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The DCC test: powerless evidence of no contagion

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Abstract

In this paper we run the DCC test proposed by Rigobon (2002a) to evaluate its applicabilty in detecting contagion. We analyse the relationship between some of the most important stock markets during the Asian crises of the second semester of 1997. We find that the DCC is not a useful tool to detect contagion and many criticisms can be made on this procedure. The main problems of this approach are two: on the one hand, even in the simplest case when analysing two markets, it is impossible to evaluate if a rejection is due to parameter shift or to the violation of the assumptions made on the heterosckedasticity under the null. On the other hand there is strong empirical evidence that the test have no power when analysing more than two markets jointly: hence it is not possible to conclude, as Rigobon (2002a) does, that no rejection is evidence of no contagion.

JEL: Classification Numbers: F30, C32, G15
Keywords: Contagion, stock market crises, international financial markets, measuring the transmission mechanism.

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1 Introduction

The last decade experienced a set of strong and widely diffused crises: in the rencent years, concern over contagion and interdependence between financial markets became a major topic . Often during financial crises we observe strong co-movements in prices and in the volatility between markets, and sometimes it is also possible to observe an increase in the covariance of the returns and in their correlation. Referring to that features of the crises the word contagion has been widely used but it has different meanings depending on the author.

Many articles concern the propagation mechanisms of recent financial crises. In particular, they have focused on the question whether the relationships between markets during tranquil periods are different from those during periods of crisis. In our paper we define contagion as a structural break that produces an intensification of the relathionship between countries during a crisis[1]. This definition is not universally accepted but it is widely used (see Forbes and Rigobon 2000b)[2]. Interdependecnce is opposite to contagion since it involves stability and no innovation in the relationship between markets.

The existence of contagion is a relevant issue at an international level: contagion is a structural break and implies that it is not possible to forecast the reaction of one country to a crisis in another country. Instead forecasting is possible if the relathionship is stable during periods of crisis (no contagion, only interdependece). This has important consequences for monetary policy, optimal asset allocation, risk measurement, capital adequacy, and asset pricing.

A central issue is how to distinguish between interdependence and contagion and what are the factors that affect such measures. Our analysis builds on the study of Rigobon (2002a) which concentrates on the econometric problems that arise when dealing with the question on whether the transmission of shocks intensified during crises. The author applies a new procedure to test for parameter stability when the data are plagued with simultaneous equations, omitted variable, and heteroskedasticity problems. In particular, Rigobon (2000a) shows that the propagation mechanisms of 36 stock markets remained relatively stable throughout the last three major international crises which have been associated with 'contagion' (i.e., Mexico 1994, Hong Kong 1997, and Russia 1998). However, some problems are not sufficiently underlined or not addressed at all with Rigobon's analysis. In particular there are three main problems that affects the DCC test and make

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[1] Bekaert G., Harvey C.R., Ng A., (2002),: "Contagion is a level of correlation over and above what is expected. […]. It is important to operate within the framework of a model. […] That is, it is necessary to undo the natural changes in correlation that result from an asset pricing model, before make statement about contagion."

[2] Other authors using this definition are: King, Wadhwani, Corsetti, Pericoli, Sbracia, Rigobon, Forbes, Favero, Bonfiglioli, Edwards, Susmel, Loretan, English.

it not useful in detecting contagion. The first is how to evaluate the cause of a rejection of the test since it could be due to parameters shift or violation of heterosckedasticity assumption under the null[3]: once a rejection is found it is almost impossible to estabilsh if it is due to contagion. The second problem is that the analysis conducted on predetermined crisis periods, which are selected arbitrairly, could be misleading: we modified the carrying out of the test to show it. The third problem is that the test have almost no power in the multivariate framework: we demonstrate it in the empirical anlysis and also by a simulation. Given these three problems it is impossible to use the DCC test to make any statement on the existence of contagion.

The paper is organized as follows: Section 2 describes the DCC procedure, Section 3 provides a description of our application and reports the results of our analysis of the Asian crisis, Section 4 concludes.

2 Rigobon's DCC test

The test aims to verify the stability of the parameters of a linear model with heteroskedasticity, omitted variable and endogenous variable problems. It consists in comparing the covariance matrix of a set of random variables (in our case stock market returns) at two different sub-samples (tranquil period and crisis). The DCC is the determinant of the change in the covariance matrix: the test consists in verifying if the DCC statistic is equal to zero.

Suppose that the stock market returns of N countries are described by the following latent factor model:

$$\underset{NxN}{A}\ \underset{Nx1}{R_t} = \underset{Nxk}{\Gamma}\ \underset{kx1}{Z_t} + \underset{Nx1}{\varepsilon_t}$$

where:

Z are k unobservable shocks;

Γ is the matrix containing the coefficients of the common shocks (the first row is normalised to one);

ε_t is the vector of idiosyncratic shocks; ε_t i.i.d.; $\varepsilon_t \approx WN(0, \Omega_t^{\varepsilon})$ where Ω_t^{ε} is diagonal;

$E(\varepsilon_t Z_t) = 0$, i.e. the idiosyncratic risks and the common shocks are not correlated;

$E(Z_t) = 0$ and $E(Z_t Z_t') = \Omega_t^Z$, where Ω_t^Z is diagonal.

Rigobon also supposes that $E(R_t) = 0$ and R_t is serially uncorrelated. If R_t is stationary, the results are independent of these assumptions. Rigobon (2000) wrote:

[3] This problem is underlined by Rigobon (2002a). In his analysis almost no rejections where found and the supported

"*...The problem of a simultaneous equation is summarised in the assumption that A is not block diagonal, the problem of omitted variables is modelled as the unobservable common shocks and the heteroskedasticity is built into the covariance matrix of both the structural and the common shocks.*"

Given the increase in volatility during crises, we can divide our dataset into two subsets, one containing stock market returns in the period of low volatility (tranquil period) and one containing stock market returns in the high volatility period (crisis). We compute two variance/covariance matrices, one for each period:

$\Omega_t^l =$ variance/covariance matrix for the low volatility period;

$\Omega_t^h =$ variance/covariance matrix for the high volatility period.

Then the DCC statistic is defined as follow:

$$\text{DCC} = DET(\Omega_t^h - \Omega_t^l) = DET(\Delta\Omega_t)$$

.

The test consists in verifying if the DCC statistic is equal to zero.

It can be shown that if the heteroskedasticity is only in a subset of the idiosyncratic shocks (ε) or only in a subset of the common shocks (Z) (not in both) and the parameters are stable across the sub sample, then the DCC statistic is equal to zero. The DCC is different from zero if the parameters are not stable but also when the specific assumption of heteroskedasticity is not satisfied: here rises the major problem of the DCC test, since rejections can due to parameters instability or to the violations of heteroskedasticity assumptions. So, it is correct to say that the DCC manages only a certain type of heteroskedasticity and not all type of heteroskedasticity. Another problem, that is common to other methods to test for contagion, is that it is necessary to know exactly the timing of a crisis or when there is a period of high volatility to define the tranquil and the crisis windows.

Since it is not possible to evaluate if the break is due to an intensification of the cross market linkages (Contagion) or to a loss of interdependence, that it is opposite to contagion (see Billio Pelizzon 2002) [4], it is not correct to define the DCC a test of contagion. To distinguisch between breaks due to contagion of loss of interdependence we have to look at other measures, for example the correlation.

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thesis was no contagion, so it was not crucial to discuss it.

[4] The loss of interdependence could be evidence of the "flight to quality".

Another problem is that it is not possible to evaluate which parametrs shift: for example a rejection of the DCC test does not tell us which countries exhibit a changement and it is impossible to evaluate if the break is in the instantaneous relationship (matrix A) or in the linkages with the unobservable shock (matrix Γ).

3 DCC test analysis

3.1 ***The data and the testing procedure***

The DCC test is executed on the residuals of a VAR(p), as suggested by Rigobon (2002a), where the endogenous variables are the two days moving averages of the stock markets returns. We repeated the analysis with differnt autoregressive orders (p has been set to 1, 3, and 5) and we did not use any exogenous variable.

Following Rigobon (2002a), we bootstrapped the distribution of the DCC and then we evaluated the proportion of realisations for which the DCC is below zero (mass below zero) that are a sort of p-value: the test is rejected if that mass is lower than 0.1 or greater than 0.9.

