package to deal with the Greek sovereign debt crisis a few days after the German local elections in May 2010.

The within-connectedness of both the EU and US banks (solid black lines in the upper panels (a) and (b)) fluctuated rather smoothly over the period from 2004 to the first half of 2006. However, following the Fed's decision to further increase Fed funds rate target in May and June 2006, the within-connectedness of the EU banks gradually increased from 30% to

reach 39% by early 2007. As the window is rolled to include March 2007 in the sample, the within-connectedness of the EU banks dropped from 39% to 31%. As the US financial crisis intensified in 2008, the within-connectedness of the EU banks increased again to reach 41% in September 2008. After declining to 37% in late 2008, the within-connectedness of the EU banks gradually increased to 42% at the end of April 2009, following the Irish banking crisis and the increased worries about the health of the EU banking sector.

After dropping down to 30% in the summer of 2009, the within-connectedness of the EU banks started to climb up again in December 2009, following the news about the Greek sovereign debt troubles. It climbed steadily during 2010 to reach 42% by the end of the year. As the EU put together a financial aid package for Greece, the sovereign debt and banking troubles continued to simmer in other members of the EU. In two months time it was Portugal's turn. In July 2010, Moody's lowered Portugal's government bond ratings by two notches from AA2 to A1. News about the Portugal's worsening public finances continued through 2010 and the first quarter of 2011, culminating in an official €78 billion bailout by the EU. As a result, the upward move in the within connectedness of the EU banks lasted until February 2011, when it reached 44%, before declining to below 40% in the spring of 2011. After Portugal, the focus shifted to the fiscal balances and banking sectors of two important members of the EU; namely, Italy and Spain. As the worries about the Spanish and Italian banking and sovereign debt problems intensified in June 2011, the within-connectedness of the EU banks increased by another 5 percentage points to reach 46% at the beginning of August 2011, before declining gradually in the first quarter of 2012.

The dynamic behavior of the within-connectedness of the US banks is in many regards significantly different from the one observed among the EU banks. To start with, it is lower than the within-connectedness of the EU banks. This is due to the higher number of EU banks (16) compared to the US banks (10) in the analysis. Furthermore, while the within-connectedness of the EU banks followed an upward trend with some corrections, the within-connectedness of the US banks fluctuated between 15 and 20% for most of the sample period considered. It increased slightly to 23% in the final months of 2007. Interestingly, even though the crisis originated in the US financial system, the within-connectedness of the US banks did not increase in the last quarter of 2008, during the heyday of the financial crisis. To the contrary, it continued its downward move with a small correction in the first half of 2009. It jumped by approximately 5 percentage points in late-April, early-May 2009, days before the announcement of the stress test results conducted on major US banks. From mid-2009 to mid-2011 the within-connectedness of the US banks fluctuated within the 16-20%

band. For most of 2011, the within-connectedness of the US banks fluctuated around 16%, with the exception of the May-August 2011 during which the worries about the disagreement between the Congress and the Obama administration on fiscal policy finally led to the S&P's lowering of the US federal government credit rating from AAA to AA+ on August 5, 2011.

At the same time, in June-July 2011 the connectedness from the EU banks to the US banks jumped by 10 percentage points. In other words, during the summer of 2011, the increased volatility of the European banks led to connectedness towards the US banks. After the appointment of Mario Draghi as its President, there was a clear change in the policy stance of the European Central Bank (ECB). On December 12, 2011, the ECB announced a new facility to provide liquidity to the banking system with a longer maturity. Through the Long-Term Refinancing Operations (LTRO) ECB aimed at providing €1 trillion loans to the EU banks with a maximum maturity of three years at an interest rate of 1.00%.

Immediately after the announcement of LTRO, fears about the EU banks subsided and the within-connectedness of the EU banks and their connectedness to the US banks started to decline. Within a quarter both indices declined by about 6-7 points. The connectedness of the EU to the US banks continued its downward move until the end of 2012, with a total decline of 10 percentage points. By the end of 2012, the connectedness of the US banks to the EU banks also declined to a level lower than the pre-crisis levels. However, the US bank stocks are under the influence of the volatility that stems from the intense debate between the Obama Administration and the Republican Party about the fiscal policy stance. The rise in the directional connectedness of the US banks to the EU banks in the first half of 2012 and at the beginning of 2013 resulted from the uncertainty caused by the political disagreement between the two wings of the US government. Finally, the small blip in the US banks' connectedness to the EU banks in late May and June 2013, was due to the Fed announcements that implied that the end of quantitative expansion policy of the US Central Bank was getting nearer. The uncertainty caused by the elections in Italy increased the volatility connectedness of the Italian banks in late 2012, and the directional connectedness from the EU banks to the US banks.

All in all, as of the end of June 2013, the directional connectedness of the US and the EU banks across the Atlantic declined to where they had been before the US financial crisis and lower. The within-connectedness of the US banks was around 20%, a couple percentage points above its value at the end of 2004. The within-connectedness of the EU banks, however, was 41%, 12 points above its value at the end of 2004. It is therefore possible to conclude that the global financial crisis and the ensuing tremors in the continental Europe

led to the intensification of the within volatility connectedness of the European banking industry.

