Testing for Financial Spillovers in Calm and Turmoil Periods*

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Abstract: In this paper, we investigate financial spillovers between stock markets during calm and turbulent times. We explicitly define financial spillovers and financial contagion in accordance with the economic literature and construct statistical models corresponding to these definitions in a Markov switching framework. Applying the new testing methodology based on transition matrices, we find that spillovers from the US stock market to the UK, Japanese, and German markets are more frequent when the latter markets are in the crisis regime. However, we reject the hypothesis of strong financial contagion from the US market to the other markets.

JEL Classification: F36, G12, G15

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1. Introduction

The importance of cross-market linkages and spillovers between international stock markets is well established. The literature on this issue allows to draw at least two main conclusions. First, the empirical studies find that the US stock market is the dominant capital market influencing other mature and developing stock markets (Eun and Shim (1989), Hamao, Masulis, and Ng (1990), Lin, Engle, and Ito (1994), Peiró, Quesada, and Uriel (1998), Ng (2000)). International stock markets are strongly correlated with the US market and past US stock returns affect present returns on other markets. Lagged spillovers are particularly interesting to investigate, because stock markets with some delay assimilate important news from other markets. The most likely reasons may be inefficiencies of international stock markets, different opening hours on those markets, and non-synchronous trading (Cheung and Ng (1996), Peiró, Quesada, and Uriel (1998)). Analyzing lead-lag effects enables investors to learn about the structure and direction of financial spillovers, which is important for effective portfolio allocation and risk management (e.g., Ang and Bekaert (2002, 2003)).

Second, investigations in the field of stock market linkages suggest that stock returns are more volatile and more correlated with each other during turbulent periods compared to tranquil periods (King and Wadhwani (1990), Karolyi and Stulz (1996), Longin and Solnik (2001), Forbes and Rigobon (2002)). A rising positive correlation may suggest a decrease of capital diversification opportunities across markets during financial crises (Ang and Bekaert (2002), Bekaert and Harvey (2003)). The differences in financial spillovers during calm and turmoil periods are of special interest to agents who want to learn about the chance of having a crisis at the home market today, when there was a negative shock to another market yesterday. International investors can adjust their portfolio strategies to a changing structure of spillovers in different regimes. Moreover, financial market regulators are concerned about the vulnerability of home capital markets to international crises.
Despite the importance of both aspects only a few studies investigate changes in lead-lag effects of financial spillovers during calm periods and financial crises. The scarce findings suggest that spillovers from one market to other markets are found to be stronger when the former market is hit by some negative shock (Malliaris and Urrutia (1992), Sola, Spagnolo, and Spagnolo (2002), Chen, Chiang, and So (2003), Climent and Meneu (2003), Sander and Kleimeier (2003)). However, whether stock markets undergoing financial distress are still vulnerable to spillovers from other markets is an open question. Finding an answer to this issue may help in analyzing sources of financial crises. Stronger spillovers to turmoil stock markets could point to contagion as the main source of crises, while weaker spillovers could suggest an individual character of financial distress. We attempt to answer this question in this paper.

Most studies analyzing spillovers between stock markets during tranquil and crisis times do not take into account that the two analyzed markets can be in two different regimes of crisis or calm, i.e., for example, the stock market following the other market can be in the state of crisis independently of the state of the leading market. Another drawback of some studies is the ad hoc method used to identify crisis and calm periods (e.g., Malliaris and Urrutia (1992), Forbes and Rigobon (2002), Dungey and Zhumabekova (2001)). For example, in Chen, Chiang, and So (2003) the two regimes are explicitly defined as past stock returns exceeding (or falling below) an estimated threshold level. Moreover, earlier studies usually concentrate on specific events.

In this paper, we consider spillover effects from the US stock market to three major markets in Japan, the United Kingdom, and Germany over the period from 1984 to 2003 as well as sub-samples. We compare spillover effects during tranquil and turbulent periods and address the problems expressed above by extending the Markov switching model proposed by Phillips (1991). Phillips developed a bivariate Markov switching model to evaluate the transmission of business cycles between countries. Sola, Spagnolo, and Spagnolo (2002)
applied this approach in the framework of financial markets to test their specific hypothesis of contagion across stock markets during the Asian crisis in 1997. Edwards and Susmel (2001) added lagged returns and conditional autoregressive heteroscedasticity into the model specification and investigated tests of independence and co-movements between international emerging stock markets in 1990s.

We construct a model of stock index returns for two markets analogous to the one proposed by Sola, Spagnolo, and Spagnolo (2002) and develop a test to investigate the hypotheses that, first, one market leads the other in both turmoil and tranquil periods and, second, one market leads the other only when the latter is already in a turmoil (calm) period. In this way we extend the methodology proposed by Edwards and Susmel (2001) and Sola, Spangolo, and Spagnolo (2002), used to test financial contagion and independence by applying tests for financial spillovers in a Markov switching framework (see also Ravn and Sola (1995), Hamilton and Lin (1996), Psaradakis, Ravn, and Sola (2004)).

Our testing procedure has several advantages over other approaches to analyze the transmission of spillovers across stock markets. First, for each stock market it differentiates between calm and turbulent regimes. Thus, the method allows for a measurement of spillovers depending on the state of the market. The empirical literature suggests that multi-regime switching models of stock returns perform better than one-regime models (Cecchetti, Lam, and Mark (1990), Turner, Stratz, and Nelson (1990), Rydén, Teräsvirta, and Åsbrink (1998), Ang and Bekaert (2002)). Second, our procedure does not require an ad hoc identification of periods to examine spillovers between stock markets. Instead it estimates the probabilities of being in the crisis in a joint framework with all parameters of the model. Third, correlation and regression measures often fail to explore non-linear relations between variables. We offer a test on cross-market spillovers which does not depend on a specific linear or non-linear structure of linkages between stock returns. Fourth, Sola, Spagnolo, and Spagnolo (2002) provide a test of
extreme spillovers, which they call a test of contagion. Our test is more flexible than the one applied there, since it examines a wider range of possible spillovers between the stock markets.

Finally, as an additional characteristics, most of the studies do not explicitly define spillovers between stock markets. In this paper, we provide a definition of one market leading other market that allows for distinguishing between lead-lag relations in calm and turbulent periods. This definition is consistent with the notion of causality, while in the context of financial crises it suits well the concept of contagion. To distinguish between extreme cases of spillovers we provide explicit definitions of independence (no spillovers) and contagion, which are in line with Sola, Spagnolo, and Spagnolo (2002), and compare the empirical results for tests based on those definitions.

The remainder of this paper is organized as follows. In the next section we describe the model based on the idea of Phillips (1991) to estimate stock index returns on two markets. Section 3 discusses our definitions of financial spillovers and discusses the tests for dependencies between the markets. Data and empirical results on spillovers from the US stock market to the Japanese, British, and German stock market are presented in section 4. Section 5 summarizes and concludes.