We analysed the relationship between the markets of three continents (America, Asia and Europe) considering five stock market indexes one for Europe (Eurostoxx), two for the U.S (Dow Jones and Nasdaq) and two from Asia (Nikkei for Japan, so we take into account the most important economy in the area and HSI for Hong Kong to take into account one of the matket that started the asian crises). The source of the data is *datastream.*

3.2 Defnition of the windows

To estimate the two covariance matrices it is necessary to define tranquil and crisis periods. The choice of the windows is based on the observation that, if the windows are too long or too short, the test loses power. Suppose, for example, that there exists a crisis regime and a tranquil regime, and that in each regime there is a different linkage between markets and so a different covariance matrix. Whether the test is based on too long a crisis window, which includes observations generated by different regimes (and not only by the crisis regime), the estimated covariance matrix for the crisis is a linear combination of the population coefficients in the two regimes. In this situation, the differences between the estimated covariance matrices calculated on the two chosen periods (tranquil and crisis period) are less marked and it is unlikely to find a rejection of the stability test. Rigobon (2000a) argues that another problem is that the longer the windows are, the higher the likelihood that most of the shocks are heteroskedastic. This increases the chance that the test is rejected because all shocks (all ε or all Z) or different kind of shocks (ε and Z) are heteroskedastic and not because the parameters are unstable.

On the other hand, when the test is based on narrower windows, the risk of including different regimes is lower, but the estimated covariance matrix are too noisy and the test loses power. Rigobon claims that the heteroskedasticity assumptions are likely to be satisfied in narrower windows and so a rejection found in those windows is probably due to parameter instability: in any case there is no way to be sure of that.

3.3 *Sequential analysis.*

The use of predetermined windows implies a series of disadvantages: on the one hand the risk of not identifying a break because the windows are not well defined, on the other hand it is very difficult, maybe impossible, to identify break periods precisely. For this reason we can say that the predetermined window strategy proceed by attempts. In order to try to solve some of these problems, we modified the carrying out of the test by suggesting a sequential analysis.

Once the tranquil period is defined, which, however, remains arbitrary as to the beginning and final date, the covariance matrix in tranquil period is estimated on the basis of this period. The covariance matrix during the crisis is instead estimated on the basis of a moving window with a fixed size of 60 observations. We considered this moving window for the whole Asian crisis period and we roll it starting from June 1997 till February 1998.

By means of the p-value of the test statistic[5], it is possible to monitor constantly the time in which the DCC becomes statistically different from zero and then evaluate if there are rejections and the timing of these rejections. This method partly allows us to obviate the arbitrary definition of windows over crisis periods, thus reducing the consequent disadvantages, such as the loss of the power of the test. This methodology allows to evaluate whether there are episodes of instability and whether it is correct to use long windows, or whether the phenomenon concerns only a period of few weeks. The problems of evaluating if heteroskedasticity assumptions are satisfied still remain.

3.4 Results

[5] Following Rigobon (2002a), we bootstrapped the distribution of the DCC and then we evaluated the proportion of realisations for which the DCC is below zero (mass below zero) which are a sort of p-value: the test is rejected if that mass is lower than 0.1 or greater than 0.9.

The test is ran on the predetermined windows reported in table 1, which are the same used by Rigobon (2002a)[6].

In principle, we are interested in evaluating if the propagation mechanism between Eurostoxx and Dow Jones remains stable during the Asian crisis. During the periods of financial turmoil it is possible that cross market linkages change not only between the market that generates the crisis and those receipting it, but also between the markets that receipt the crisis. For this reason we try to verify whether the relationship between European and U.S. stock Markets (represented by Eurostoxx and Dow Jones indexes respectively) changed during the Asian crisis, using the DCC test.

As Rigobon (2002a) argues, since we are analysing Eurostoxx (EU henceforth) and Dow Jones (DJ) and the crisis rises in Asia, we are not including any generator market in the regression and so the crisis depends on the increase of the variance of an unobservable shock (Z). It is then possible (but there is no way of being sure of that) that the heteroskedasticity involves only Z and so the rejections should be due to the parameter instability. Using other methodologies to test for contagion such as the tests on correlation (see Forbes and Rigobon, 2002 and Billio and Pelizzon, 2002) it is not possible to test the stability of the linkages among the markets which receipt the crises because the presence of omitted variables biases this kind of tests as showed by Billio and Pelizzon (2002).

As one can see from the first three columns of table 2 there are many rejections of the null of stability. The results seem to be stable even using different lags in the initial VAR specification. Anyway, we are not sure that these rejections are due to parameter instability because, as one can observe from table 4, the residuals exhibit auto-correlation and also ARCH effects which could cause rejections. Looking at the first three columns of table 2 one can see that the rejections in windows HK and K, related to the crises of Hong Kong and Korea, are stable: anyway it is a surprising that using VAR(3) residuals (column 2) we reject the null in the windows HK and K but we accept it in the window HK+K which is the sum of HK and K. Even in the simplest bivariate case it is difficult to evaluate the cause of a rejection, but following Rigobon's interpretation, we should conclude that rejections are due to the shift in the parameters.

We then used the test in a multivariate framework (as did by Rigobon in 2002a), considering more than two markets: our aim is to evaluate if the results are stable and if in some way the ntroduction

[6] Rigobon argues that the power of the test depends on the average increase in volatility. Rigobon ran a simulation using a sample of 60 observations and assuming that α and β are lower than 0.8 and the unconditional correlation is lower than 0.85. If the increase in the volatility in the crisis period is bigger than five times, then the power of the DCC test is higher than 90%. Since the power of the tests depends on the increase in the variance we constantly monitor it. In table 8 it is reported the average increase in the variance in each predetermined window, while all the figures concerning the DCC test report the average increase in the variance calculated in the moving window.

of other markets improve our ability to evaluate the causes of a rejection. We firstly add to the analysis the Nasdaq index (NA henceforth) and secondly also the Nikkei (NI). Since none of those markets is the generator of the crisis, as in the case of EU and DJ, we are allowed to suppose that the heteroskedasticity assumptions are still satisfied: in this case we expect that the rejections we found in the bivariate analysis at least are confirmed or they increase if other markets are infected by the crisis or produce a violation of the heterosckedasticity assumptions . As shown in table 2 (column 4 to 9), the rejections diminish when we increase the number of markets and the number of lags in the VAR specification: when we analyse the residuals of a VAR(3) and a VAR(5) modelled on four markets (EU, DJ, NA, and NI) (columns 8 and 9), the rejections disappear in the predetermined windows. This is surprising because, if the propagation mechanism between EU and DJ changes, as we found in the bivariate analysis, we should find the same rejections also in the multivariate analysis. Either the DCC is misleading in the bivariate analysis, or it is powerless in the multivariate set up.

To empirically evaluate the power of the test we finally add to the analysis the HSI index. In this way we introduce the Hong Kong market in the analysis. Since we include the generator market, the crisis is now modelised as an the increase of the variance of the idiosyncratic shock of Hong Kong. Anyway, since Hong Kong is not the only generator in the analysed predetermined windows, we expect that also an unobservable shock exhibits heteroskedasticity in some windows: if this is true the number of rejections should increase due to the different types of shocks (Z and ε). As one can see from table 2 (column 10 to 12) no rejections are found. This fact suggests that the test have very little power in the multivariate set up.

However, as already observed, the predetermined window analysis proceeds by attempts and, even if breaks in the parameters occurred, we could not be able to find them because the crisis windows are bad specified. To avoid this problem we ran sequential analysis using a fixed size crisis window of 60 observations[7]. This enable us to verify if there are breaks in some periods not analysed with the predetermined windows and to approximate the starting and ending dates of a break in the cross market linkages. Figure 1 refers to the analysis with the EU and DJ indexes and reports the mass below zero and the average increase in variance at every observation from June 1997 to February 1998. As one can see, the test rejects the stability since August 1997 till the end of our sample period. Anyway, as already underlined it is difficult to take the rejection as a proof of parameter instability since it could depend on the violation of heteroschedasticity assumptions. By extending the analysis to other markets we see that the "instability" window found in the bivariate analysis

[7] We choose this length to minimise noisy signals. We repeat the analysis with fixed windows of different size (40 and 50 observations), and as one can see by comparing figures 7, 8 and 9, the results are not sensitive to this change, but in the shorter windows there are more "false signals".

narrows: first of all, by adding the NA index (figure 2), it starts from August 1997 and ends at the beginning of February 1998; then by adding the NI index (figure 3) and at last the HSI index (figure 1), it starts at the beginning of November 1997 and ends at the beginning of December 1997. As we have said, including the Hong Kong stock market in the regression should add a cause of rejection due to heteroskedasticity assumptions that are violated, but as one can see from figure 7 nothing changes in the instability window after HSI is introduced. We ran the test on filtered data (with a VAR(3) and a VAR(5))[8] and we changed the size of the moving window but, even if the rejection periods are shorter, the conclusions are the same: some rejection periods are always found and they become narrower when we include other markets in the analysis.