5.2.2 Connectedness Across Countries

In this section, I analyze the connectedness of the major banks in each country with their counterparts in other countries. In the previous section, I analyzed the volatility connectedness from the US banks to the EU banks and from the EU banks to the US banks. The difference between the two series is by definition the net-connectedness of the US banks vis-a-vis the other seven countries in the sample, all of which are members of the EU. As could be observed in the previous section, it was positive during the US financial crisis, but moved into negative territory since 2010. These results are consistent with the essence of Figure 4. The net-connectedness of the US banks were the highest during the last 4 months of 2007 and early 2008, and the second quarter of 2009. It moved to negative territory in late 2010 and stayed negative since then.

Before moving to a detailed analysis of the “net-connectedness”, let me briefly discuss the main characteristics of the “to-” and “from-connectedness” measures. For the majority of the countries in the sample from-connectedness plots are smoother. Actually, from-connectedness plots for six continental EU member countries resemble the total connectedness plot presented in Figure 1. The from-connectedness plots for the US differ from the from-connectedness plots for other countries, because American banks actually generated the volatility connectedness to others during 2007 and 2008 until the collapse of Lehman Brothers. While the from-connectedness of other countries’ banks increased in 2007 and through 2008, American banks’ from-connectedness actually decreased in 2007 and fluctuated around 300 percentage points until the collapse of Lehman Brothers in mid-September 2008. The from-connectedness of the American banks also jumped significantly (150 percentage points) following the collapse of Lehman Brothers. The from-connectedness of the British banks jumped by 80 percentage points. Increases in other countries’ from-connectedness was much less compared to the jumps experienced by the US and the UK banks’ from-connectedness.

The dynamic behavior of the to-connectedness measures for each country are quite different from the dynamic behavior of the total connectedness measure. This is expected: when an idiosyncratic shock that originates in the banking system of a country spreads to others, this will only contribute to other countries’ from-connectedness with no effect on their to-connectedness. As the total connectedness measure is an average of the to-connectedness measures, its upward move will be limited compared to the to-connectedness of the country

