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MEASURING COMOVEMENT IN THE TIME-FREQUENCY SPACE

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Measuring comovement in the time-frequency space

António Rua*

Abstract

The measurement of comovement among variables has a long tradition in the economic and financial literature. Traditionally, comovement is assessed in the time domain through the well-known correlation coefficient while the evolving properties are investigated either through a rolling window or by considering non-overlapping periods. More recently, Croux, Forni and Reichlin [Review of Economics and Statistics 83 (2001)] have proposed a measure of comovement in the frequency domain. While it allows to quantify the comovement at the frequency level, such a measure disregards the fact that the strength of the comovement may vary over time. Herein, it is proposed a new measure of comovement resorting to wavelet analysis. This wavelet-based measure allows one to assess simultaneously the comovement at the frequency level and over time. In this way, it is possible to capture the time and frequency varying features of comovement within a unified framework which constitutes a refinement to previous approaches.

Keywords: Comovement; Wavelets; Time-frequency; Growth cycles.

JEL classification: C40, E32.

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1 Introduction

The measurement of comovement among economic variables is key in several areas of economics and finance. From the innumerous fields where such assessment is crucial, one can mention business cycle analysis or asset allocation and risk management, just to name a few.

Traditionally, comovement is assessed in the time domain. The most popular measure of comovement is the well-known correlation coefficient. The contemporaneous correlation coefficient provides in a single number the degree of comovement between the series over the sample period. However, being a synthetic measure it can be rather limited unfolding the relationship between economic variables. For instance, it has been long acknowledged that the degree of comovement may vary over time. To take this feature into account, it has been the current practice in the literature to compute a rolling window correlation coefficient or to consider non-overlapping sample periods to evaluate the evolving properties of comovement.

Another strand of literature focus on the frequency domain analysis which is a complementary tool to time domain analysis. In fact, with Fourier analysis, one can obtain additional insights through the study of the relationship between variables at the frequency level (see, for example, A'Hearn and Woitek (2001), Pakko (2004), Breitung and Candelon (2006) and Lemmens, Croux and DeKimpe (2008)). In this respect, Croux, Forni and Reichlin (2001) have proposed a spectral-based measure, the dynamic correlation, which allows one to measure the comovement between two series at each individual frequency. This measure, which ranges between -1 and 1, is conceptually similar to the contemporaneous correlation between two series in the time domain. However, unlike the correlation coefficient in the time domain, one now obtains a comovement measure that can vary across frequencies. Several applications of the dynamic correlation can be found in recent literature (see, Crone (2005), Rua and Nunes (2005), Camacho, Perez-Quiros and Saiz (2006), Eickmeier and Breitung (2006), Lemmens, Croux and DeKimpe (2007), among others). However, as the dynamic correlation is defined in the frequency domain it disregards the time dependence of comovement. That is, it provides only a snapshot of the comovement at the frequency level not allowing to capture time-varying features.

Wavelet analysis merges both approaches, in the sense that both time and frequency domains are taken into account. Through wavelet analysis one can assess simultaneously how variables are related at different frequencies and how such relationship has evolved over time, allowing to capture non-stationary features. This is a distinct and noteworthy aspect as both time- and frequency-varying behaviour cannot be captured using previous approaches. Hence, wavelet analysis constitutes a very promising tool as it represents a refinement in terms of analysis which can provide rich insights about several economic phenomena (see, for example, the pioneer work of Ramsey and Zhang (1996, 1997) and Ramsey and Lampart (1998a,b)). Recent work drawing on wavelets includes, Kim and In (2005) who investigate the relationship between stock returns and inflation, Gençay *et al.* (2005) and Fernandez (2005) study the Capital Asset Pricing Model, Gallegati *et al.* (2008) and Yogo (2008) resort to wavelets for business cycle analysis, Rua and Nunes (2009) focus on international stock market returns, among others (see, for example, Crowley (2007) for a survey).

In this paper, it is proposed a measure of comovement in the time-frequency space by resorting to wavelet analysis. The wavelet-based measure of comovement herein suggested allows one to assess the extent to which two variables move together over time and across frequencies within an unified framework. To illustrate the use of such measure, the comovement of growth cycles among the major euro area countries over the last three decades is assessed. Through such empirical application, the usefulness of the proposed wavelet-based measure of comovement is highlighted as it allows to unveil both time- and frequency varying features. In fact, it is found that the strength of comovement of growth cycles among the major euro area countries depends on the frequency and has changed over time.