It is important to underline that the predetermined window analysis is misleading: looking at table 2, in the case of multivariate analysis, one can conclude that the Asian crisis is a stable period. On the contrary, using a moving window analysis we always find periods of rejections and we are able to approximate their timing.

3.5 Multivariate analysis: power of the test

In this section we analyse if the increase in the number of markets under analysis has an impact on the power of the test against a parameter shift. This is crucial because in Rigobon 2002a, a large set of markets have been analysed wtih the DCC test and no evidence of contagion have been found. This conclusion could be biased if the test have litlle power in the multivariate framework. To assess the power of the DCC test in the multivariate set up we run a simple experiment.

We simulate the returns of five financial markets from a simple linear simultaneous equation model with, heteroskedasticity and without omitted variables. We generate two sub-samples: a tranquil sample of 100 observations and a crisis one of 60 observations. The model satisfies the heteroskedasticity assumptions and we allow the propagation mechanism during the tranquil period to be different from that during the crisis. The model has the following form:

$$AX_t = \Phi X_{t-1} + \mathrm{E}_t$$

A is a *5x5* matrix that allows for a simultaneous relationship among the endogenous variables; X_t is a *5x1* vector and contains the endogenous variables; X_{t-1} contains the lagged values of X and Φ is a *5x5* matrix containing the coefficients of the lagged variables. E_t is a *5x1* vector and contains the

[8] Figures 9 and 10 report the result in the case of EU and DJ.

idiosyncratic components of the analysed markets. The matrix Φ is the same during the two subset (crisis and non crisis) and is the following:

$$\Phi = \begin{pmatrix} 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \end{pmatrix}.$$

Contagion is modelised by differentiating the matrix A between the two periods. In the tranquil period the matrix A is the following:

$$A^{l} = \begin{pmatrix} 1 & -0.05 & -0.05 & -0.05 & -0.05 \\ -0.05 & 1 & -0.05 & -0.05 & -0.05 \\ -0.05 & -0.05 & 1 & -0.05 & -0.05 \\ -0.05 & -0.05 & -0.05 & 1 & -0.05 \\ -0.05 & -0.05 & -0.05 & -0.05 & 1 \end{pmatrix}.$$

We keep the simulation study as simple as possible by setting the relations across markets equal in each equation of the model. Contagion occurs in the first market and it is modelled with a shift in the parameter $\alpha_{1,5}$ which describes the relationship between the first and the fifth market and switches from -0.05 to -0.2. The crisis is represented by a 3 time increase in the standard error of the idiosyncratic component of the fifth market. The standard error of the country specific component of each market is arbitrary set to 0.01. After generating the samples we run the DCC test to evaluate if the power of the test changes when the number of market under analysis increases. In each simulation we run 1000 replications.

The model is calibrated to asymptotically obtain the correlation matrices reported in table 8 and 9**,** and to increase the variance as reported in table 10. Moreover, we calibrate the model to get an increase in the correlation between markets and an increase volatility if the generator market of nine times: these conditions are similar to those we found in the empirical analysis. Anyway the calibration of the model is not crucial since we are evaluating if other things equal the power of the test diminishes when increasing the number of the analysed markets.

Firstly we analyse the relationship between the generator market and the one which is subject to contagion. These markets have some linkages with those not included in the regression, so we are running the test in the presence of omitted variables. Since the generator market is included in the regression, the crisis is assimilated to an increase in the variance of the idiosyncratic shock of this market, then the heteroskedasticity assumptions are satisfied and the only cause of rejection is the parameter instability. As one can see from table 11 the proportion of realisations greater than 0.9 and lower than 0.1 in 1000 replication is 18,3%, which represents the power of the test.

We increased the number of markets and we evaluated if the power of the test changes. Table 11 shows that, other things equal, the power of the test diminishes when the number of the analysed markets increases. The test has almost no power against the parameter shift when we analyse simultaneously the five markets.

Since there is evidence that in the multivariate set up the test loses power, it may be useless to study a large set of markets to support the thesis of no contagion during crisis periods, as Rigobon (2000a) did. Our results suggest that the test properties in the multivariate set up, require further study.

4. Conclusions

In this paper we applyed the DCC test (Rigobon 2002a) to evaluate if it is a useful tool of analysis in evaluating if cross country linkages among some important financial markets were stable during the Asian crisis.

The DCC test does not allows us to evaluate if a break is due to intensification of cross market linkages (contagion) or to a loss of interdependence (Billio and Pelizzon 2002): hence it is difficult to consider it a test of contagion. If we find a rejection when using the test in the multivariate set up to analyse the relationships between many markets it is also impossible to evaluate in which relationships is the break.

Firstly, we run the test on the crisis windows predetermined by Rigobon (2002a) and we found many rejections of stability: anyway, there is no way to evaluate if they are due to the parameter shift or to the violation of heteroskedasticity assumptions under the null. In order to solve problems arising when using predetermined windows, the carrying out of the test has been modified and a sequential analysis is done. In this way, we show that the analysis based on predetermined windows is misleading because it proceeds by attempts and many rejections are not found because windows are not well specificated. Using a sequential analysis rejections are always found and the results are stable to changes in the test carrying out: anyway it remains difficult to evaluate the cause of a rejection.

We noticed that in both predetermined windows analysis and sequential anaysis, when the number of market under analysis increases the rejections disappear even if it is likely that the assumptions on heteroskedasticity are violated (this could produce a rejection). To investigate this absence of rejecetions, we run a simulation to evaluate the loss of power in a multivariate framework and it confirms that, other things equal, increasing the number of the analysed markets the power of the test against a parameter shift diminishes. Since there is evidence that in the multivariate set up the test loses power, it may be useless to study a large set of markets to support the thesis of no contagion during the crisis, as done by Rigobon (2002a). Anyway, the test properties in the multivariate set up, require further study.

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TABLE 1: Definition of the windows. They are the same analysed in Rigbon (2002a).

PERIOD	TRANQUIL WINDOW	CRISIS WINDOW
HK	1/2/97-6/2/97	10/27/97-11/28/97
K	1/2/97-6/2/97	12/1/97-1/30/98
HK+K	1/2/97-6/2/97	10/27/97-1/30/98
THAI	1/2/97-6/2/97	6/10/97-29/8/97
HK+K+THAI	1/2/97-6/2/97	6/10/97-1/30/98

TABLE 2: DCC test results. R means that we found a rejection, N means that we accepted the null of parameter stability.

PERIOD	EU DJ			EU DJ NA			EU DJ NA NI			EU DJ NA NI HK		
lag	*1*	*3*	*5*	*1*	*3*	*5*	*1*	*3*	*5*	*1*	*3*	*5*
HK	**R**	**R**	**R**	**R**	**R**	**R**	N	N	N	N	N	N
K	**R**	**R**	**R**	N	N	N	**R**	N	N	N	N	N
HK+K	**R**	N	**R**	**R**	N	N	N	N	N	N	N	N
THAI	**R**	N	**R**	**R**	N	N	N	N	N	N	N	N
HK+K+THAI	N	N	N	**R**	N	N	N	N	N	N	N	N

TABLE 3: Average increase rate of the residuals variance during the analysed crisis windows. We refer to the VAR(1) residuals.

PERIOD	EU DJ	EU DJ NA	EU DJ NA NI	EU DJ NA NI HK
HK	3,7841	3,1040	3,3891	4,6963
K	1,5779	1,5979	1,7000	3,0886
HK+K	2,3727	2,1626	2,3410	3,6278
THAI	1,6624	1,3231	1,1021	1,4025
HK+K+THAI	2,1009	1,8846	1,6751	2,5576

TABLE 4: Eurostoxx and Dow Jones residual tests. We checked for the presence of autocorrelation in mean (Box Pierce test, rows BP1 in the table), in variance (Box Pierce test, rows BP2 in the table), and ARCH effects (LM test, rows LM) in every equation of the different VARs from which the residuals are obtained. Columns (1), (3) and (5) refer to the lags included in the VAR specification. Columns 5, 10 and 20 refer to the lag included in the diagnostic tests.