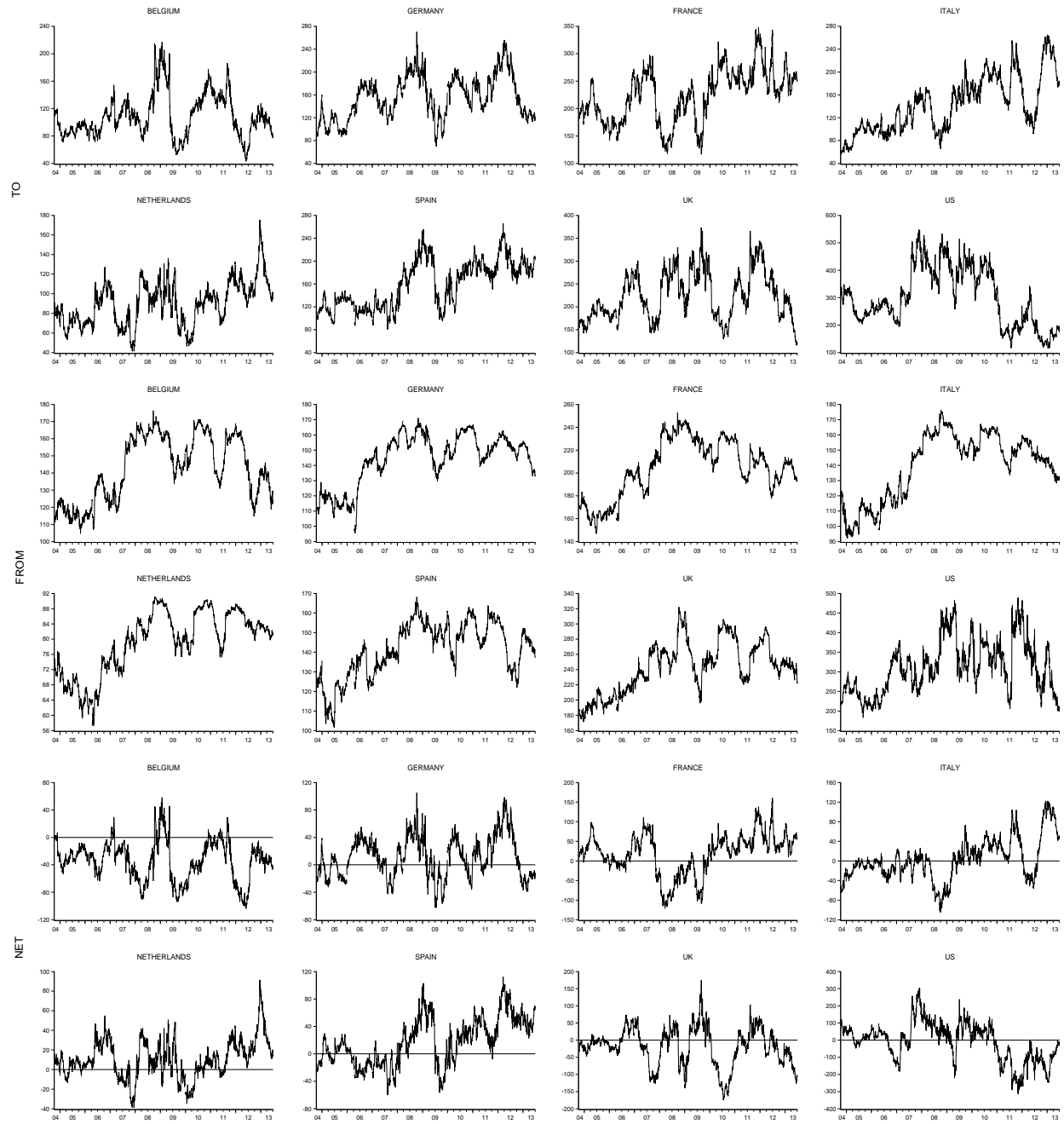


Figure 4: Directional Volatility Connectedness Across Countries

that was hit by the idiosyncratic shock. For example, the to-connectedness of the American banks actually declined in 2011 and stayed low for much of the remaining period, while the to-connectedness of the continental European banks increased further.

For the same reason, the to-connectedness of the countries in the sample differ from each other as well. While the to-connectedness of the German, French, Dutch and British banks increased following the Fed's decision to raise policy interest rates further in May and June 2006, the to-connectedness of the Italian, Spanish, Belgian and American banks did not increase much during that episode.

The to-connectedness of the US banks increased from 200% to 300% at the end of February 2007. It again increased during the liquidity crisis of August 2007, this time from 300% to 500%. After a downward trend during much of 2008, the to-connectedness of the American banks jumped again in mid-September 2008 from 300% to 500%. The to-connectedness of the US banks increased again in 2009 following the announcement of the stress test results in May 2009 and once more in spring and summer of 2010 along with the build up of the Greek crisis.

High to- and positive net-connectedness of French banks during the liquidity crisis of August 2007 show their troubles during this period. On August 9, 2007, BNP Paribas announced that it had frozen redemptions from three hedge funds, citing its inability to value structured products. German banks also suffered badly from the crisis. IKB, a small German Bank was rescued through operations involving private and public banks. As the crisis worsened, by the first quarter of 2008 almost all German banks made losses from their investments in the US. The value of assets they had to write down from their books during the crisis reached close to \$25 billion. Following the news about the write downs, "net" connectedness of German banks increased in the second and third quarter of 2008 and reached a maximum following the collapse of Lehman Brothers. Netherlands had high net-connectedness during 2006 and 2008-2009. UK banks had significant losses in late 2008 and the first half of 2009 and their high to- and net-connectedness measures reveals the stress they were under. Belgian banks were in trouble following the bankruptcy of Lehman Brothers, during which their to- and net-connectedness stayed high. Both Fortis and Dexia were in the brink of collapse. In September 2008, the French and Belgian governments supported Dexia with more than 6 billion euros. However, as the Greek crisis got worse the two governments decided to nationalize Dexia in October 2011. Fortis operations in Belgium, Netherlands and Luxembourg were broken up into three. While banking operations in Netherlands were nationalized by the Dutch the government, banking operations in Belgium was sold to BNP

Paribas.

In the summer of 2012 Italian banks were hit by consecutive downgrades by the credit rating agencies Moody's and S&P. First, Moody's downgraded 26 Italian banks in May 15, 2012, followed by another round of credit rating downgrade for 13 Italian banks by Moody's on July 17 and further by another round of downgrade for 15 Italian banks on August 4 by S&P. Following these the downgrades both the to- and net-connectedness of the Italian banks increased substantially in several months. The to-connectedness increased from around 110% in May 2012 to 260% in late November 2012. The bad news for the Italian banks were followed by the worries about the outcome of the Italian elections of February 28, 2013. As a result the to- and the net-connectedness of the Italian banks did not start declining until March 2013.

The net-connectedness measures of Spain, Germany, France, Italy, and Netherlands were mostly positive since the beginning of 2010. The net-connectedness measures for Belgium, the UK and the US, on the other hand, were mostly negative during the 2010-2013 period. The Belgium banks already suffered big blows in late 2008 and early 2009, and were put on life support from the government. Afterwards, they were in a passive mode, which explains their negative net-connectedness for most of the 2010-2013 period.

During the faithful months of the summer of 2011, the sharpest increase in the net-connectedness was observed for the Italian, Dutch, French and German banks. Interestingly, after the global financial crisis Spanish banks' net-connectedness increased only towards the end of 2010. This shows that in the summer of 2011, the markets were more worried about the sustainability of the Italian sovereign debt stock and the future of Italian banks, rather than the Spanish banks. The net-connectedness of Italy declined sharply in late 2011 and early 2012 following the ECB's announcement of long-term refinancing operation (LTRO) in December 2011. However, there was not an immediate impact on the net-connectedness of the Spanish banks. Instead, following the two rounds of LTRO the net-connectedness of the Spanish banks started to increase in the first quarter of 2012. From around 10-20% levels their net-connectedness reached to 100% level by mid-March 2012. Their net-connectedness started to decline afterwards and fell as low as 40% levels in late 2012 and for most of 2013. However, the signs from the US Federal Reserve that they might eventually wind-down the quantitative easing program in late 2013 or early 2014 led to a major reversal in capital outflows. The Spanish banks were affected as their net-connectedness increased from 31% on May 20 to 68% by the end of June.⁶