The paper is organised as follows. In section 2, the wavelet-based measure of comovement is presented while in section 3, the empirical application is discussed. Finally, section 4 concludes.

2 A wavelet-based measure of comovement

The well-known Fourier transform involves the projection of a series onto an orthonormal set of trigonometric components (see, for example, Priestley (1981)). In particular, it uses sine and cosine base functions that have infinite energy (do not fade away) and finite power (do not change over time). Hence, the Fourier transform does not allow for any time dependence of the signal and therefore cannot provide any information about the time evolution of its spectral characteristics. To circumvent such limitation it has been suggested the so-called short-time or windowed Fourier transform. It consists of applying a short-time window to the signal and performing the Fourier transform within this window as it slides across all the data. A caveat of the windowed Fourier transform is that the window width and thus the time resolution is constant for all frequencies. When a wide range of frequencies is involved, the fixed time window tends to contain a large number of high frequency cycles and a few low frequency cycles which results in an overrepresentation of high frequency components and an underrepresentation of the low frequency components. Hence, as the signal is examined under a fixed time-frequency window with constant intervals in the time and frequency domains, the windowed Fourier transform does not allow an adequate resolution for all frequencies. In contrast, the wavelet transform uses local base functions that can be stretched and translated with a flexible resolution in both frequency and time. In the case of the wavelet transform, the time resolution is intrinsically adjusted to the frequency with the window width narrowing when focusing on high frequencies while widening when assessing low frequencies. As it enables a more flexible approach in time series analysis, wavelet analysis is seen as a refinement of Fourier analysis.

Mathematically, the wavelet transform decomposes a time series in terms of some elementary functions, $\psi_{\tau,s}(t)$, which are derived from a time-localized mother wavelet $\psi(t)$ by translation and dilation (see, for example, Percival and Walden (2000)). Wavelets have finite energy and compact support, that is, they grow and decay in a limited time period and are defined as

$$\psi_{\tau,s}(t) = \frac{1}{\sqrt{s}}\psi\left(\frac{t-\tau}{s}\right)$$

where τ is the time position (translation parameter), s is the scale (dilation parameter), which is related with the frequency, and $\frac{1}{\sqrt{s}}$ is a normalization factor to ensure that wavelet transforms are comparable across scales and time series. To be a mother wavelet, $\psi(t)$, must fulfil certain criteria: it must have zero mean, $\int_{-\infty}^{+\infty}\psi(t)dt = 0$; its square integrates to unity, $\int_{-\infty}^{+\infty}\psi^2(t)dt = 1$, which means that $\psi(t)$ is limited to an interval of time; and it should also satisfy the so-called admissibility condition, $0 < C_\psi = \int_0^{+\infty}\frac{|\widehat{\psi}(\omega)|^2}{\omega}d\omega < +\infty$ where $\widehat{\psi}(\omega)$ is the Fourier transform of $\psi(t)$, that is, $\widehat{\psi}(\omega) = \int_{-\infty}^{+\infty}\psi(t)e^{-i\omega\tau}dt$.

The continuous wavelet transform of a time series $x(t)$ with respect to $\psi(t)$ is given by the following convolution

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

where * denotes the complex conjugate.

As with its Fourier counterpart, there is an inverse wavelet transform, defined as

$$x(t) = \frac{1}{C_\psi}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\psi_{\tau,s}(t)W_x(\tau,s)\frac{d\tau ds}{s^2}$$

This allows to recover the original series, $x(t)$, from its wavelet transform by integrating over all scales and time positions.

Likewise in Fourier analysis, several interesting quantities can be defined in the wavelet domain. For instance, one can define the wavelet power spectrum as $|W_x(\tau,s)|^2$. It measures the relative contribution at each time and at each scale to the time series' variance. In fact, the wavelet power spectrum can be integrated across τ and s to recover the total variance of the series as follows

$$\sigma_x^2 = \frac{1}{C_\psi} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} |W_x(\tau,s)|^2 \, \frac{d\tau ds}{s^2}$$

Another quantity of interest is the cross-wavelet spectrum which captures the covariance between two series in the time-frequency space. Given two time series $x(t)$ and $y(t)$, with wavelet transforms $W_x(\tau,s)$ and $W_y(\tau,s)$ one can define the cross-wavelet spectrum as $W_{xy}(\tau,s) = W_x(\tau,s)W_y^*(\tau,s)$. As the mother wavelet is in general complex, the cross-wavelet spectrum is also complex valued and it can be decomposed into real and imaginary parts.