2. Modeling index returns on two markets

Our econometrical starting point is a Markov switching model of index returns on two markets. Let $Z$ be the vector $[X, Y]'$, where $X = \{x_t, t \in N\}$ and $Y = \{y_t, t \in N\}$ are the two time series that can be interpreted as stock market index returns on two separate markets. Both index returns are allowed to enter one of the two complementary states of "crisis" and "calm" periods. Using all four combinations of these states we construct a Markov process with four regimes and we use the index $s$ to denote these regimes. "$X$ and $Y$ are in the calm states" defines the first regime ($s = 1$). "$X$ is in the calm state and $Y$ is in the crisis state" denotes the
second one \((s = 2)\). The third regime indicates that "\(X\) is in the crisis state and \(Y\) is in the calm state" \((s = 3)\). "\(X\) and \(Y\) are in the crisis states" defines the fourth regime \((s = 4)\).

At each point in time, the state \(s\) is determined by an unobservable Markov chain. The dynamics of the Markov chain are described by a \(4 \times 4\) transition matrix \(P\):

\[
P = \begin{pmatrix}
p_{11} & p_{12} & p_{13} & p_{14} \\
p_{21} & p_{22} & p_{23} & p_{24} \\
p_{31} & p_{32} & p_{33} & p_{34} \\
p_{41} & p_{42} & p_{43} & p_{44}
\end{pmatrix},
\]

(1)

where \(p_{ij}\) denotes the probability of changing the state from \(i\) to \(j\). Assume that the \(2 \times 1\) vector \(z_i = [x_i, y_i]'\) is driven by the four-state regime switching process:

\[
z_t = \mu_s + \Theta u_t,
\]

(2)

where \(u_t\) is a Gaussian process with zero mean and positive-definite covariance matrix \(\Sigma\). The vector \(z_t\) is generated by the mixture of normal distributions with the mean \(\mu_s\) and the covariance matrix \(\Sigma_s\), both depending on the state \(s\):

\[
z_t \mid (s_t = s) \sim N(\mu_s, \Sigma_s)
\]

(3)

and:

\[
\Sigma_s = \Theta_s'\Sigma\Theta_s
\]

(4)

for \(s = 1, 2, 3, 4\). Thus, the model is called a (four-state) Markov switching mixture of normal distributions and it consists of 32 independent parameters, namely two parameters of means for each state, three independent parameters from \(\Sigma_s\) for each state, and twelve independent parameters from the transition matrix \(P\). In this model no constraints are imposed on the parameters of means, variances, correlations, and parameters from the transition matrix \(P\).

Economists highlight the significance of changes in return volatility during crisis periods. The high variance of index returns characterizes turmoil periods and the low variance characterizes tranquil periods. Additionally, the correlation coefficients between returns on
different markets tend to increase when one of the markets enters the crisis regime (e.g. King and Wadhwani (1990), Karolyi and Stulz (1996), Longin and Solnik (2001), Forbes and Rigobon (2002)). However, some authors define crisis regimes as low average returns observed over longer periods or appearance of unusually low returns (Longin and Solnik (2001), Chen, Chiang, and So (2003), Mishkin and White (2003), Hartmann, Straetmans, and de Vries (2004)).

Therefore, in our paper we highlight the importance of changes in the variance and correlation by allowing them to take different values in all four regimes. Moreover, we restrict the parameter space by assuming that the mean of returns on each market switches between its high and low value depending on the state of this market. The high value of mean describes a market in the calm regime and the low value of mean describes a market in the tranquil regime. We expect low mean returns, high variances, and high correlation when both markets are in the crisis regime and high means, low variances, and low correlation when both markets are in the tranquil regime. The parameter space for means, variances, and correlations between returns on the two markets is defined as follows:

$$\mu = \begin{cases} \mu_{s=1} = \begin{bmatrix} \mu_{T}^X \\ \mu_{T}^Y \\ \mu_{C}^X \\ \mu_{C}^Y \end{bmatrix}, & \mu_{s=2} = \begin{bmatrix} \mu_{T}^X \\ \mu_{T}^Y \\ \mu_{C}^X \\ \mu_{C}^Y \end{bmatrix}, & \mu_{s=3} = \begin{bmatrix} \mu_{T}^X \\ \mu_{T}^Y \\ \mu_{C}^X \\ \mu_{C}^Y \end{bmatrix}, & \mu_{s=4} = \begin{bmatrix} \mu_{C}^X \\ \mu_{C}^Y \end{bmatrix} \end{cases} \quad (5a)$$

$$\sigma = \begin{cases} \sigma_{s=1} = \begin{bmatrix} \sigma_{T_1}^X \\ \sigma_{T_1}^Y \\ \sigma_{C_1}^X \\ \sigma_{C_1}^Y \end{bmatrix}, & \sigma_{s=2} = \begin{bmatrix} \sigma_{T_2}^X \\ \sigma_{T_2}^Y \\ \sigma_{C_2}^X \\ \sigma_{C_2}^Y \end{bmatrix}, & \sigma_{s=3} = \begin{bmatrix} \sigma_{C_3}^X \\ \sigma_{C_3}^Y \end{bmatrix}, & \sigma_{s=4} = \begin{bmatrix} \sigma_{C_4}^X \\ \sigma_{C_4}^Y \end{bmatrix} \end{cases} \quad (5b)$$

and

$$\rho = \begin{cases} \rho_{s=1} = \rho_{T_1}^{XY}, & \rho_{s=2} = \rho_{T_2}^{XY}, & \rho_{s=3} = \rho_{C_3}^{XY}, & \rho_{s=4} = \rho_{C_4}^{XY} \end{cases} \quad (5c)$$

Symbols $T_1$, $T_2$, and $C_1$ denote the state of tranquility on the respective market (the numbers are to distinguish between different values of a particular parameter in different regimes). Symbols $C$, $C_1$, and $C_2$ denote the crisis state. The transition matrix remains unconstrained, therefore we call this model a "general" or "unconstrained" model.
In order to examine how our model fits the data we use several tests proposed by Breunig, Najarian, and Pagan (2003). We compare the means, variances, and peaks of the empirical distributions of the original data and the data simulated from our model. Additionally, we investigate a "leverage effect" for both sets of data. The leverage effect is a common feature of stock returns indicating higher volatility of returns when past returns are negative (e.g. Black (1976), Engle and Ng (1993)). We find that our models are consistent with the original data in all cases and for all tests. Detailed results are presented in Appendix.

3. Independence, Spillovers, and Contagion

In addition to the Markov switching model we need definitions of regime-independence, contagion and spillovers. These definitions enable us to assess the strength of shock transmission between the markets during stable and turmoil periods. Moreover, the definitions provide us the basis to distinguish between spillovers when one of the markets is in the crisis or in the calm state. We also describe the tests for no spillovers and contagion and propose our testing procedures to analyze the hypotheses of, first, one market leading the other during calm periods and, second, one market leading the other during crisis periods. The null hypothesis is that a spillover effect exists between the markets in both periods.

Definition 1. Let \( Z = [X' \ Y'] \) be described by the Markov switching model introduced above. \( Y \) is said to be "regime-independent" of \( X \) if the event that \( Y \) enters the state \( i \) at time \( t \) is independent of the present and past states of \( X \), where \( i \) is the crisis or calm regime in our Markov switching model.