⁶Being the largest banks in the Spanish system, BBVA and Bank Santander, are included in the analysis

5.2.3 Connectedness at the Institution Level

US Banks

As we have seen above, American banks as a whole generated high levels of net volatility connectedness during the build up phase of the US financial crisis that eventually led to the global financial crisis of 2008-2009. In the post global financial crisis era, however, the direction of volatility connectedness has been mostly from the EU towards the US banks. Above I have also analyzed the directional volatility connectedness across the borders. In the remainder of this section, I analyze the directional volatility connectedness of each of the US and the EU banks in order to understand the link between the volatility connectedness and the developments at an institutional level.

Let me start with Citigroup, the US bank that generated the largest net volatility connectedness among all 26 banks in the analysis. The Citigroup stock created net positive volatility connectedness starting from October 2007 through the second quarter of 2008, as well as following the collapse of Lehman Brothers. The fact that Citigroup had high net volatility connectedness at various instants during the crisis shows how troubled the bank was during the financial crisis. On October 1, 2007, Citigroup announced a \$5.9 billion write-down due to subprime losses. Such a big loss led to the resignation of its CEO, Chuck Prince, in a few weeks time. Citigroup's losses increased over time. As of March 2008, Citigroup accumulated a total of \$22.4 billion in write-downs and credit losses stemming from the collapse of the US subprime mortgage market.⁷ From October 2007 onwards Citigroup's net volatility connectedness increased to reach 50% in March 2008 (see Figure 5).

After a decline in the second and third quarters of 2008, Citi's net volatility connectedness increased again to reach 80% in January 2009, following the collapse of Lehman Brothers and its net losses in the previous five quarters accumulated to reach \$37 billion as of the end of 2009. On February 27, 2009, the US federal government and the Citigroup reached accord on a third bailout package which effectively converted \$25 billion in preferred shares into common shares, increasing the government stake to 34% of its market value. Following the third rescue package, the net volatility connectedness of the Citigroup stock declined to as low as 5% in April 2009. According to the stress test results the Citigroup needed to raise

to represent returns and volatility in the Spanish banking system. The fact that the Spanish banking system was in trouble, however, does not necessarily imply that the two Spanish banks that are included in the sample were in trouble per se. Despite their strong balance sheets, their stocks came under great pressure along with the rest of the Spanish banking system.