In a similar fashion to Croux, Forni and Reichlin (2001), one can obtain the following measure

$$\rho_{xy}(\tau,s) = \frac{\Re\left(W_{xy}(\tau,s)\right)}{\sqrt{|W_x(\tau,s)|^2 \, |W_y(\tau,s)|^2}}$$

where $\Re$ denotes the real part of the cross-wavelet spectrum which measures the contemporaneous covariance. The wavelet-based measure $\rho_{xy}(\tau,s)$ allows one to quantify the comovement in the time-frequency space and assess over which periods of time and frequencies is the comovement higher. Basically, it plays a role as a contemporaneous correlation coefficient around each moment in time and for each frequency. Likewise the standard correlation coefficient and the dynamic correlation proposed by Croux, Forni and Reichlin (2001), $\rho_{xy}(\tau,s)$ ranges between -1 and 1. While the dynamic correlation measure suggested by Croux, Forni and Reichlin (2001) is the Fourier counterpart of the standard correlation coefficient allowing to assess in which frequencies is the contemporaneous comovement higher, the measure herein proposed can be seen as a generalisation of such measure in the sense that $\rho_{xy}(\tau, s)$ provides information about the comovement not only at the frequency level but also over time.[1] This feature is of striking importance as it has been long acknowledged that the strength of the comovement may vary over time. In particular, by inspecting the contour plot of the above measure, one can identify the regions in the time-frequency space where the two time series comove and assess both time and frequency varying features of the comovement. Hence, the suggested wavelet-based measure allows for a richer description on the comovement between the variables of interest.

3 An empirical application

For illustration purposes, we assess the comovement of growth cycles among the major euro area countries, namely Germany, France, Italy and Spain. As usual, the growth cycle is defined as the quarter-on-quarter real GDP growth rate. The data are from Thompson Financial Datastream and the sample period for GDP runs from the first quarter of 1981 up to the fourth quarter of 2008.[2] Concerning the mother wavelet, the most frequent choice is the Morlet wavelet (see, for example, Adisson (2002) for further details) which will be the one used here.[3] All computations are done using Matlab.

The results for all possible country pairs are presented in Figures 1 up to 6. The wavelet-based measure of comovement is presented through a contour plot as there are three dimensions involved. The horizontal axis refers to time while the vertical axis refers to frequency. To ease interpretation,

[1] Note that, the herein proposed measure is closely related with the wavelet squared coherency, likewise dynamic correlation of Croux, Forni and Reichlin (2001) is related with squared coherency. However, as also mentioned by Croux, Forni and Reichlin (2001), the phase differences between the variables are entirely disregarded in the latter case.

[2] In the case of Germany, the growth rate before 1991 refers to West Germany.

[3] The Morlet wavelet can be defined as $\psi(t) = \pi^{-\frac{1}{4}} e^{i\omega_0 t} e^{\frac{-t^2}{2}}$, *i.e.* the Morlet wavelet is a complex sine wave within a Gaussian envelope whereas ω_0 is the wavenumber. In practice, ω_0 is set to 6 as it provides a good balance between time and frequency localization. In this case, the wavelet scale is almost equal to the Fourier period.

the frequency is converted to time units (years). The gray scale is for the wavelet-based measure whereas increasing darkness corresponds to an increasing value and mimics the height in a surface plot. Hence, by inspecting the contour plot one can identify both frequency bands (in the vertical axis) and time intervals (in the horizontal axis) where the series move together and assess if the strength of the comovement changes across frequencies and over time.

From the analysis of the results several interesting findings emerge. In general, there is a high degree of comovement at lower frequencies, *i .e.* long-term fluctuations, among the major euro area countries. Only in the case of Germany and Italy, the comovement is weak at low frequencies. Regarding the typical business cycle frequency range, *i .e.* fluctuations between two and eight years, one can see that, for example, Germany and France only show signs of relatively high comovement since the mid-90's while Germany and Italy present a high degree of comovement almost over the entire sample period although it has also become stronger since the mid-90s. In the remaining country pairs, there seems to be a high degree of comovement since the 90's at the business cycle frequency range. In contrast, the comovement is in general weak at frequencies associated with fluctuations that last less than two years. Note, however, that the strength of comovement seems to have increased at the latter part of the sample at higher frequencies. This feature is more clear in the case of Germany and France and in the case of Germany and Italy.