Sola, Spagnolo, and Spangolo (2002) employ the definition of regime-independence of \( X \) and \( Y \) to test for contagious spillovers between financial markets. In case \( Y \) and \( X \) are regime-independent the following restrictions are imposed on the transition matrix \( P \):
\[
P = \begin{pmatrix}
\pi_{TT}^X \pi_{TT}^Y & \pi_{TT}^X (1-\pi_{TT}^Y) & (1-\pi_{TT}^X)\pi_{TT}^Y & (1-\pi_{TT}^X)(1-\pi_{TT}^Y) \\
\pi_{TT}^X (1-\pi_{CC}^Y) & \pi_{CC}^X \pi_{CC}^Y & (1-\pi_{TT}^X)(1-\pi_{CC}^Y) & (1-\pi_{TT}^X)\pi_{CC}^Y \\
(1-\pi_{TT}^X)\pi_{TT}^Y & (1-\pi_{TT}^X)(1-\pi_{CC}^Y) & \pi_{CC}^X \pi_{TT}^Y & \pi_{CC}^X (1-\pi_{TT}^Y) \\
(1-\pi_{TT}^X)(1-\pi_{CC}^Y) & (1-\pi_{TT}^X)\pi_{CC}^Y & \pi_{CC}^X (1-\pi_{CC}^Y) & \pi_{CC}^X \pi_{CC}^Y 
\end{pmatrix}, \quad (6)
\]

where \( \pi_{ij}^Q \) denotes the probability of entering the state \( j \) by the time series \( Q \) at time \( t \) when it was in the state \( i \) at time \( t-1 \). \( Q \in \{X,Y\} \), \( i, j \in \{T,C\} \), and \( T \) and \( C \) denote the calm and crisis regimes, respectively. It should be noted that regime-independence does not imply independence of \( X \) and \( Y \), since they are still allowed to be correlated with each other.

**Definition 2.** Contagion from \( X \) to \( Y \) is present when the probability that \( Y \) enters the state \( i \) at time \( t \) conditional on the information that \( X \) was in this state at time \( t-1 \) is equal one, where \( i \) denotes the crisis or calm regime in our Markov switching model.

According to this definition the stock index return \( Y \) has to enter a specific regime, e.g. the crisis regime, if the stock index return \( X \) was there one period earlier. Thus, the sum of conditional probabilities \( p_{11} \) and \( p_{13} \) in the transition matrix \( P \) can be formulated as:

\[
p_{11} + p_{13} = 1. \quad (7)
\]

Calm and crisis are complementary events and we can express the sum of the probabilities as:

\[
p_{11} + p_{13} = \Pr(Y_t \text{ in calm } \mid X_{t-1} \text{ in calm and } Y_{t-1} \text{ in calm}) \quad (8)
\]

because:

\[
p_{11} = \Pr(X_t \text{ in calm and } Y_t \text{ in calm } \mid X_{t-1} \text{ in calm and } Y_{t-1} \text{ in calm}), \quad (9)
\]

\[
p_{13} = \Pr(X_t \text{ in crisis and } Y_t \text{ in calm } \mid X_{t-1} \text{ in calm and } Y_{t-1} \text{ in calm}). \quad (10)
\]

Analogously, the other constraints on the transition matrix are:

\[
p_{21} + p_{23} = 1, \quad (11)
\]

\[
p_{32} + p_{34} = 1, \quad (12)
\]

\[
p_{42} + p_{44} = 1 \quad (13)
\]

and the transition matrix \( P \) takes on the form:
Our definition of contagion is a less restrictive version of the one put forward by Sola, Spagnolo, and Spagnolo (2002) and is inspired by the work of Phillips (1991). Sola, Spagnolo, and Spagnolo set additional constraints assuming that $p_{11} = p_{21}$ and $p_{32} = p_{42}$, i.e. the probability that both markets, $X$ and $Y$, enter the crisis or the calm regime does no depend on the regime of $Y$ in the previous period. Thus, the past realizations of $Y$ do not influence $X$ when there is contagion from $X$ to $Y$. Such an additional restriction has been criticized in the financial contagion literature due to the possibility of an estimation bias coming from overlooking the bi-directional transmission of shocks between the markets (Forbes and Rigobon (2002), Billio and Pelizzon (2003), Moser (2003), Rigobon (2003)).

Additionally, the idea of contagion is usually associated with financial crises spilling over from one market to other markets. One can expect that one market infects the other market only when it is in the crisis regime. Such a definition of "contagion in the crisis regime" corresponds to the transition matrix:

$$P = \begin{pmatrix}
    p_{11} & 0 & 1 - p_{11} & 0 \\
    p_{21} & 0 & 1 - p_{21} & 0 \\
    0 & p_{32} & 0 & 1 - p_{32} \\
    0 & p_{42} & 0 & 1 - p_{42}
\end{pmatrix}. \quad (14)$$

The above definitions are closely related to the original definition of contagion discussed in Eichengreen, Rose, and Wyplosz (1996), Pericoli and Sbracia (2003), Hartmann, Straetmans, and de Vries (2004) among others. Contagion is defined there as "a significant increase in the probability of a crisis in one country, conditional on a crisis occurring in another country". The important characteristics of our definitions are identification of direction of contagion and financial spillovers from one market to another occurring with a lag, which
allows for identification of delays in information or capital flows between markets (Climent and Meneu (2003), Sander and Kleimeier (2003)).\footnote{Moreover, multiple regimes in our model enable testing changes in the correlation structure between returns on different markets during crisis periods, i.e. "shift-contagion" hypothesis, introduced by Forbes and Rigobon (2002). Nevertheless, we concentrate on the tests of financial spillovers based on the probability measures in this paper.} Other definitions of contagion and their applications are surveyed in Dornbusch, Park, and Claessens (2000), Claessens and Forbes (2001), Billio and Pelizzon (2003), Karolyi (2003), Moser (2003), Pericoli and Sbracia (2003).

Our contagion definitions in the spirit of Sola, Spagnolo, and Spagnolo (2002) are very restrictive in comparison with the original definition of contagion presented above. Even rejecting them does not imply that one market does not lead the other (Ravn and Sola (1995)). Therefore, we propose a weaker form of inter-market dependency that fits well the idea of increased probability of a crisis at home, given the crisis occurred abroad and is based on the notion of financial spillovers and causality (e.g., Geweke (1984)).

\textit{Definition 3.} $X$ leads $Y$ by one period if the magnitude of the probability that $Y$ enters the state $i$ at time $t$ depends on whether $X$ was in the state $j$ at time $t-1$, where $i$ and $j$ are allowed to be the crisis or calm regimes in our Markov switching model.

We understand dependence as evidence of the difference in conditional probabilities of $Y$ entering the state $i$, when $X$ was in the calm state or in the crisis state at time $t-1$, respectively. The case of $X$ leading $Y$ is interpreted in the context of inter-market linkages as a presence of financial spillovers from one market to the other. For example, the definition of spillovers comprises the situation when the probability of one market entering the crisis regime depends not only on whether this market was in the state of crisis one period earlier, but also on whether the other market was there in the previous period:

\[
\Pr(Y_t \text{ in crisis} \mid X_{t-1} \text{ in crisis and } Y_{t-1} \text{ in crisis})
\]
\[ \neq \Pr(Y_t \text{ in crisis} \mid X_{t-1} \text{ in calm and } Y_{t-1} \text{ in crisis}), \quad (16) \]

which can be expressed in terms of parameters from the transition matrix \( P \) as:

\[ p_{22} + p_{24} \neq p_{42} + p_{44}. \quad (17) \]