⁷See "Subprime Losses Reach \$195 Billion," March 14, 2008. www.bloomberg.com

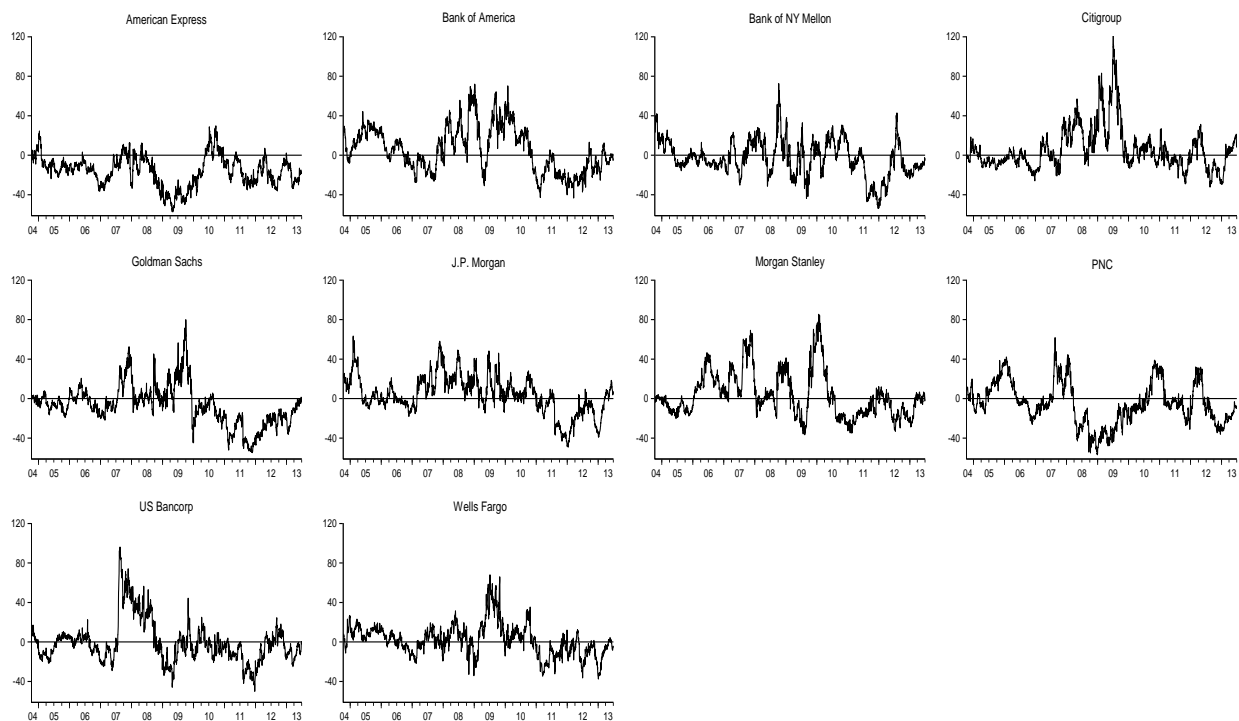


Figure 5: Net Directional Volatility Connectedness of the US Banks

\$5.5 billion in fresh capital to strengthen its balance sheet. Since it was an amount that could be raised from private investors without much difficulty, the announcement did not lead to an increase of the volatility of the Citigroup stock. However, several weeks after the announcement, the Federal Reserve and the US Treasury increased the pressure on Citigroup to revamp its board of directors by appointing new independent members. According to news report, Federal Deposit Insurance Corporation (FDIC) was said to be pushing for the departure of the top management, including the CEO of the company. After a brief hiatus, the Citigroup's net volatility connectedness started to increase in May 20 again and reached its highest level, 127%, on July 3, 2009. As the February 27 deal between the government and the Citigroup was approved by other preferred shareholders and following the appointments of eight new independent members to the board of directors, the net-connectedness of the Citigroup stock started to decline and became negligible by the end of 2009. From then on, the bank's net-connectedness fluctuated within a band of $(-30\%, +30\%)$.

Bank of America was the other major US bank that generated substantial net volatility connectedness to major US and EU banks. Unlike Citigroup, Bank of America itself did not

directly get involved in the US subprime mortgage market. However, its decisions to purchase Countrywide Financial, one of the leading mortgage generators, in January 2008 and Merrill Lynch in September 2008 exposed Bank of America directly to the risks associated with the US subprime mortgage market. As a reflection of this fact, the net-connectedness of BAC increased gradually in 2008 reaching the highest level following the bankruptcy of Lehman Brothers.

Merrill Lynch's investments in the MBS and ABCP continued to haunt BAC even after the US financial system had left the worst behind. The announcement of the stress test results put Bank of America on the spotlight again. The stress tests showed that Bank of America had to raise \$33.9 billion in new capital. This was the largest amount to be raised by the US banks that were subjected to the test. Following the announcement, the net volatility connectedness of BAC increased further to reach 65% by October 2009.

The bulk of BAC's problems, including the negative stress test results, that led to higher volatility in the stock followed from its acquisition of Merrill Lynch in late 2008. The stock was under pressure from shareholder anger following the news about a total of \$3.6 billion bonuses being paid by Merrill Lynch management to their employees days before the closing of the acquisition by BAC. On May 16, 2009, regulators pressured Bank of America management to overhaul its board of directors. The pressure continued throughout the summer, which eventually led to the resignation of the CEO of the company, Ken Lewis, on October 5, 2009. As a result of these developments BAC stock went through a period of high volatility throughout the summer. Even though, the net volatility connectedness of BAC declined slightly to below 40% in the last quarter of 2009, following Ken Lewis' resignation, it increased again to around 60% in the first months of 2010. Since the second-half 2010, the net-connectedness of the Bank of America mostly stayed in the negative territory.

J. P. Morgan Chase (JPM) experienced a period of sizable net volatility connectedness once the problems in the US subprime mortgage market had started in 2007. However, its net-connectedness never increased above 60% during this period. Furthermore, its net volatility connectedness stayed high only for short periods of time. Being one of the largest US banks, it makes sense to see JPM to be one of the banks that generated positive net-connectedness during the heyday of the US financial crisis. A comparison of JPM's net-connectedness plot with those of the Citigroup and Bank of America shows that JPM contributed much less to the systemic risk than its main competitors during the US financial crisis.

A similar case could have been made for Wells Fargo (WFC), had it not purchased

Wachovia, one of the major US banks that suffered substantial losses during the crisis. In the pre-Wachovia acquisition period, the net volatility connectedness of WFC never rose above 30%, and most of the time fluctuated around zero line. During the heyday of the crisis, the net-connectedness of WFC was in the negative territory, indicating how it was affected from systemic risk generated by others. Despite the strength of its own financial position, Wells Fargo was affected badly from the balance sheet troubles of the firm it acquired. Before and after the stress tests, WFC's stock volatility and volatility connectedness increased substantially. Stress test results revealed that WFC was expected to raise \$13.7 billion in additional capital. After Bank of America, this was the largest amount of capital the authorities required any US bank to raise. As a result of these developments, WFC's net-connectedness increased substantially in the summer of to reach 60%. The troubles of WFC did not last long as the bank's balance sheet excluding Wachovia was in good shape.

Aside from the top four US banks, other major banks also experienced substantial increases in their net volatility connectedness during the US financial crisis. Here I briefly discuss their connectedness plots. US Bancorp experienced a substantial increase in its net-connectedness during the liquidity crisis of 2007, reaching close to 100%. During this time period, the stock price declined from \$34.5 in May 2007 to around \$30 in July 2007. Its net-connectedness declined gradually over the rest of 2007 and 2008, but it was still around 40% just before the collapse of Lehman Brothers. After Lehman's collapse, the net-connectedness of US Bancorp declined sharply to negative territory and fluctuated below or around zero. The fact that USB's net-connectedness was negative after Lehman's bankruptcy shows how some of the major US banks were affected from the systemic risk generated by Lehman and AIG.