The above findings suggest that the synchronization of growth cycles among the major euro area countries has always been high at low frequencies, *i.e.* long-term developments. In turn, at the typical business cycle frequency range, the synchronization was, in general, relatively low at the beginning of the sample period but increased since the mid-90s attaining a high degree of synchronization thereafter. This may reflect the deepening of European economic integration reinforced with the establishment of the monetary union in 1999. In contrast, the comovement of growth cycles at high frequencies is, with a few minor exceptions, rather low throughout the whole sample period. This may result from the fact that very short-term fluctuations are essentially idiosyncratic. Furthermore, the synchronization of growth cycles seems to be higher among the major euro area countries than between those countries and countries like, for example, the United States[4].

All these results highlight the usefulness of the proposed wavelet-based measure of comovement. In fact, the degree of comovement can change across frequencies and over time and being able to capture such evolving features is crucial for a richer comovement assessment.

4 Conclusions

The assessment of the comovement among economic variables is of key importance in several strands of the literature. One can distinguish two main approaches for measuring comovement, the more traditional approach in the time domain and the one based on spectral analysis. While the first approach discards all the information concerning the relationship at the frequency level, the second one does not take into account the possible time dependence of such relationship. To overcome such caveats one can resort to wavelet analysis. Wavelet analysis allows one to take into account both the time and frequency domains within a unified framework.

In this paper, it is proposed a wavelet-based measure of comovement. The wavelet-based measure allows one to quantify the degree of comovement in the time-frequency space. That is, it allows one to assess simultaneously over which time periods and at which frequencies is comovement higher. Besides allowing one to identify the regions in the time-frequency space where the two time series comove, one can also assess if the degree of comovement

[4] The results are available from the author upon request.

has been changing across frequencies and over time. Hence, the suggested wavelet-based measure allows for a richer description on the comovement between the variables of interest and can be seen as a refinement of previous approaches.

An empirical application is provided to illustrate the use of such a measure. In particular, the comovement of growth cycles among the major euro area countries is assessed. The results highlight the usefulness of the wavelet-based measure of comovement, as it is found that the degree of comovement depends on the frequency and has changed over time.

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Figure 1 - Comovement between the growth cycles of Germany and France