Analogously, the following inequalities must be valid if \( X \) leads \( Y \) in all regimes:

\[ p_{11} + p_{13} \neq p_{31} + p_{33}, \quad (18) \]
\[ p_{21} + p_{23} \neq p_{41} + p_{43}, \quad (19) \]
\[ p_{12} + p_{14} \neq p_{32} + p_{34}, \quad (20) \]
\[ p_{22} + p_{24} \neq p_{42} + p_{44}. \quad (21) \]

If one assumes that no spillovers exist between the markets in any regimes, the inequalities (18) to (21) become equalities and then the transition matrix \( P \) is defined as:

\[
\begin{pmatrix}
p_{11} & p_{12} & p_{13} & p_{14} \\
p_{21} & p_{22} + p_{44} - p_{24} & p_{41} + p_{43} - p_{21} & p_{24} \\
p_{31} & p_{12} + p_{14} - p_{34} & p_{11} + p_{13} - p_{31} & p_{34} \\
p_{41} & p_{42} & p_{43} & p_{44}
\end{pmatrix}.
\quad (22)
\]

It can be shown that the constraint \( p_{22} = p_{42} + p_{44} - p_{24} \) is equivalent to \( p_{23} = p_{41} + p_{43} - p_{21} \) and that the constraint \( p_{32} = p_{12} + p_{14} - p_{34} \) is equivalent to \( p_{33} = p_{11} + p_{13} - p_{31} \). Therefore, the parameters \( p_{23} \) and \( p_{33} \) can be set unconstrained in the estimation process.

Additionally, one can assume that no spillovers from \( X \) to \( Y \) will be present at time \( t+1 \) in case \( Y \) is in the crisis state at time \( t \). For example, the influence of the US market on the Japanese market could strongly diminish, when the Japanese market is hit by the strong internal crisis. In this case the transition matrix \( P \) will be defined as follows:

\[
\begin{pmatrix}
p_{11} & p_{12} & p_{13} & p_{14} \\
p_{21} & p_{22} & p_{23} & p_{24} \\
p_{31} & p_{12} + p_{14} - p_{34} & p_{11} + p_{13} - p_{31} & p_{34} \\
p_{41} & p_{42} & p_{43} & p_{44}
\end{pmatrix}.
\quad (23)
Alternatively, the opposite hypothesis of no spillovers from $X$ to $Y$ when $Y$ is in the calm regime may be denoted by:

$$
P = \begin{pmatrix}
    p_{11} & p_{12} & p_{13} & p_{14} \\
    p_{21} & p_{42} + p_{44} - p_{24} & p_{41} + p_{43} - p_{21} & p_{24} \\
    p_{31} & p_{32} & p_{33} & p_{34} \\
    p_{41} & p_{42} & p_{43} & p_{44}
\end{pmatrix}.
$$

(24)

Generally, the Markov switching approach fits well the idea of investigating spillovers and contagion between the markets during stable and turmoil periods. Analyzing differences between spillovers to calm and crisis markets is made possible by setting the suitable restrictions on parameters from the transition matrix. Thus, one does not need to assume any specific linear or nonlinear structure of spillovers between the markets, like in autoregressive and ARCH models, since both contagion and spillovers are introduced directly through the probability measures.

The definitions introduced above are helpful in building tests of financial contagion, spillovers, and independence between the markets. The general model, described by the equations (1) to (5), imposes no restrictions on the transition matrix $P$ and assumes financial spillovers in both stable and turbulent regimes. It can be estimated using the standard Expectation-Maximization (EM) algorithm, similarly to Hamilton (1989, 1990). A similar technique is applied to estimate the contagion models, employing equations (2) to (5) and transition matrices (14) and (15). The models assuming regime-independence (no spillovers), no spillovers in crisis periods, no spillovers in calm periods, and no spillovers in any regime use the transition matrices (6), (23), (24), and (22), respectively.

These models with constrained transition matrices are estimated using an algorithm analogous to the one described by Phillips (1991). Details are available upon request. The log-likelihood values corresponding to the estimates are denoted by $L_{SPILLOVERS}$ for the general model with no constraint on the transition matrix $P$, $L_{INDEPENDENCE}$ for the regime-
independence model, $L_{\text{CONTAGION}}$ for the contagion model, $L_{\text{CONTAGION in CRISIS}}$ for the "contagion during crises" model, and $L_{\text{NO SPILOVERS}}$, $L_{\text{NO SPILOVERS in CRISIS}}$, $L_{\text{NO SPILOVERS in CALM}}$ for the no-spillover models with the transition matrices (22), (23), and (24), respectively.

We describe now our testing procedure used to explore possible interdependencies between capital markets. In Figure 1 the testing hypotheses are ordered in the general-to-specific sequence. Exceptions are Hypotheses 3a and 3b, which are not nested in Hypothesis 2. We start with testing the null hypothesis assuming that there is contagion from $X$ to $Y$ when both markets are in the crisis regime (Hypothesis 1) against the alternative of no contagion. Under the null hypothesis, the likelihood ratio statistic:

$$LR = 2(L_{\text{SPILOVERS}} - L_{\text{CONTAGION in CRISIS}}) \sim \chi^2(4)$$

has the standard asymptotic $\chi^2$ distribution with four degrees of freedom. If the null hypothesis can be accepted, we continue with testing the hypothesis that contagion exists in both calm and crisis regimes (Hypothesis 2). We use the likelihood ratio statistic:

$$LR = 2(L_{\text{SPILOVERS}} - L_{\text{CONTAGION}}) \sim \chi^2(8),$$

which has the asymptotic $\chi^2$ distribution with eight degrees of freedom (Sola, Spagnolo, and Spagnolo (2002)).

If the Hypothesis 1 is rejected then no contagion exists in any regimes and we follow the procedure by analyzing the hypothesis that no spillovers from $X$ to $Y$ are present in cases $Y$ was in the calm regime at time $t-1$ (Hypothesis 3a). Alternatively, one can test the
hypothesis of no spillovers to $Y$ in case $Y$ was in the crisis regime at time $t-1$ (Hypothesis 3b). The respective statistics are:

$$LR = 2(L_{\text{spillovers}} - L_{\text{no spillovers in calm}}) \sim \chi^2(1)$$

(27)

and:

$$LR = 2(L_{\text{spillovers}} - L_{\text{no spillovers in crisis}}) \sim \chi^2(1).$$

(28)

If the both hypotheses are rejected, we conclude that financial spillovers from $X$ to $Y$ are present in both regimes (Hypothesis 6) and finish the procedure here. When one of the above hypotheses, 3a or 3b, is accepted, we utilize the following statistic to test the Hypothesis 4 of no spillovers between the markets in any regime:

$$LR = 2(L_{\text{spillovers}} - L_{\text{no spillovers}}) \sim \chi^2(2).$$

(29)

When this hypothesis is accepted, we conclude that $X$ does not lead $Y$ by one period, but some interdependencies between stock index returns on both markets, which take place simultaneously (e.g. on the same day) may still be present. The probability of one market entering the crisis or calm regime may still depend on the regime that the other market will enter collaterally. To rule out such dependencies between the markets we test the hypothesis that markets are regime-independent (Hypothesis 5) by applying the following test statistic:

$$LR = 2(L_{\text{spillovers}} - L_{\text{independence}}) \sim \chi^2(12).$$

(30)

If this hypothesis is accepted, the markets enter any regimes independently of other markets (Phillips (1991), Sola, Spangolo, and Spagnolo (2002)). The flexibility of the test rests on the fact that both markets are still allowed to be correlated in each regime. This characteristic can almost always be observed between financial markets (e.g., Forbes and Rigobon (2002)).