	VAR	**(1)**			**(3)**			**(5)**		
	lag	**5**	**10**	**20**	**5**	**10**	**20**	**5**	**10**	**20**
eq. 1 (EU)	**BP 1**	0,00	0,00	0,00	0,00	0,00	0,00	0,10	0,16	0,07
	BP 2	0,21	0,01	0,00	0,06	0,05	0,01	0,70	0,10	0,11
	LM	0,00	0,00	0,00	0,00	0,00	0,00	0,04	0,05	0,04
eq. 2 (DJ)	**BP 1**	0,00	0,00	0,00	0,01	0,00	0,00	0,24	0,00	0,00
	BP 2	0,00	0,00	0,00	0,21	0,66	0,93	0,34	0,67	0,92
	LM	0,00	0,00	0,00	0,00	0,00	0,00	0,17	0,00	0,01

TABLE 5: Eurostoxx, Dow Jones and Nasdaq residual tests. We checked for the presence of autocorrelation in mean (Box Pierce test, rows BP1 in the table), in variance (Box Pierce test, rows BP2 in the table), and ARCH effects (LM test, rows LM) in every equation of the different VARs from which the residuals are obtained. Columns (1), (3) and (5) refer to the lags included in the VAR specification. Columns 5, 10 and 20 refer to the lag included in the diagnostic tests.

	VAR	**(1)**			**(3)**			**(5)**		
	lag	**5**	**10**	**20**	**5**	**10**	**20**	**5**	**10**	**20**
eq. 1 (EU)	**BP 1**	0,00	0,00	0,00	0,00	0,00	0,00	0,34	0,32	0,12
	BP 2	0,01	0,00	0,00	0,00	0,00	0,00	0,11	0,11	0,06
	LM	0,00	0,00	0,00	0,00	0,00	0,00	0,18	0,25	0,17
eq. 2 (DJ)	**BP 1**	0,00	0,00	0,00	0,11	0,00	0,01	0,75	0,01	0,05
	BP 2	0,00	0,00	0,00	0,36	0,84	0,90	0,45	0,75	0,83
	LM	0,00	0,00	0,00	0,05	0,00	0,02	0,70	0,01	0,11
eq. 3 (NA)	**BP 1**	0,00	0,00	0,00	0,03	0,04	0,13	0,47	0,24	0,47
	BP 2	0,00	0,00	0,00	0,00	0,03	0,04	0,00	0,01	0,03

	LM	0,00	0,00	0,00	0,01	0,01	0,15	0,37	0,23	0,48

TABLE 6: Eurostoxx, Dow Jones, Nasdaq and Nikkei residual tests. We checked for the presence of autocorrelation in mean (Box Pierce test, rows BP1 in the table), in variance (Box Pierce test, rows BP2 in the table), and ARCH effects (LM test, rows LM) in every equation of the different VARs from which the residuals are obtained. Columns (1), (3) and (5) refer to the lags included in the VAR specification. Columns 5, 10 and 20 refer to the lag included in the diagnostic tests.

	VAR	**(1)**			**(3)**			**(5)**		
	lag	**5**	**10**	**20**	**5**	**10**	**20**	**5**	**10**	**20**
eq. 1 (EU)	**BP 1**	0,00	0,00	0,00	0,10	0,05	0,11	0,62	0,31	0,37
	BP 2	0,79	0,05	0,11	0,83	0,41	0,09	0,79	0,48	0,20
	LM	0,00	0,00	0,00	0,07	0,02	0,03	0,51	0,22	0,20
eq. 2 (DJ)	**BP 1**	0,00	0,00	0,00	0,35	0,09	0,06	0,93	0,17	0,05
	BP 2	0,00	0,00	0,00	0,72	0,96	0,96	0,69	0,93	0,95
	LM	0,00	0,00	0,00	0,21	0,06	0,02	0,88	0,16	0,02
eq. 3 (NA)	**BP 1**	0,00	0,00	0,01	0,35	0,26	0,79	0,98	0,87	0,98
	BP 2	0,00	0,00	0,00	0,05	0,12	0,18	0,04	0,10	0,18
	LM	0,00	0,00	0,00	0,20	0,19	0,66	0,92	0,80	0,97
eq. 4 (NI)	**BP 1**	0,00	0,00	0,00	0,00	0,00	0,00	0,63	0,52	0,74
	BP 2	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	LM	0,00	0,00	0,00	0,00	0,00	0,00	0,48	0,41	0,54

TABLE 7: Eurostoxx, Dow Jones, Nasdaq, Nikkei and HSI residual tests. We checked for the presence of autocorrelation in mean (Box Pierce test, rows BP1 in the table), in variance (Box Pierce test, rows BP2 in the table), and ARCH effects (LM test, rows LM) in every equation of the different VARs from which the residuals are obtained. Columns (1), (3) and (5) refer to the lags included in the VAR specification. Columns 5, 10 and 20 refer to the lag included in the diagnostic tests.

	VAR	(1)			(3)			(5)		
	lag	**5**	**10**	**20**	**5**	**10**	**20**	**5**	**10**	**20**
eq. 1 (EU)	**BP 1**	0,00	0,01	0,02	0,39	0,49	0,45	0,90	0,74	0,84
	BP 2	0,54	0,00	0,02	0,35	0,00	0,00	0,14	0,00	0,00
	LM	0,00	0,00	0,00	0,36	0,30	0,26	0,88	0,63	0,67
eq. 2 (DJ)	**BP 1**	0,00	0,00	0,01	0,87	0,58	0,50	0,99	0,43	0,20
	BP 2	0,00	0,00	0,00	0,34	0,42	0,73	0,40	0,28	0,63
	LM	0,00	0,00	0,00	0,85	0,42	0,38	0,98	0,40	0,18
eq. 3 (NA)	**BP 1**	0,00	0,00	0,07	0,75	0,93	0,95	1,00	0,97	0,95
	BP 2	0,00	0,00	0,00	0,53	0,09	0,18	0,45	0,21	0,19
	LM	0,00	0,00	0,00	0,67	0,85	0,89	0,99	0,95	0,95
eq. 4 (NI)	**BP 1**	0,00	0,00	0,00	0,02	0,01	0,01	1,00	0,91	0,83
	BP 2	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	LM	0,00	0,00	0,00	0,01	0,07	0,07	0,99	0,89	0,61
eq. 5 (HK)	**BP 1**	0,01	0,02	0,13	0,18	0,18	0,38	0,99	0,49	0,46
	BP 2	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	LM	0,00	0,00	0,04	0,11	0,14	0,41	0,99	0,55	0,52

TABLE 8: Correlation matrix in the tranquil period**.** We generated 1000 tranquil period samples of 1000 observations.

market	1	2	3	4	5
1	1	0,26	0,27	0,27	0,27
2	0,26	1	0,26	0,26	0,26
3	0,27	0,26	1	0,27	0,27
4	0,27	0,26	0,27	1	0,27
5	0,27	0,26	0,27	0,27	1

TABLE 9: Correlation matrix in the crisis period. We generated 1000 crisis samples of 1000 observations.

market	1	2	3	4	5
1	1	0,51	0,52	0,52	0,58
2	0,51	1	0,49	0,49	0,33
3	0,52	0,49	1	0,49	0,33
4	0,52	0,49	0,49	1	0,33
5	0,58	0,33	0,33	0,33	1

TABLE 10: Average increase in the variance and in the standard error during the crisis in the simulation.

market	1	2	3	4	5
variance	1,9	1,4	1,4	1,4	8,2
std err	1,4	1,2	1,2	1,2	2,9

TABLE 11: Power of the test against the alternative hypothesis of a shift in the parameters. The test is rejected if the mass below zero is greater than 0.9 or lower than 0.1.