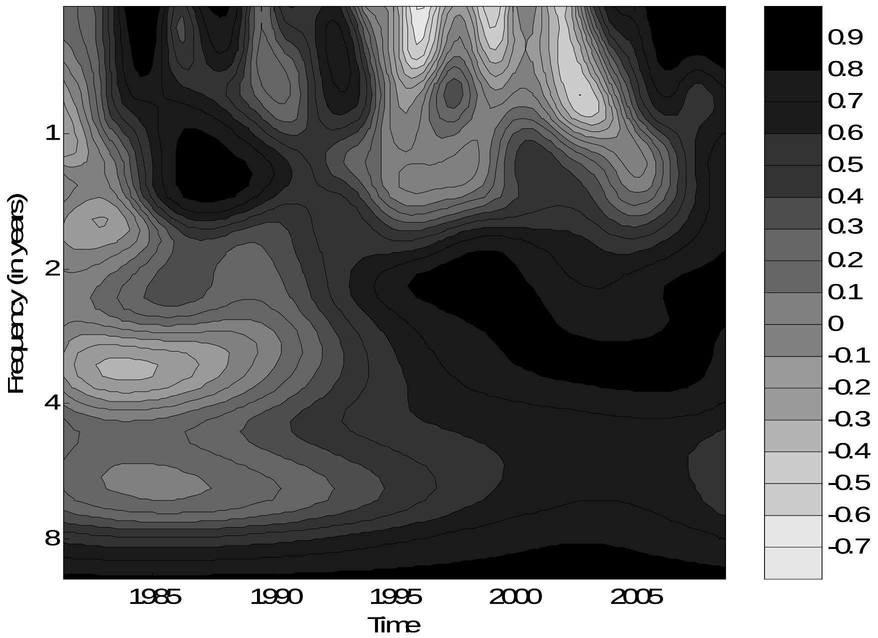


Figure 2 - Comovement between the growth cycles of Germany and Italy

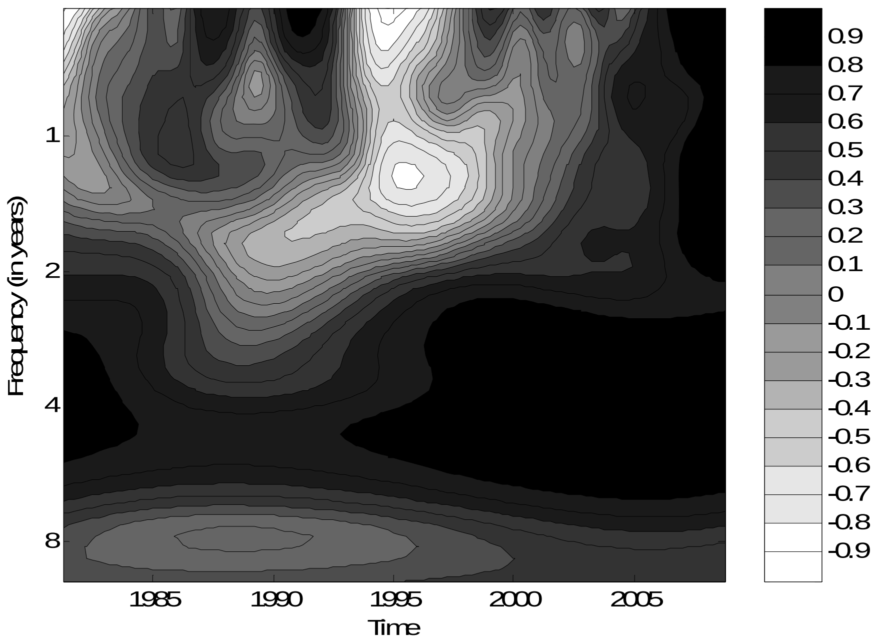


Figure 3 - Comovement between the growth cycles of Germany and Spain

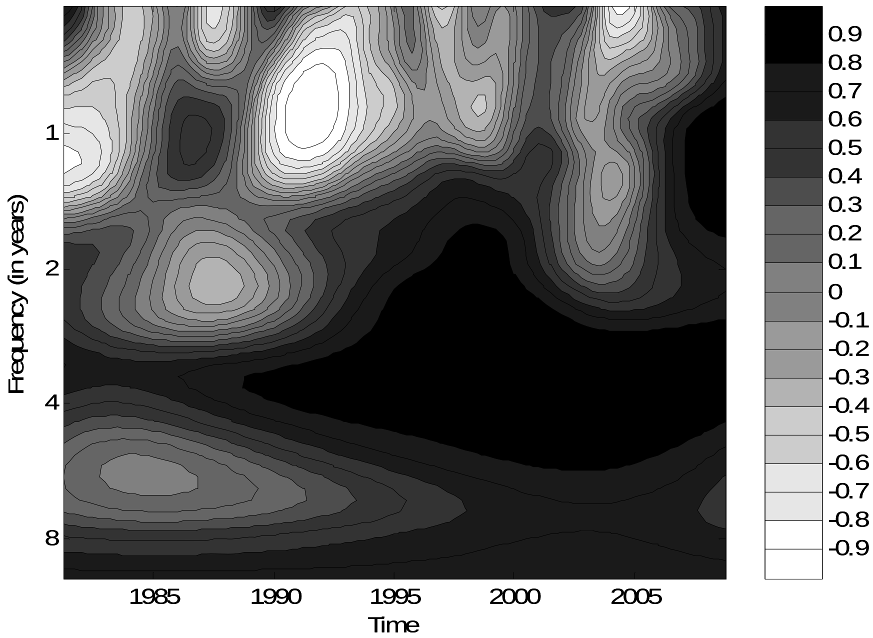


Figure 4 - Comovement between the growth cycles of France and Italy