The Markov switching models, employed by testing different hypotheses, differ only in parameters of the transition matrix $P$. In this way we avoid the problem of existence of some nuisance parameters that would be unidentified under the null hypotheses – a typical obstacle in testing multi-regime models. Therefore, our likelihood ratio statistics have their standard

The testing procedure outlined here is not meant to compare spillovers between the markets depending on the regime of the leading market. The important feature of the hypotheses 3a, 3b, and 4 is that they enable us to analyze the question raised in the introduction, whether markets undergoing a financial distress are more or less vulnerable to spillovers from other markets.

4. Data and Empirical Results

In this section, we report the results obtained from the testing methodology outlined above and present the calculated probabilities of a crisis on each market when there was a crisis on the US market one day earlier. In our analysis we employed the standard capital market indices from the four largest markets in the world. The S&P 500 index represents the US market, the NIKKEI 225 is the index for the Japanese market, the FTSE 100 index corresponds to the UK market, and the DAX stands for the German index. The index returns are computed as first differences of logged daily closing prices from the four markets and cover the period from April 3, 1984 to May 30, 2003, which corresponds to 4423 observations.

As argued in the introduction, the US is believed to be the dominating market leading other stock markets independently of crisis and calm periods. Therefore, in the empirical analysis we concentrate on spillovers from the US market to the other three markets, although the model applied here complies bi-directional interdependencies. Using the proposed algorithm, we check whether the structure of dependencies of the British, German, and Japanese markets on the US market should be called spillovers or rather contagion. In addition, we test for possible changes in the linkages between the markets during turbulent and calm periods. Next, we present the final models obtained from the testing procedure and compute
the probabilities of the potential turmoil on the British, German, and Japanese market individually conditional on the information that the US market was in the turmoil regime one period earlier.

In order to analyze whether linkages between the markets have varied over time independently of crisis and calm regimes, we additionally calculate all tests for three non-overlapping sub-periods from April 3, 1984 to December 28, 1988, from January 4, 1989 to December 29, 1995, and from January 4, 1996 to May 30, 2003. The 1996 – 2003 sub-sample is characterized by a considerable high variance of index returns on all markets in comparison to previous periods, which could eventually influence the general results. We also divide the rest of the time series into the two sub-periods, where the 1989 – 1995 interval is a relatively stable period and the 1984 – 1988 period comprises the great crash of the 1987 that has been found to influence spillovers from the US to other markets (Malliaris and Urrutia (1992)).

Each model of the bilateral linkages between the US market and the other market is estimated in seven different versions. The first version corresponds to the general model with no restrictions on the transition matrix $P$, which allows for potential spillovers between the markets. The second model assumes that both markets are regime-independent from each other and the third one assumes no spillovers from the US market to the other market. The fourth model is estimated under the constraint that no spillovers exist when the dependent market is in the state of crisis and the fifth one assumes no spillovers when the dependent market is in the calm regime. The sixth and seventh cases are the models of contagion from the US to the other market and contagion only in the crisis periods, respectively.

In Table 1 the log-likelihood values from the estimated models are presented. The general model has the highest likelihood value for each pair of markets, since all other models are restricted versions of the general model. Additionally, the "regime-independence" models are special cases of the "no-spillovers" models, which in turn set additional constraints in
comparison to the "no-spillovers in crisis" and "no-spillovers in calm periods" models. Finally, the both "contagion" models are restricted forms of the general model.

Table 1 about here

To distinguish which models are statistically justified and which are too restrictive we employ the likelihood ratio statistics described in the previous section. All the results from our testing procedure are presented in Table 2. For all pairs of markets, the hypotheses of contagion and a weaker hypothesis of contagion in the crisis regime is rejected, which corresponds to the result of Sola, Spagnolo, and Spangolo (2002). Hence, we continue the procedure by testing the null hypotheses of no spillovers in crisis periods, no spillovers in calm periods, and no spillovers in any regimes. All of them are also rejected and we interpret these results as existence of spillovers from the US to the Japanese, British, and German markets independently of whether these latter markets are in crisis or calm regimes.

Table 2 about here

It is interesting to note that the test statistics for the hypothesis of no spillovers during crises always have higher values than the statistics for the hypothesis of no spillovers during calm periods. Assuming no spillovers when the Japanese, British, and German markets are in crisis regimes would be a more likely choice than assuming no spillovers in calm regimes. However, these both hypotheses, and models, are rejected as too restrictive. Finally, the regime-independence is also rejected in all cases, which confirms that some interdependencies are present between the US and other markets.
According to our results the best models of dependencies between the markets are the general unconstrained models allowing for spillovers in all regimes, but not restricting these spillovers only to contagion effects. We present the parameters of these final models in Table 3. It is important that all the models match the main empirical patterns found on international capital markets. First, the regime with low average index returns on both markets is characterized by higher volatility of index returns than the regime with both markets in calm periods. It is interesting to note that the highest (lowest) volatilities are always obtained in the same regime for both markets. Moreover, in each model the regime with highest volatilities on the two markets is the one with one market in the state of crisis and the other market in the state of calm.

Table 3 about here

Second, when both markets are in the crisis regime they become more correlated with each other than when they are in their calm regimes (e.g., Longin and Solnik (2001)). Thus, using our framework it would be possible to compute the tests of contagion in the spirit of Forbes and Rigobon (2002), but without using any ad hoc procedures to identify crisis and calm sub-periods. However, this is beyond the scope of the paper.

Finally, from the elements of the transition matrices it can be observed that the probability of staying in the same regime is always highest for all regimes and all estimated models. This result can be interpreted as evidence of persistence of high (low) volatility in stock market index returns and evidence of autocorrelation in index returns due to high (low) returns following past high (low) returns. Finding is in line with the well-known characteristics of autocorrelation and conditional heteroscedasticity in stock index returns. Moreover, comparing the estimated transition matrices in Table 3 with constraints proposed in
equations (14) and (15) leads to the conclusion that the high values of the parameters $p_{22}$ and $p_{33}$, which can be interpreted as indicators of persistence of the states 2 and 3, are main reasons for rejecting both contagion hypotheses in the spirit of Sola, Spagnolo, and Spagnolo (2002).

Our results, suggesting that the spillovers hypothesis is true, are consistent with the literature defining contagion as an increase in the probability of having a crisis at home when there is a crisis on the other market. Eichengreen, Rose, and Wyplosz (1996) and Hartmann, Streatmans, and de Vries (2004) also find evidence of contagion when they apply the same definition of contagion.

Having estimated transition matrices for each model we are able to compute the probabilities of some market entering the state of crisis or calm, conditional on the information that this market and the US market were in their respective states yesterday. These results are of special importance for international investors and the great advantage of the model is that they can be obtained directly using standard computations on the elements of the transition matrix. We additionally provide results on the probability of one market entering the crisis (calm) regime conditional on the state of the US market one day earlier. The results are presented in Table 4.