Markets	power of the test
1-5	0.183
1-2-5	0.083
1-2-3-5	0.012
all markets	0.002

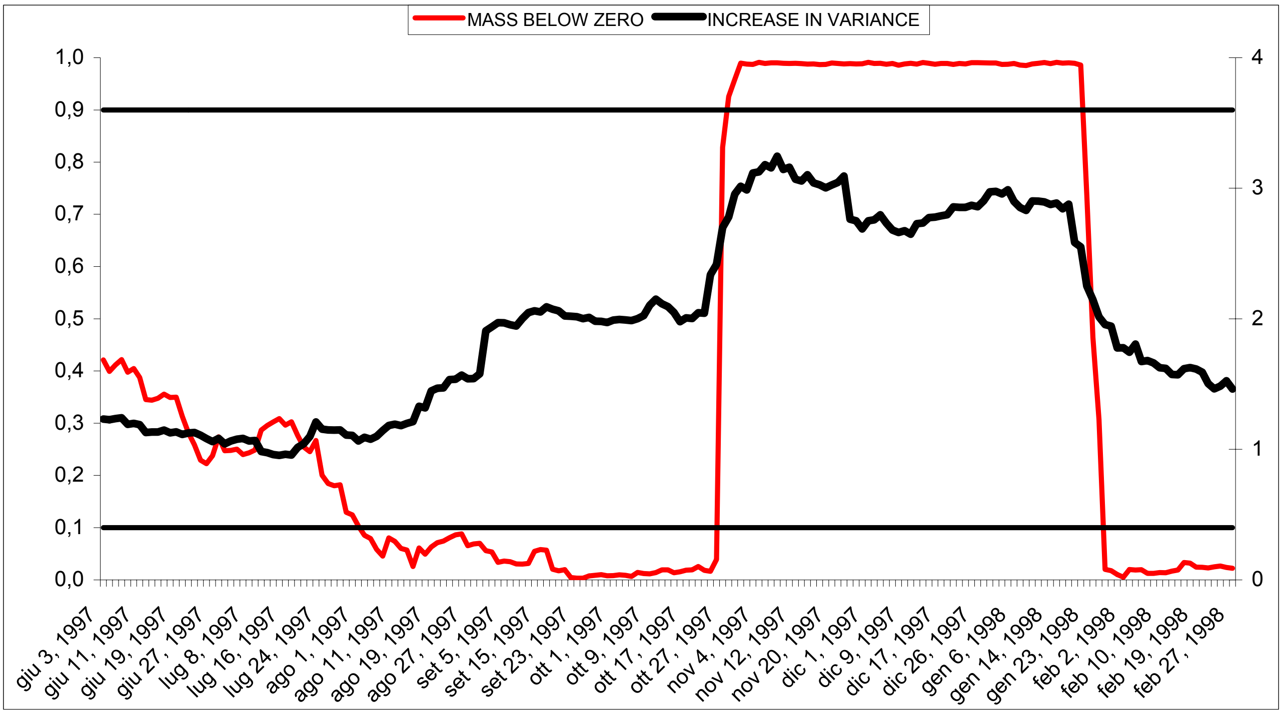

Figure 1: DCC moving window result for Eurostoxx and Dow Jones. The figure shows the mass below zero of the DCC and the average increase of the variance at every observation, starting from June 1997 till February 1998. If the mass is greater than 0.9 or lower than 0.1 we reject the null of interdependence. We considered a moving window of 60 observations.

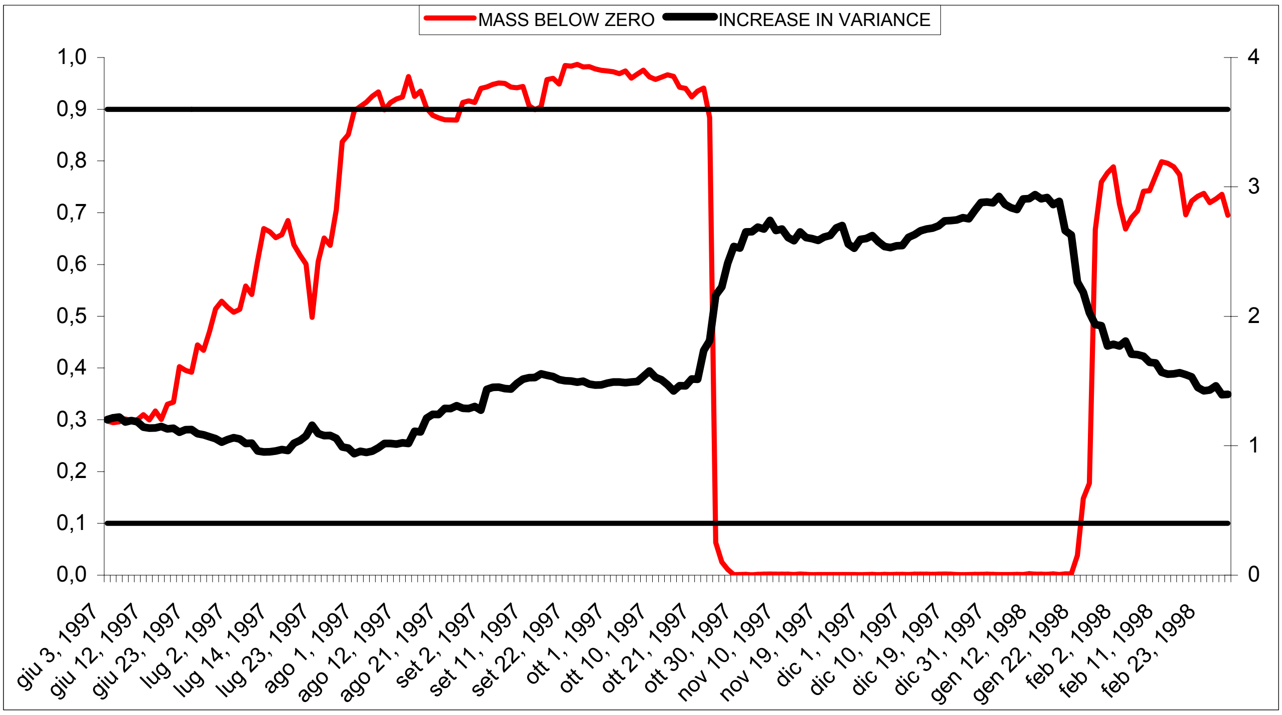

Figure 2: DCC moving window result for Eurostoxx, Dow Jones and Nasdaq. The figure shows the mass below zero of the DCC and the average increase of the variance at every observation, starting from June 1997 till February 1998. If the mass is greater than 0.9 or lower than 0.1 we reject the null of interdependence. We considered a moving window of 60 observations.