Morgan Stanley's stock was one of the more volatile stocks among the major US banks. Over the sample period, Morgan Stanley experienced five upticks in its net volatility connectedness. Its net volatility connectedness moved to positive territory in early 2006 and increased further to reach 40% following the Federal Reserve's decision in May 2006 to increase the federal funds rate target further. There was another upward move in early 2007, following the collapse of several mortgage originators. It was one of the stocks that suffered the most during the liquidity crisis of 2007. During this episode, its net volatility connectedness increased to 60%. Its net-connectedness increased again following Lehman's collapse, but this time only up to 40%. Finally, it suffered the worst increase in the second half of 2009 and early 2010 as a result of its continuing losses in the second half of 2009. Its net-connectedness moved above 80% in the first few weeks of 2010. The pressure on the stock

dissipated since mid-2010, with its net-connectedness falling below zero.

Even though it is an investment bank, Goldman Sachs has been one of the less problematic banks in the US. Its net-connectedness increased during the liquidity crisis of 2007 and in the period from May through September 2009. Both of these periods coincided with the sector-wide high connectedness episodes. Goldman Sachs had negative net volatility connectedness since the end of 2009.

American Express had positive net-connectedness in late 2010, but even then its net-connectedness was at most 20%. PNC had four episodes during which its net volatility connectedness reached to levels as high as 60%. However, all of these episodes did not last very long. Bank of New York Mellon also had low net-connectedness for most of the 2004-2013 period. Its net-connectedness increased to 80% levels only in late 2008 following the collapse of Lehman Brothers. Its net-connectedness also increased during the summer of 2012, but only for a very brief period. This increase followed a court ruling against the bank for its trustee role for the mortgage backed securities sold by Countrywide Financial Corporation to four big pension funds in the Chicago Metropolitan Area.

EU Banks

As I have already discussed above, in the connectedness analysis each European country is represented by a few large financial institutions. As a consequence, one would expect the dynamic net volatility connectedness plots at the country level resemble the corresponding plots for individual banks.

I start with the Belgian banks. The country's net-connectedness plot looks like an average of the plots for Dexia and KBC (see Figure 6). Dexia's net-connectedness shut up briefly in early 2007. Then, following Lehman's bankruptcy in September 2008, KBC experienced a significant increase in its net-connectedness until mid-2009. The increase in Dexia's net-connectedness was smaller, even though, Dexia was in worse shape than KBC. At the end of this period, Dexia received €6 billion in 2008. For the second quarter of 2011, Dexia posted a loss of €4 billion due to losses in the Greek sovereign bond market. As a result, Dexia's net-connectedness briefly rose to 40% during the summer 2011 phase of the European crisis, but subsided down quite quickly when it was taken to the custody of the Belgian government.

In the case of Germany, the behavior of net volatility connectedness at the country level is determined by Deutsche Bank. There are four major coincident cycles in the connectedness plots of Germany and Deutsche Bank. The fluctuations in the net volatility connectedness of Commerzbank are less pronounced and short-lived. The only time Commerzbank's net-