The main conclusion from the calculated probabilities is that entering one regime by the market is most likely and even close to one when this market and the US market were in the same regime one period earlier. If the US market was not in that regime one period earlier then the probability of entering the regime by the other market drops in almost all cases. The probability is close to zero that the market enters the state of calm (crisis) when the US market
and this respective market were in the opposite regime one period earlier. This finding illustrates how the past information about the US market spills over to other mature markets on the next day. Furthermore, we are able to forecast the future state of the market more accurately having the information about the present state of both markets rather than having the information only about the US market. This in turn explains why the hypothesis of contagion is rejected in our analyses. The past information about each market is significant for its present performance.

We continue the analysis with studying the relations between the markets in the selected three non-overlapping sub-samples to learn how the dependencies between international capital markets change over time. The results from testing all hypotheses of contagion, spillovers, and regime-independence are presented in Table 5. The general findings from this exercise are that the US leads Japan, the UK and Germany, but the patterns of spillovers from the US to those markets vary over time.

Some evidence of asymmetry in spillover effects between calm and crisis regimes is present the investigated sub-samples. In the 1984 – 1988 period we can accept the hypothesis that the S&P 500 index returns do not lead the DAX and NIKKEI 225 index returns when the latter indices are in the calm regimes. Similarly, from 1996 to 2003 returns on the Japanese market follow the US market returns only in the state of crisis and any spillover effects to Japan are quite weak in this period. The lack of spillovers in any regime to the UK is accepted in the 1989 – 1995 sub-sample. Since regime-independence is also rejected there, we interpret this result as evidence of the inter-dependencies between the US and UK capital markets, which take place without delay. One possible explanation for the lack of spillovers to the UK
from the US could be the ERM currency crisis of 1992 that affected most strongly the British market. In the most recent period 1996 – 2003, S&P 500 index returns lead very strongly the DAX returns and one can observe the contagion effect when the German index is in the crisis regime. Likely reasons for this contagion effect could be recent shocks which took place on the US market and spread to other markets after the terrorist attack on September 11 and after the burst of the "dot.com" bubble. In all other cases there are significant spillovers from the US to the other markets independently of the crisis and calm regimes.

From Table 5 one can observe that spillovers between capital markets evolve over time independently of changing regimes. There are naturally some factors other than changing states of the markets which can influence the strength of spillovers and future applications may extend the proposed models by introducing additional elements or varying parameters. Nevertheless, our results show that spillovers between the four big stock capital markets exist in all periods.

There is less evidence of spillovers to the markets in the calm regime than to the stock markets which are in the crisis regime in the sub-periods. This finding could indicate that the market not involved in some international crash often remains resistant to spillovers from the US stock market. As soon as it allows for the high volatility regime at home it becomes more vulnerable to the influence of the US market, because concerned investors observe more carefully the performance of the US market in the context of the international turmoil.

This could also suggest that in some periods the analyzed markets are robust to any contagion from the US market, because they enter crisis regimes independently of the US market or simultaneously with the US market. If the latter case was true, then the direction of contagion would be toward the US market rather than from the US market due to possible crises on other not investigated markets that could cause the US market and other analyzed markets to enter the crisis regime in the same time. Additionally, the US market has less
influence on the European and Asian markets on the same day because of different trading
hours on the stock exchanges in Asia, Europe, and America. American stock markets open and
close after the European and Asian markets each day, although some trading hours overlap. In
contrast, European and Asian stock index returns may influence the American index returns on
the same day (e.g., Cheung and Ng (1996)).

5. Conclusions

In this article, we investigate international financial spillovers from the US stock
market to the Japanese, British, and German markets. We introduce a statistical framework to
deal with the problem of asymmetries in financial spillovers in calm and turbulent regimes.
Spillovers and contagion to stock markets during crisis and calm periods are explicitly defined
and new tests are proposed to distinguish between financial spillovers in crisis and calm
regimes.

Our testing framework is capable of distinguishing between different types of relations
connecting two markets, i.e., contagion, spillovers, and independence. Thus, we compare the
results from testing financial spillovers with outcomes from the tests of contagion and
independence and obtain evidence that the Japanese, UK, and German stock markets are
dependent on the past performance of the US market, but encounter almost no indication of
contagion in the spirit of Sola, Spagnolo, and Spangolo (2002). We find that spillovers taking
place when the dependent markets are in the crisis regime are more frequent than spillovers to
the markets in the state of calm, which is in line with the results of Chen, Chiang, and So
(2003). This result suggests that financial crashes on the US market do not always directly
cause turmoil on the Japanese, UK, and German markets. However, the crashes on the US
market increase the probability of a crisis on the three other mature markets, which is in line
with the hypothesis of contagious crises introduced by Eichengreen, Rose, and Wyplosz (1996).

Additionally, we present the probabilities for the Japanese, UK, and German stock markets individually entering the states of calm and crisis periods, conditional on the information about the past performance of those markets and the US market. Information from both markets is found to be relevant for efficient forecasting of future stock market index returns on those markets, therefore further research could incorporate our framework in testing for diversification benefits from asset allocation on international markets, as in Ang and Bekaert (2002, 2003).
References


Mishkin, Frederic and Eugene N. White (2003), U.S. Stock Market Crashes and Their Aftermath: Implications for Monetary Policy, in William C. Hunter, George G.


Table 1: Log-likelihood Values of the Estimated Markov Switching Models

<table>
<thead>
<tr>
<th>Model</th>
<th>S&amp;P 500 and NIKKEI 225</th>
<th>S&amp;P 500 and FTSE 100</th>
<th>S&amp;P 500 and DAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{spillovers}}$</td>
<td>– 13222.11</td>
<td>– 11780.00</td>
<td>– 12957.88</td>
</tr>
<tr>
<td>$L_{\text{NS in crisis}}$</td>
<td>– 13238.43</td>
<td>– 11834.50</td>
<td>– 12988.96</td>
</tr>
<tr>
<td>$L_{\text{NS in prosperity}}$</td>
<td>– 13235.73</td>
<td>– 11821.00</td>
<td>– 12979.50</td>
</tr>
<tr>
<td>$L_{\text{NS}}$</td>
<td>– 13247.70</td>
<td>– 11863.07</td>
<td>– 13006.06</td>
</tr>
<tr>
<td>$L_{\text{independence}}$</td>
<td>– 13390.40</td>
<td>– 11858.60</td>
<td>– 13062.95</td>
</tr>
<tr>
<td>$L_{\text{contagion}}$</td>
<td>– 13386.00</td>
<td>– 11840.58</td>
<td>– 13069.87</td>
</tr>
<tr>
<td>$L_{\text{contagion in crisis}}$</td>
<td>– 13331.62</td>
<td>– 11816.13</td>
<td>– 13003.45</td>
</tr>
</tbody>
</table>

Note: The log-likelihood values corresponding with the estimates are denoted by $L_{\text{spillovers}}$ for the general model, $L_{\text{independence}}$ for the independence model, $L_{\text{contagion}}$ for the contagion model, $L_{\text{contagion in crisis}}$ for the "contagion during crises" model, and $L_{\text{NS}}$, $L_{\text{NS in crisis}}$, $L_{\text{NS in prosperity}}$ for the no-spillover models with the transition matrices (23), (24), and (22), respectively.
Table 2: Tests of Linkages between the Markets