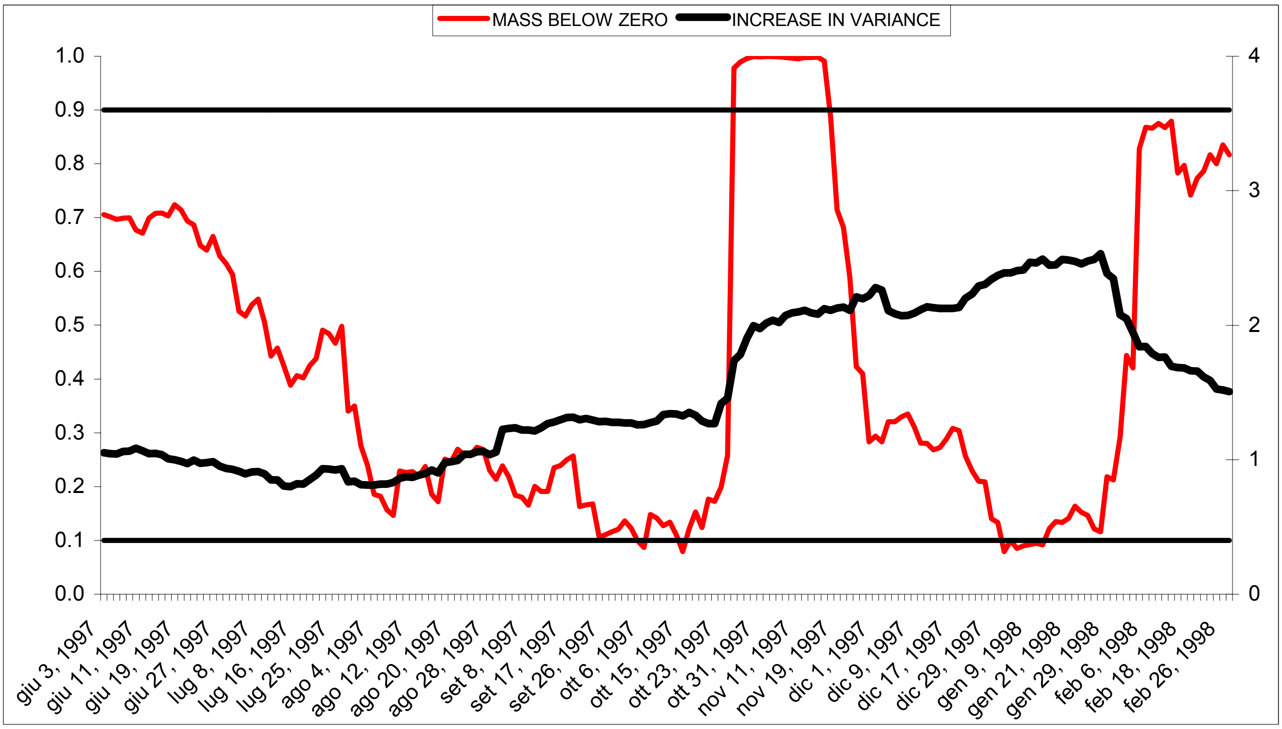

Figure 3: DCC moving window result for Eurostoxx, Dow Jones, Nasdaq and Nikkei. The figure shows the mass below zero of the DCC and the average increase of the variance at every observation, starting from June 1997 till February 1998. If the mass is greater than 0.9 or lower than 0.1 we reject the null of interdependence. We considered a moving window of 60 observations.

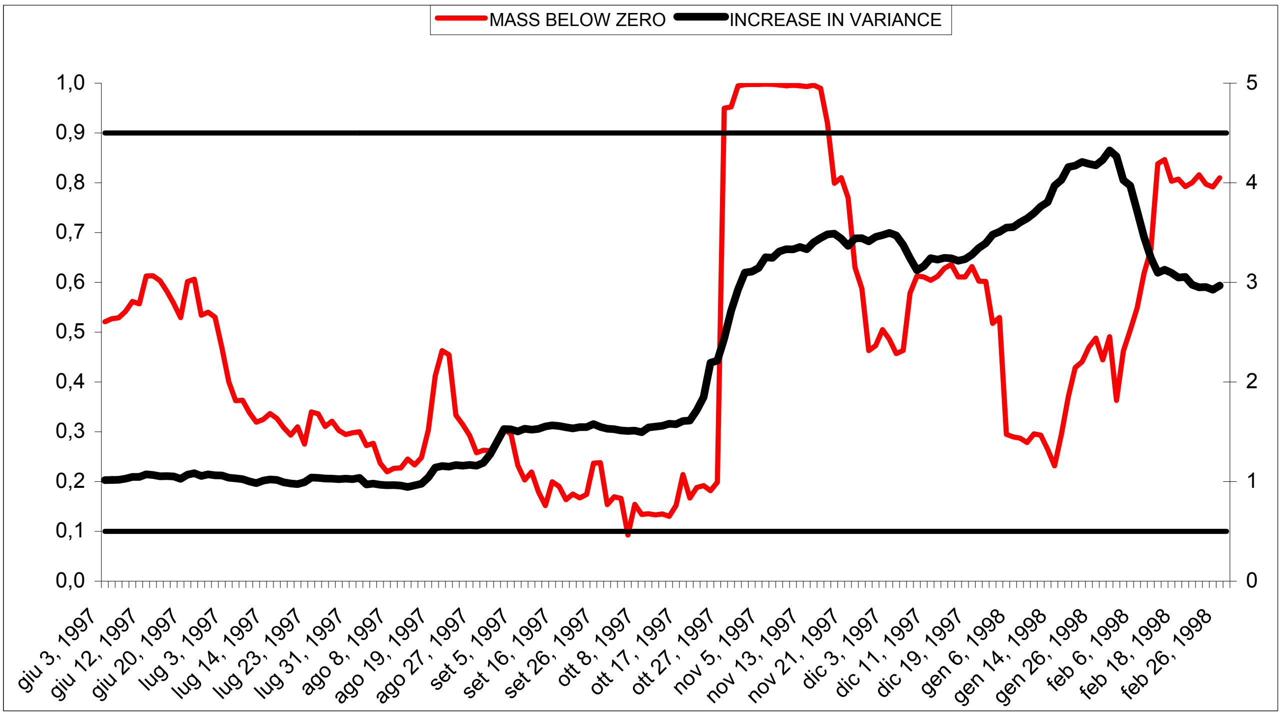

Figure 4: DCC moving window result for Eurostoxx, Dow Jones, Nasdaq, Nikkei and HSI. The figure shows the mass below zero of the DCC and the average increase of the variance at every observation, starting from June 1997 till February 1998. If the mass is greater than 0.9 or lower than 0.1 we reject the null of interdependence. We considered a moving window of 60 observations.

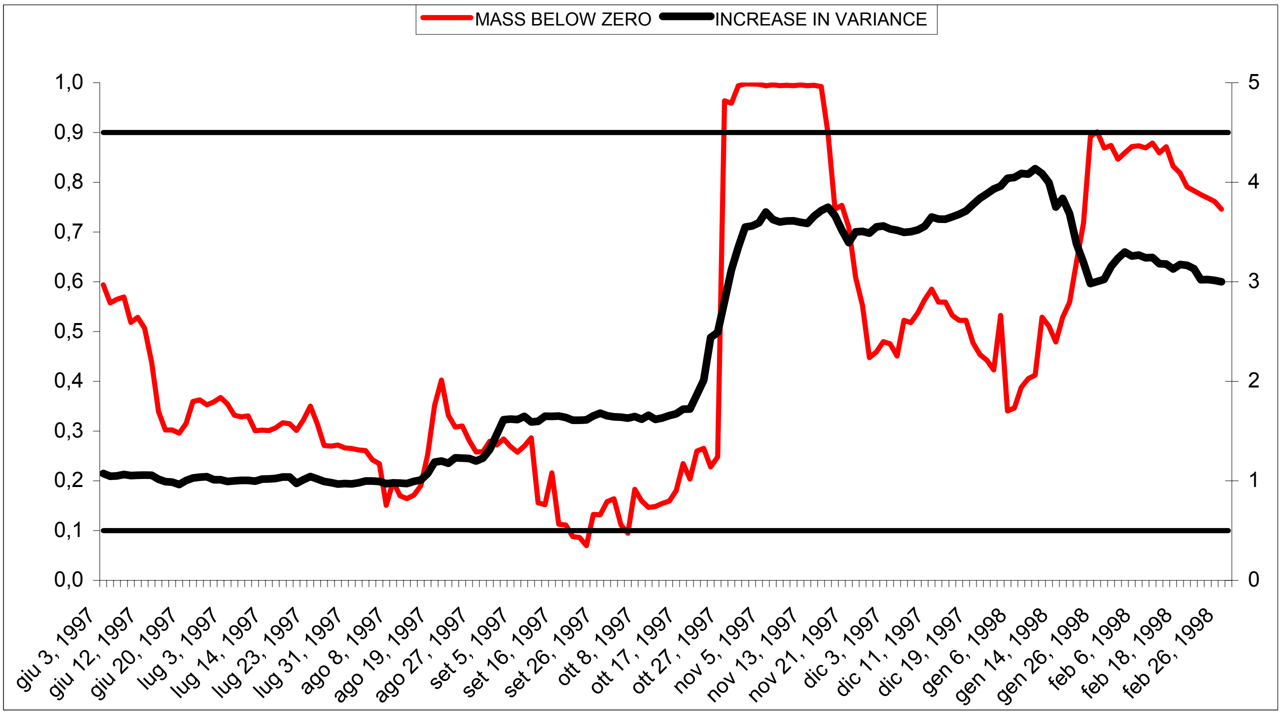

Figure 5: DCC moving window result for Eurostoxx, Dow Jones, Nasdaq, Nikkei and HSI. The figure shows the mass below zero of the DCC and the average increase of the variance at every observation, starting from June 1997 till February 1998. If the mass is greater than 0.9 or lower than 0.1 we reject the null of interdependence. We considered a moving window of 50 observations.