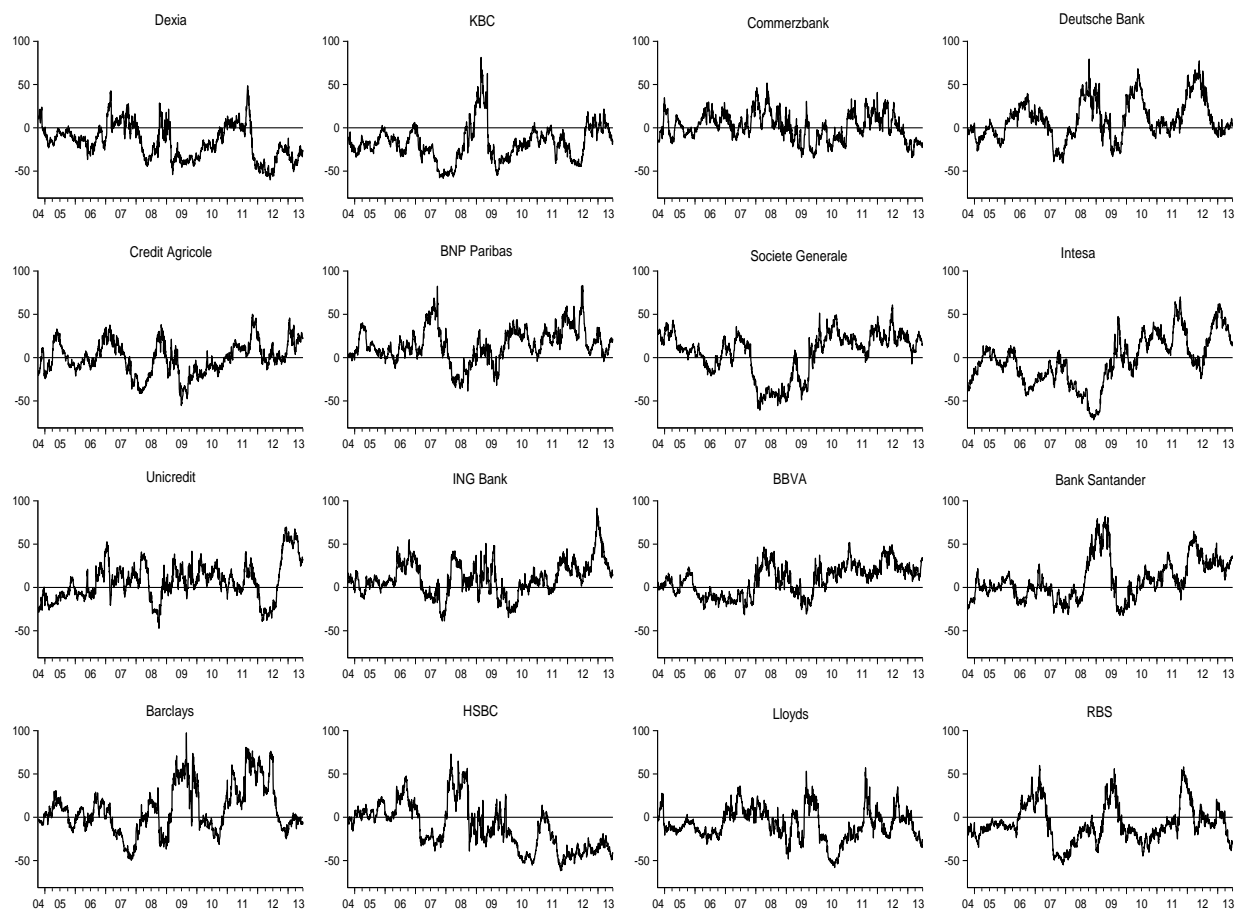


Figure 6: Net Directional Volatility Connectedness of the EU Banks

connectedness seems to affect the net-connectedness at the country level was in late 2010 early 2011. That is perhaps not unexpected. Since its acquisition of Dresdner Bank at the height of the financial crisis in August 2008, Commerzbank has always been the more problematic number two bank in Germany. In December 2008, German government bailed Commerzbank with a cash injection of €18.2 billion. Since the end of 2008, Commerzbank has been trying to deleverage. It has cut its assets by 26%, from €841 billion at the end of 2009 to €633 billion as of the end of 2012.

In the case of France, BNP Paribas and Societe Generale stocks play more important roles in determining the country's net-connectedness. This is even more true during the European sovereign debt and banking crisis since 2010. Both banks had significant holdings of Greek government bonds, and their profits were hit by write-downs amounting to billions of euros

related to Greek sovereign debt. They had sizable net-connectedness from 2010 through the end of 2012. Credit Agricole, on the other hand, had negative net-connectedness in 2010. It moved to positive territory after the crisis was spread to Italy and Spain in the summer of 2011. Credit Agricole had to book a €2 billion net loss after selling Emporiki, its Greek banking subsidiary, for just €1 in mid-October 2012. To go back in time, all three French banks had an increase in their net volatility connectedness in 2005. While Credit Agricole and Societe Generale experienced increases in their net-connectedness following the unexpected extra monetary tightening by Fed, BNP Paribas experienced a sizable increase in its net-connectedness to 50% when the first-tremors of the subprime crisis were felt in the US in February-March 2007.

Among the two Italian banks, the net-connectedness of Unicredit fluctuated substantially over time. From the second half of 2006 to the Lehman's collapse in September 2008, its net-connectedness fluctuated within the 0-50% band. After having negative net-connectedness after the collapse of Lehman Brothers, its net-connectedness moved to positive territory and fluctuated within the 0-40% band until the end of 2011. Since then it dived down to -40%, before moving up to 60% in October 2012. Intesa San Paolo's net-connectedness, on the other hand, fluctuated more widely than that of Unicredit. The stock experienced mostly substantial degree of negative connectedness in 2006 and during the global financial crisis. With the European crisis, since 2010, its net-connectedness moved into positive territory and increased over time, reaching the highest level, 60%, in the summer of 2011. As a result of the political uncertainty before the general elections of 2013, the net connectedness of Unicredit and Intesa increased to reach 50-60% band. In particular, Unicredit's connectedness fluctuated within the 50-60% band for at least three months.⁸

Among the two Spanish banks, BBVA had positive net-connectedness in early 2008, reaching as high as 45%. Bank Santander, on the other hand, had its highest net-connectedness in the aftermath of the Lehman bankruptcy for almost a year. During the European debt crisis, both banks had positive net-connectedness, gradually increasing towards late 2011. BBVA's net-connectedness was higher than Santander's in 2010 and early 2011. The ranking of the two banks in terms of net-connectedness was reversed from August 2011 onwards.

Among the four British banks in our sample, Lloyds had lower net-connectedness compared to others. The increases in Lloyds' net-connectedness (in mid-2009, and in the summers of 2011 and 2012) were all short-lived compared to others. On August 4, 2011, trading in

⁸This result is consistent with the findings of Black et al. (2013) which showed that the marginal contribution of the Italian banks to the systemic risk of the European banking industry increased significantly during the European debt and banking crisis, and in 2011 in particular.

shares of Lloyds and Barclays was suspended as both banks' stocks lost more than £1 billion in value. Volatility shocks to Barclays' stock, on the other hand, tend to generate substantial connectedness to others, as can be witnessed in Barclays' net-connectedness plot. Throughout 2009, its net-connectedness fluctuated between 60 and 100%. Its net-connectedness increased again in early 2011 and stayed high until the second half of 2012.