<table>
<thead>
<tr>
<th>Null hypothesis</th>
<th>S&amp;P 500 and NIKKEI 225</th>
<th>S&amp;P 500 and FTSE 100</th>
<th>S&amp;P 500 and DAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regime-independence</td>
<td>336.58**</td>
<td>157.20**</td>
<td>210.14**</td>
</tr>
<tr>
<td>No spillovers during calm</td>
<td>26.64**</td>
<td>82.00**</td>
<td>43.24**</td>
</tr>
<tr>
<td>No spillovers during crises</td>
<td>33.24**</td>
<td>109.00**</td>
<td>62.16**</td>
</tr>
<tr>
<td>No spillovers at any regimes</td>
<td>51.18**</td>
<td>127.19**</td>
<td>96.36**</td>
</tr>
<tr>
<td>Contagion</td>
<td>327.78**</td>
<td>121.16**</td>
<td>223.98**</td>
</tr>
<tr>
<td>Contagion during crises</td>
<td>219.02**</td>
<td>72.26**</td>
<td>91.14**</td>
</tr>
</tbody>
</table>

Note: * and ** denote rejection of the null hypothesis at the 5% and 1% levels, respectively.
Table 3: Final Models of Dependencies between the Markets

<table>
<thead>
<tr>
<th>State of $X$</th>
<th>State of $Y$</th>
<th>$\mu^X$ (%)</th>
<th>$\sigma^X$ (%)</th>
<th>$\mu^Y$ (%)</th>
<th>$\sigma^Y$ (%)</th>
<th>$\text{corr}(X,Y)$</th>
<th>Transition matrix $P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S&amp;P 500</td>
<td>DAX</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>calm</td>
<td>Calm</td>
<td>0.080</td>
<td>0.670</td>
<td>0.107</td>
<td>0.845</td>
<td>0.175</td>
<td>0.982 0.002 0.001 0.015</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.007)</td>
<td>(0.023)</td>
<td>(0.013)</td>
<td>(0.035)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>calm</td>
<td>crisis</td>
<td>0.080</td>
<td>5.944</td>
<td>0.019</td>
<td>4.994</td>
<td>0.315</td>
<td>0.000 0.566 0.043 0.391</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.007)</td>
<td>(1.891)</td>
<td>(0.001)</td>
<td>(1.044)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>crisis</td>
<td>calm</td>
<td>0.037</td>
<td>1.842</td>
<td>0.107</td>
<td>3.007</td>
<td>0.684</td>
<td>0.000 0.000 0.972 0.028</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.004)</td>
<td>(0.495)</td>
<td>(0.013)</td>
<td>(0.747)</td>
<td></td>
<td></td>
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<tr>
<td>crisis</td>
<td>crisis</td>
<td>0.037</td>
<td>1.127</td>
<td>0.019</td>
<td>1.493</td>
<td>0.378</td>
<td>0.025 0.007 0.005 0.962</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.004)</td>
<td>(0.297)</td>
<td>(0.001)</td>
<td>(0.444)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S&amp;P 500</td>
<td>FTSE 100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>calm</td>
<td>calm</td>
<td>0.082</td>
<td>0.666</td>
<td>0.065</td>
<td>0.732</td>
<td>0.315</td>
<td>0.978 0.000 0.022 0.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.006)</td>
<td>(0.084)</td>
<td>(0.005)</td>
<td>(0.091)</td>
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<tr>
<td>calm</td>
<td>crisis</td>
<td>0.082</td>
<td>8.717</td>
<td>-0.088</td>
<td>5.250</td>
<td>0.493</td>
<td>0.000 0.513 0.382 0.105</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.006)</td>
<td>(2.110)</td>
<td>(0.007)</td>
<td>(1.417)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>crisis</td>
<td>calm</td>
<td>-0.064</td>
<td>1.222</td>
<td>0.065</td>
<td>1.138</td>
<td>0.444</td>
<td>0.035 0.005 0.953 0.007</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.009)</td>
<td>(0.195)</td>
<td>(0.005)</td>
<td>(0.214)</td>
<td></td>
<td></td>
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<tr>
<td>crisis</td>
<td>Crisis</td>
<td>-0.064</td>
<td>1.946</td>
<td>-0.088</td>
<td>2.174</td>
<td>0.517</td>
<td>0.000 0.000 0.037 0.963</td>
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<tr>
<td></td>
<td></td>
<td>(0.009)</td>
<td>(0.280)</td>
<td>(0.007)</td>
<td>(0.540)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S&amp;P 500</td>
<td>NIKKEI 225</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>calm</td>
<td>calm</td>
<td>0.099</td>
<td>0.738</td>
<td>0.099</td>
<td>0.640</td>
<td>0.066</td>
<td>0.970 0.014 0.000 0.016</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.010)</td>
<td>(0.135)</td>
<td>(0.095)</td>
<td>(0.140)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>calm</td>
<td>crisis</td>
<td>0.099</td>
<td>0.637</td>
<td>-0.027</td>
<td>1.659</td>
<td>0.154</td>
<td>0.016 0.969 0.008 0.007</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.010)</td>
<td>(0.102)</td>
<td>(0.012)</td>
<td>(0.342)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>crisis</td>
<td>calm</td>
<td>-0.005</td>
<td>3.066</td>
<td>0.099</td>
<td>3.289</td>
<td>0.142</td>
<td>0.000 0.057 0.850 0.092</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.002)</td>
<td>(0.980)</td>
<td>(0.095)</td>
<td>(0.917)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>crisis</td>
<td>crisis</td>
<td>-0.005</td>
<td>1.234</td>
<td>-0.027</td>
<td>1.363</td>
<td>0.176</td>
<td>0.017 0.000 0.018 0.965</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.002)</td>
<td>(0.123)</td>
<td>(0.012)</td>
<td>(0.202)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: For further explanations see text.
Table 4: Probability of a Crisis or Calm Today and the Information from Yesterday

<table>
<thead>
<tr>
<th>Event Combination</th>
<th>NIKKEI 225</th>
<th>FTSE 100</th>
<th>DAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pr((Y_t) in calm</td>
<td>Pr((Y_{t-1}) in calm and (X_{t-1}) in calm)</td>
<td>0.970</td>
<td>1.000</td>
</tr>
<tr>
<td>Pr((Y_t) in calm</td>
<td>Pr((Y_{t-1}) in calm and (X_{t-1}) in crisis)</td>
<td>0.850</td>
<td>0.988</td>
</tr>
<tr>
<td>Pr((Y_t) in crisis</td>
<td>Pr((Y_{t-1}) in calm and (X_{t-1}) in calm)</td>
<td>0.024</td>
<td>0.382</td>
</tr>
<tr>
<td>Pr((Y_t) in crisis</td>
<td>Pr((Y_{t-1}) in calm and (X_{t-1}) in crisis)</td>
<td>0.035</td>
<td>0.037</td>
</tr>
<tr>
<td>Pr((Y_t) in crisis</td>
<td>Pr((Y_{t-1}) in crisis and (X_{t-1}) in calm)</td>
<td>0.030</td>
<td>0.000</td>
</tr>
<tr>
<td>Pr((Y_t) in crisis</td>
<td>Pr((Y_{t-1}) in crisis and (X_{t-1}) in crisis)</td>
<td>0.150</td>
<td>0.012</td>
</tr>
<tr>
<td>Pr((Y_t) in crisis</td>
<td>Pr((Y_{t-1}) in crisis and (X_{t-1}) in calm)</td>
<td>0.976</td>
<td>0.618</td>
</tr>
<tr>
<td>Pr((Y_t) in crisis</td>
<td>Pr((Y_{t-1}) in crisis and (X_{t-1}) in crisis)</td>
<td>0.965</td>
<td>0.963</td>
</tr>
</tbody>
</table>