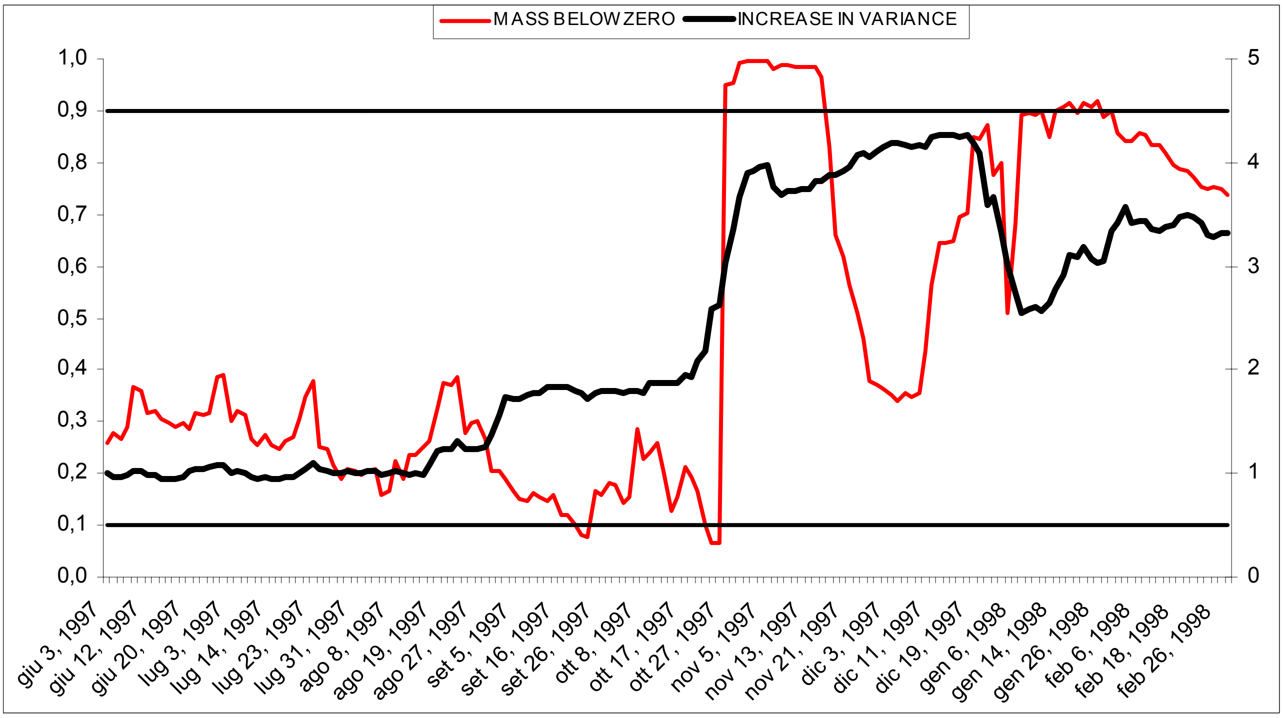

Figure 6: DCC moving window result for Eurostoxx, Dow Jones, Nasdaq, Nikkei and HSI. The figure shows the mass below zero of the DCC and the average increase of the variance at every observation, starting from June 1997 till February 1998. If the mass is greater than 0.9 or lower than 0.1 we reject the null of interdependence. We considered a moving window of 40 observations.

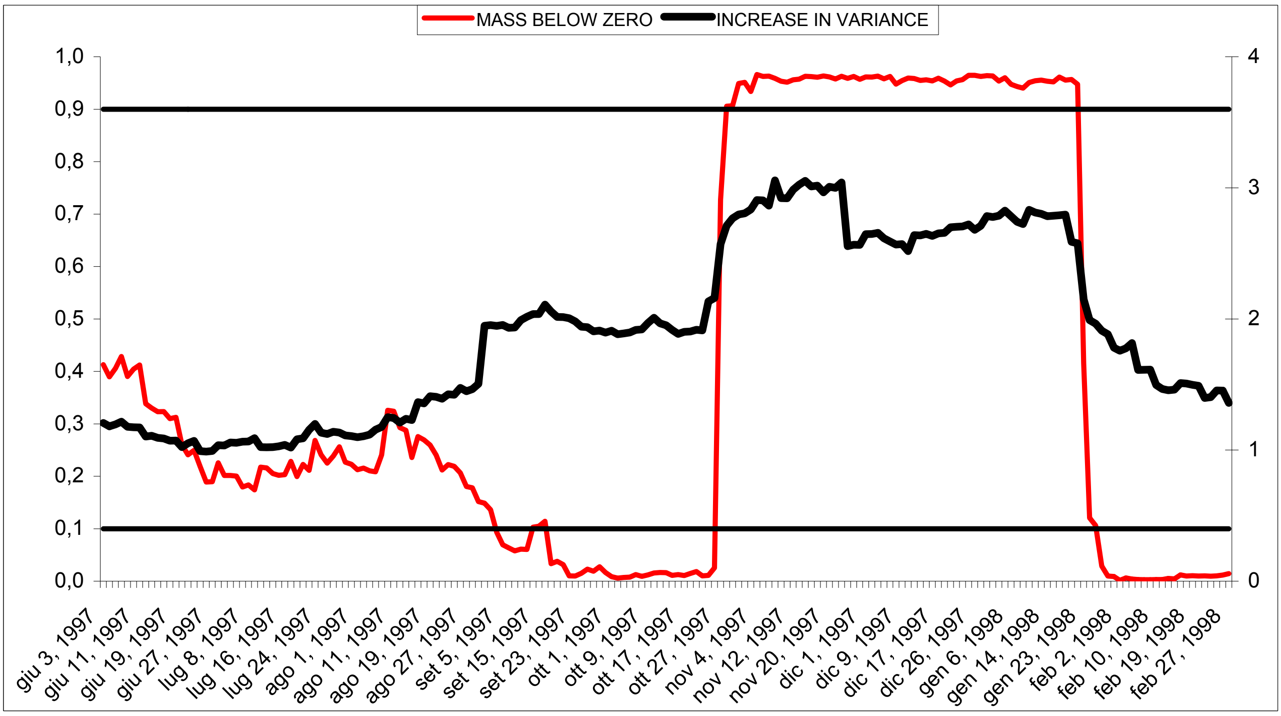

Figure 7: DCC moving window result for Eurostoxx and Dow Jones. The figure shows the mass below zero of the DCC and the average increase of the variance at every observation, starting from June 1997 till February 1998. If the mass is greater than 0.9 or lower than 0.1 we reject the null of interdependence. We considered a moving window of 60 observations. The test is ran on the residuals of a VAR with 3 lags.