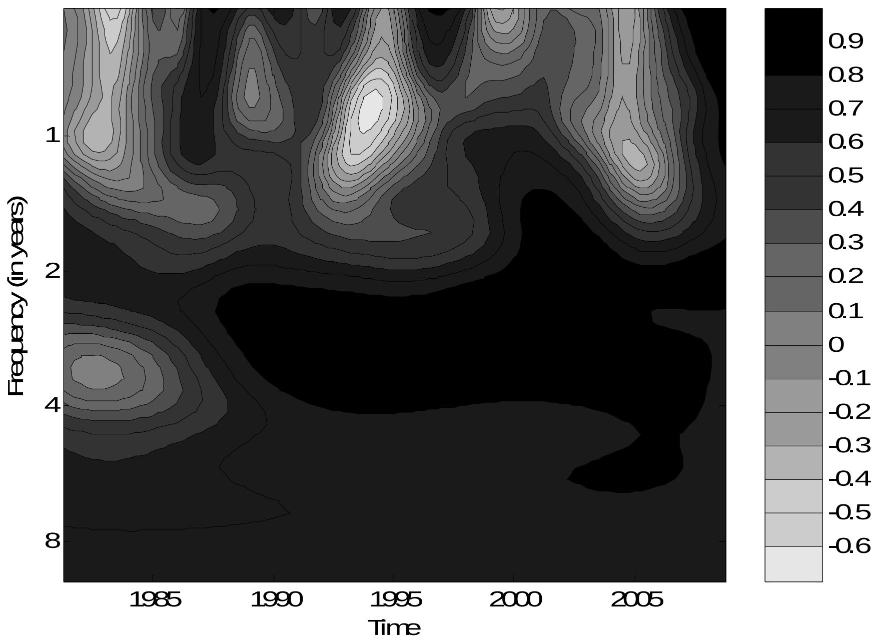


Figure 5 - Comovement between the growth cycles of Italy and Spain

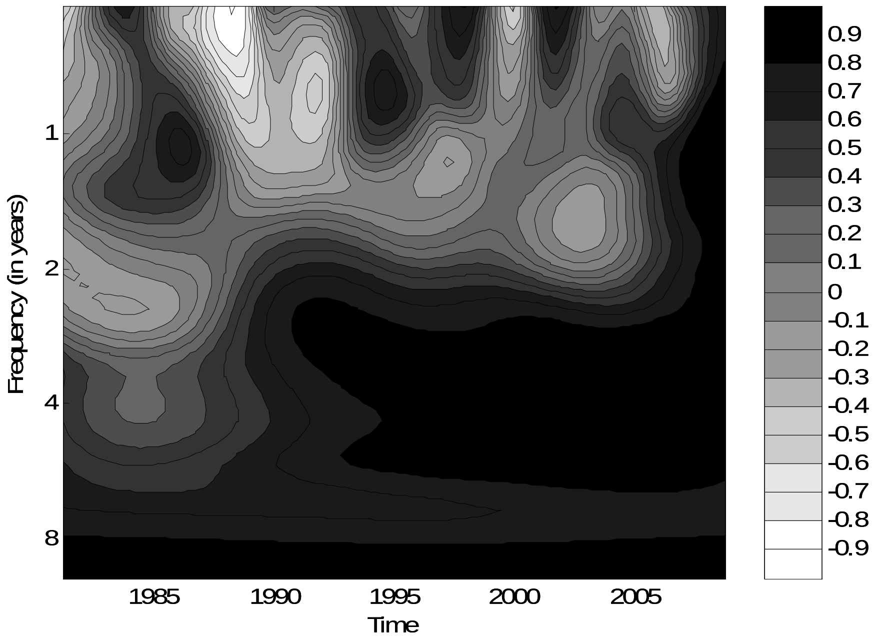
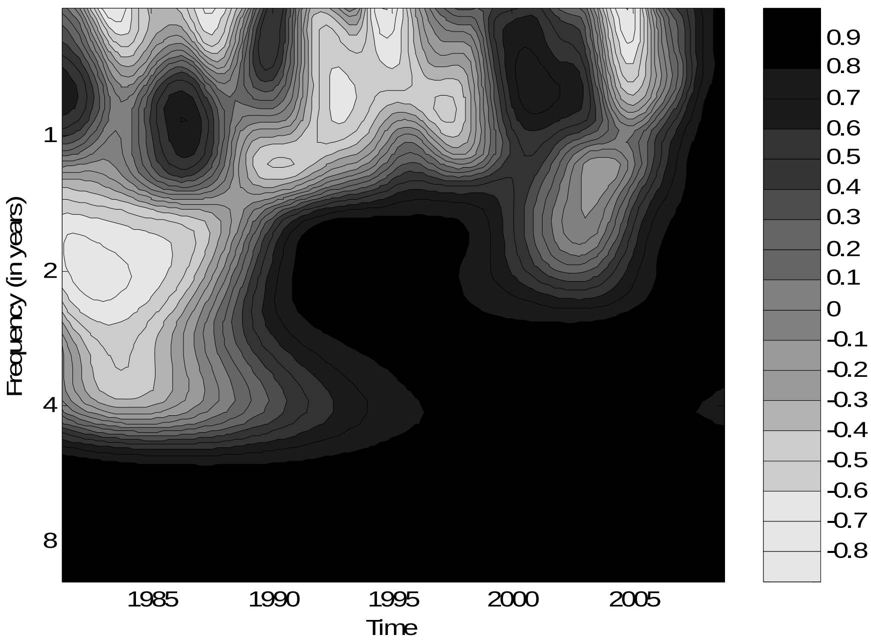


Figure 6 - Comovement between the growth cycles of France and Spain



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