Probabilities conditional on the information from \(X_{t-1}\) and \(Y_{t-1}\)

<table>
<thead>
<tr>
<th>Event Combination</th>
<th>NIKKEI 225</th>
<th>FTSE 100</th>
<th>DAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pr((Y_t) in calm</td>
<td>Pr((X_{t-1}) in calm)</td>
<td>0.564</td>
<td>0.929</td>
</tr>
<tr>
<td>Pr((Y_t) in calm</td>
<td>Pr((X_{t-1}) in crisis)</td>
<td>0.149</td>
<td>0.206</td>
</tr>
<tr>
<td>Pr((Y_t) in crisis</td>
<td>Pr((X_{t-1}) in calm)</td>
<td>0.436</td>
<td>0.071</td>
</tr>
<tr>
<td>Pr((Y_t) in crisis</td>
<td>Pr((X_{t-1}) in crisis)</td>
<td>0.851</td>
<td>0.794</td>
</tr>
</tbody>
</table>

Note: For further explanations see text.
Table 5: Tests of Linkages between the Markets in Sub-Samples

<table>
<thead>
<tr>
<th>Sub-periods</th>
<th>Null hypothesis</th>
<th>S&amp;P 500 and NIKKEI 225</th>
<th>S&amp;P 500 and FTSE 100</th>
<th>S&amp;P 500 and DAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984/04/03 – 1988/12/28</td>
<td>Regime-independence</td>
<td>93.18**</td>
<td>53.12**</td>
<td>63.24**</td>
</tr>
<tr>
<td></td>
<td>No spillovers during calm</td>
<td>3.20</td>
<td>7.23**</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>No spillovers during crises</td>
<td>7.02**</td>
<td>15.77**</td>
<td>4.28*</td>
</tr>
<tr>
<td></td>
<td>No spillovers at any regimes</td>
<td>53.24**</td>
<td>25.52**</td>
<td>4.52</td>
</tr>
<tr>
<td></td>
<td>Contagion</td>
<td>105.38**</td>
<td>87.82**</td>
<td>66.42**</td>
</tr>
<tr>
<td></td>
<td>Contagion during crises</td>
<td>22.58**</td>
<td>71.88**</td>
<td>61.88**</td>
</tr>
<tr>
<td>1989/01/04 – 1995/12/29</td>
<td>Regime-independence</td>
<td>61.98**</td>
<td>56.96**</td>
<td>65.00**</td>
</tr>
<tr>
<td></td>
<td>No spillovers during calm</td>
<td>8.96**</td>
<td>1.16</td>
<td>9.42**</td>
</tr>
<tr>
<td></td>
<td>No spillovers during crises</td>
<td>19.14**</td>
<td>2.76</td>
<td>24.04**</td>
</tr>
<tr>
<td></td>
<td>No spillovers at any regimes</td>
<td>25.98**</td>
<td>5.84</td>
<td>37.42**</td>
</tr>
<tr>
<td></td>
<td>Contagion</td>
<td>56.14**</td>
<td>71.30**</td>
<td>61.24**</td>
</tr>
<tr>
<td></td>
<td>Contagion during crises</td>
<td>40.58**</td>
<td>56.02**</td>
<td>31.52**</td>
</tr>
<tr>
<td>1996/01/04 – 2003/05/30</td>
<td>Regime-independence</td>
<td>94.56**</td>
<td>112.26**</td>
<td>95.46**</td>
</tr>
<tr>
<td></td>
<td>No spillovers during calm</td>
<td>3.00</td>
<td>12.48**</td>
<td>8.82**</td>
</tr>
<tr>
<td></td>
<td>No spillovers during crises</td>
<td>5.86*</td>
<td>23.04**</td>
<td>11.80**</td>
</tr>
<tr>
<td></td>
<td>No spillovers at any regimes</td>
<td>7.76*</td>
<td>56.64**</td>
<td>20.90**</td>
</tr>
<tr>
<td></td>
<td>Contagion</td>
<td>41.94**</td>
<td>42.68**</td>
<td>24.04**</td>
</tr>
<tr>
<td></td>
<td>Contagion during crises</td>
<td>28.96**</td>
<td>27.30**</td>
<td>9.14</td>
</tr>
</tbody>
</table>

Note: * and ** denote rejection of the null hypothesis at the 5% and 1% levels, respectively.
Figure 1: The Financial Spillovers Hypotheses and Their Testing Sequence

Hypothesis 1: Contagion in crisis regimes

Hypothesis 2: Contagion in all regimes

Hypothesis 3a: No spillovers in calm periods

Hypothesis 3b: No spillovers in crisis periods

Hypothesis 4: No spillovers in any regime (possible interdependencies)

Hypothesis 5: Regime-independence (no spillovers)

Hypothesis 6: Spillovers in crisis and calm regimes (general model)
# Appendix

## Table A1: Specification Tests for the Estimated Markov Switching Models

<table>
<thead>
<tr>
<th>Null hypothesis</th>
<th>S&amp;P 500 (X) and NIKKEI 225 (Y)</th>
<th>S&amp;P 500 (X) and FTSE 100 (Y')</th>
<th>S&amp;P 500 (X) and DAX (Y')</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu^X_S = \mu^X_D )</td>
<td>0.122 [0.9030]</td>
<td>-0.653 [0.5138]</td>
<td>-0.293 [0.7694]</td>
</tr>
<tr>
<td>( \mu^Y_S = \mu^Y_D )</td>
<td>-0.420 [0.6748]</td>
<td>0.670 [0.5026]</td>
<td>-0.498 [0.6182]</td>
</tr>
<tr>
<td>( \sigma^X_S = \sigma^X_D )</td>
<td>1.02 [0.5191]</td>
<td>0.99 [0.7629]</td>
<td>1.01 [0.6949]</td>
</tr>
<tr>
<td>( \sigma^Y_S = \sigma^Y_D )</td>
<td>0.98 [0.5769]</td>
<td>1.02 [0.4323]</td>
<td>0.99 [0.6369]</td>
</tr>
<tr>
<td>( Leverage^X_S = Leverage^X_D )</td>
<td>0.044 [0.9647]</td>
<td>0.358 [0.7203]</td>
<td>0.167 [0.8677]</td>
</tr>
<tr>
<td>( Leverage^Y_S = Leverage^Y_D )</td>
<td>0.588 [0.5568]</td>
<td>0.820 [0.4121]</td>
<td>0.067 [0.9469]</td>
</tr>
<tr>
<td>( Peak^X_S = Peak^X_D )</td>
<td>-1.036 [0.3003]</td>
<td>0.316 [0.7523]</td>
<td>-0.940 [0.3473]</td>
</tr>
<tr>
<td>( Peak^Y_S = Peak^Y_D )</td>
<td>-0.765 [0.4445]</td>
<td>-0.518 [0.6046]</td>
<td>-0.936 [0.3493]</td>
</tr>
</tbody>
</table>

Note: The symbols D and S denote the original and simulated data, respectively. P-values are presented in squared parentheses under the values of test statistics. * and ** denote rejection of the null hypothesis at the 10% and 5% levels, respectively.