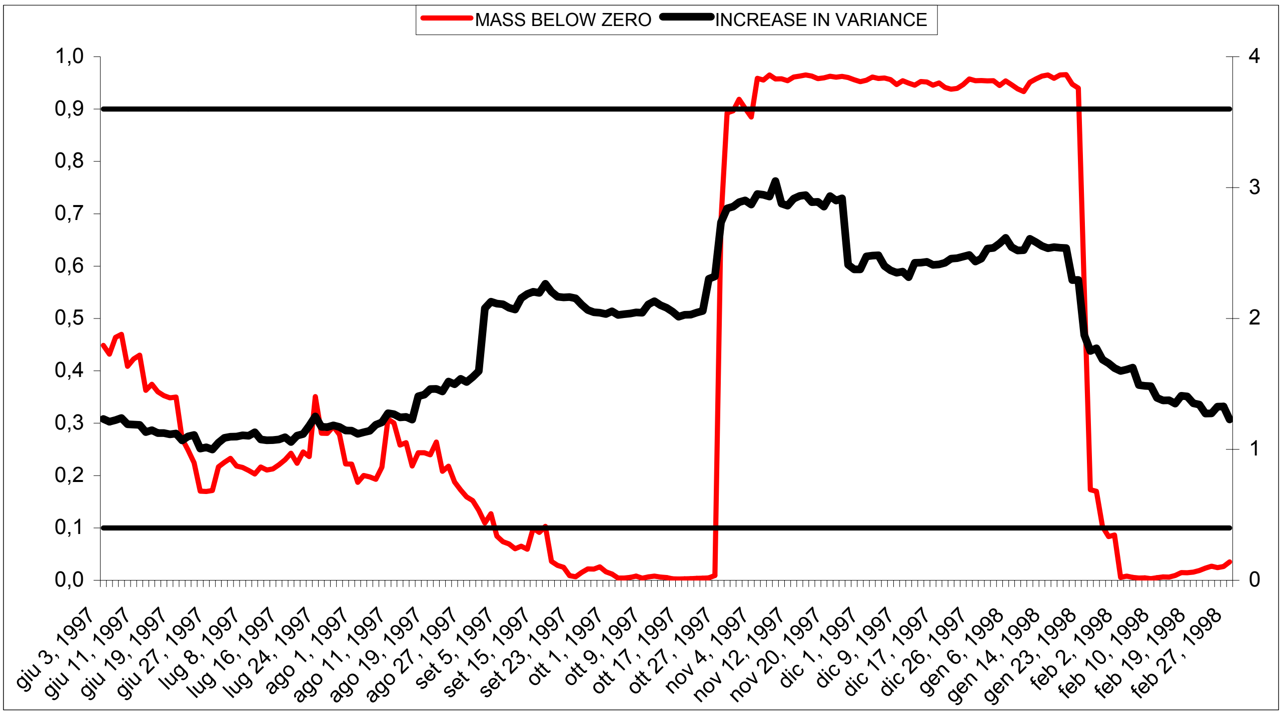

Figure 8: DCC moving window result for Eurostoxx and Dow Jones. The figure shows the mass below zero of the DCC and the average increase of the variance at every observation, starting from June 1997 till February 1998. If the mass is grater than 0.9 or lower than 0.1 we reject the null of interdependence. We considered a moving window of 60 observations. The test is ran on the residuals of a VAR with 5 lags.

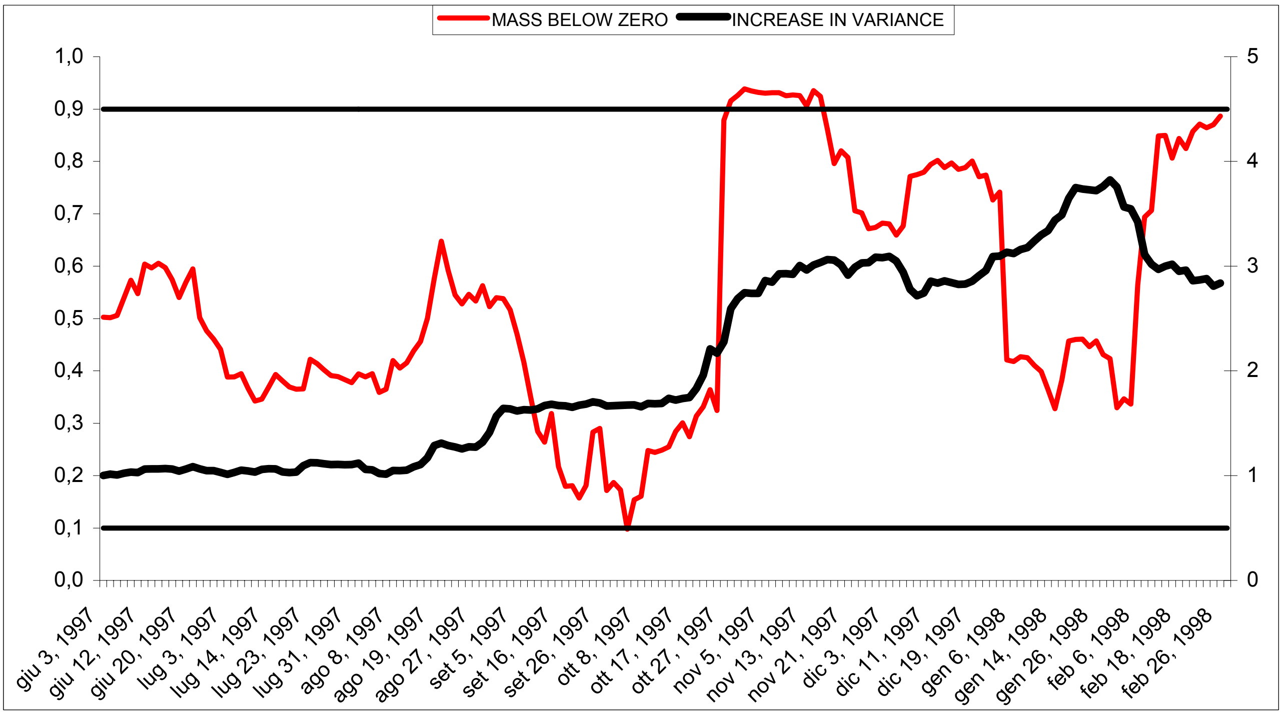

Figure 9: DCC moving window result for Eurostoxx, Dow Jones, Nasdaq, Nikkei and HSI. The figure shows the mass below zero of the DCC and the average increase of the variance at every observation, starting from June 1997 till February 1998. If the mass is greater than 0.9 or lower than 0.1 we reject the null of interdependence. We considered a moving window of 60 observations. The test is ran on the residuals of a VAR with 3 lags.

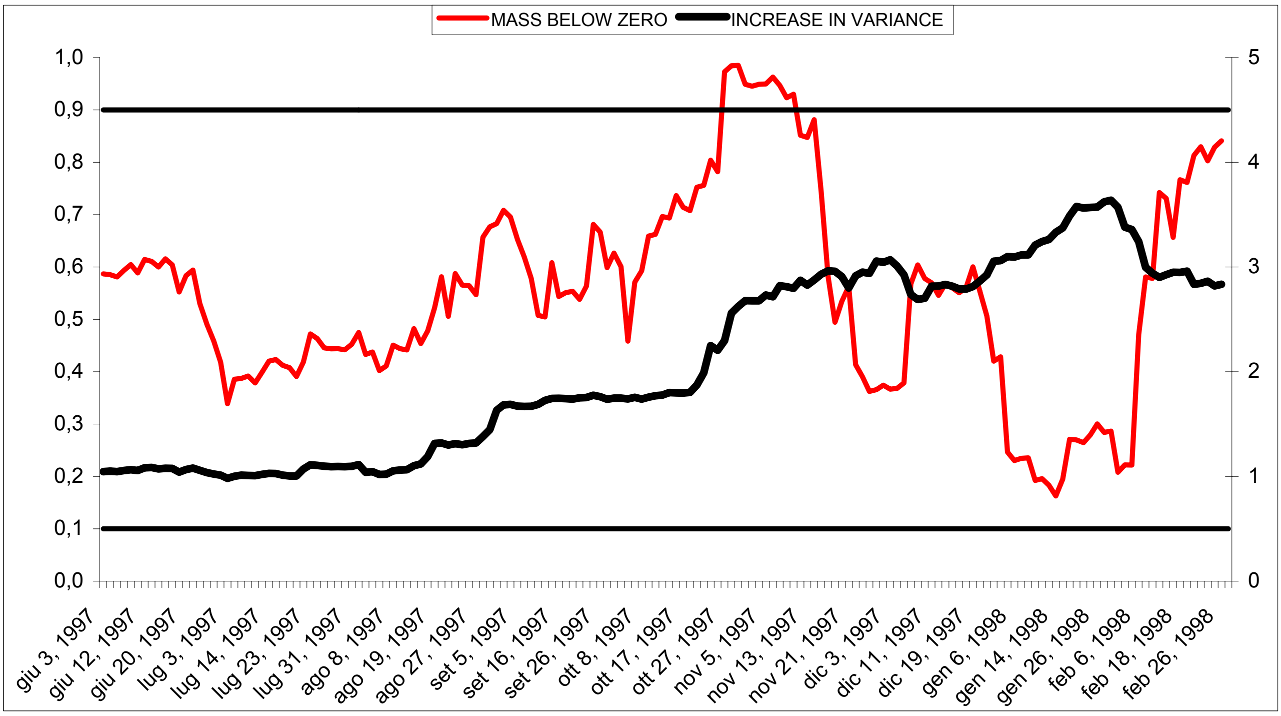

Figure 10: DCC moving window result for Eurostoxx, Dow Jones, Nasdaq, Nikkei and HSI. The figure shows the mass below zero of the DCC and the average increase of the variance at every observation, starting from June 1997 till February 1998. If the mass is greater than 0.9 or lower than 0.1 we reject the null of interdependence. We considered a moving window of 60 observations. The test is ran on the residuals of a VAR with 5 lags.