The net volatility connectedness of HSBC followed quite a different path compared to that of Barclays. It was positive in 2006 following the Fed's decision to raise interest rates, but it reached to 40% at the maximum. During the US financial crisis, its net-connectedness first increased closed to 70% at the end of 2007 and fluctuated in the 25-60% band throughout 2008. Following the Lehman bankruptcy, its net-connectedness dropped to negative values, indicating that it was viewed as a safer financial institution at a time when the global financial system was in jeopardy. Since 2009, HSBC's net volatility connectedness mostly stayed in the negative territory.

RBS's net volatility connectedness increased in mid-2006 following the unwinding of the carry trades around the world. During the first phases of the US financial crisis, however, RBS had a net volatility connectedness from others. While major US banks were announcing huge losses, RBS announced a profit of £10 billion in the fall of 2007. October 2007 proved to be the fateful month that sealed RBS's fate: Despite signs of worsening in the UK banking sector (such as the liquidity problems faced by Northern Rock), RBS went ahead with the £49 billion takeover of ABN Amro, the biggest bank in the Netherlands.⁹ A year later, in October 2008, RBS sought for a multibillion pound bailout package from the UK government. On February 26, 2009, RBS announced the largest annual loss in UK corporate history of £24.1bn. Following the announcement, its net-connectedness jumped to reach 50%. By the end of 2009, its net-connectedness declined and moved to the negative territory. However, its net-connectedness increased again in the summer of 2011. On August 5, 2011, trading in RBS shares was halted in order to stem the free fall in the share price. As downward move in RBS stock followed the moves in Barclays and Lloyds (both of which reached to very high levels), RBS' net-connectedness stayed in the negative territory. However, as days went by, RBS's net-connectedness sharply increased to reach close to 57%.

Finally, the Netherlands is represented by ING Bank, the largest bank in the country. ING Bank had sizable net volatility connectedness following the Fed's rate decision in May 2006, in the first half of 2008, throughout 2009 and in the second half of 2011. However,

⁹In September 2007, Northern Rock had suffered the first run on a British bank for more than 100 years, exposing the vulnerability of the UK banks to the US financial crisis.

from the beginning of July 2012 its volatility connectedness increased substantially to reach the maximum level, 91%, on December 14, 2012. ING Bank itself was not the source of the problem. The fourth largest bank of the Netherlands, SNS Reaal NV, went into serious trouble in the second half of 2012 and the beginning of 2013. In the end, the Dutch government decided to nationalize SNS Reaal NV on February 1, 2013. As a result, ING Bank's net volatility connectedness declined quickly and fell below 20% as of the end of our sample. Interestingly, during this period ING Bank was one of the banks that generated very high net volatility connectedness to other banks. As we've already discussed above, the two Italian banks were the other banks with increased connectedness during this period.

6 Concluding Remarks

Within a year after its outbreak the US subprime mortgage crisis of 2007 was transformed into a global financial crisis, with serious long-run effects on the global capitalist system. In 2009, the crisis moved across the Atlantic, with devastating effects on European banks and governments. As in other crises before, during the global financial crisis and the European banking and sovereign debt crisis volatility shocks spread quite rapidly across individual assets, markets and countries connecting them in a state of high volatility.

In this paper I used the Diebold-Yilmaz connectedness framework to study the volatility connectedness of major banks across the Atlantic. The Diebold-Yilmaz framework allowed us to understand how each individual bank contributed to the total volatility connectedness. In addition, given that there are many banks that need to be included in the analysis, I aggregate the individual bank effects at the country level and analyze how the volatility shocks in one or several countries affect the major banks in other countries.

I obtained several important results from the analysis of the volatility connectedness of major banks. I was able to match the behavior of the connectedness measures over time with the major developments that affected individual bank stocks as well as the whole banking systems of the countries in our sample. Perhaps the most important result of the paper concerns the volatility connectedness of the banks across the Atlantic. Until the collapse of Lehman Brothers, the direction of the volatility connectedness was from the US banks towards the EU banks. Once Lehman Brothers went bankrupt in mid-September 2008, the financial crisis was transformed into a global one. As a reflection of this fact, the volatility connectedness across the Atlantic became bi-directional, with net-connectedness From late 2010 onwards, however, there had been a change in the direction of volatility connectedness.

The net volatility connectedness of the US banks had become negative. Once the sovereign debt and banking crisis intensified in the EU periphery all European bank stocks suffered from high volatility, spreading this high volatility to their counterparts across the Atlantic.

The power of the Diebold-Yilmaz connectedness framework rests with its dynamic nature. It can be used to gauge how volatility shocks in some stocks, markets or asset classes spread to others over time. There are likely to be other significant volatility shocks in 2013 and beyond. It is therefore important to follow the volatility connectedness of the major banks on both sides of the Atlantic.

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