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No Contagion, Only Interdependence: Measuring Stock Market Comovements

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ABSTRACT

Heteroskedasticity biases tests for contagion based on correlation coefficients. When contagion is defined as a significant increase in market comovement after a shock to one country, previous work suggests contagion occurred during recent crises. This paper shows that correlation coefficients are conditional on market volatility. Under certain assumptions, it is possible to adjust for this bias. Using this adjustment, there was virtually no increase in unconditional correlation coefficients (i.e., no contagion) during the 1997 Asian crisis, 1994 Mexican devaluation, and 1987 U.S. market crash. There is a high level of market comovement in all periods, however, which we call interdependence.

IN OCTOBER 1997, THE HONG KONG STOCK MARKET declined sharply and then partially rebounded. As shown in Figure 1, this movement affected markets in North and South America, Europe, and Africa. In December 1994, the Mexican market dropped significantly, and as shown in Figure 2, this fall was quickly reflected in other Latin American markets. Figure 3 shows that in October 1987, the U.S. market crash affected major stock markets around the world. These cases show that dramatic movements in one stock market can have a powerful impact on markets of very different sizes and structures across the globe. Do these periods of highly correlated stock market movements provide evidence of contagion?

Before answering this question, it is necessary to define contagion. There is widespread disagreement about what this term entails, and this paper utilizes a narrow definition that has historically been used in this literature.[1] This paper defines contagion as a significant increase in cross-market linkages after a shock to one country (or group of countries).[2] According to

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[1] For a discussion of alternate definitions and their advantages and disadvantages, see Forbes and Rigobon (2001) or the web site http://www.worldbank.org/economicpolicy/managing%20volatility/contagion/Definitions_of_Contagion/definitions_of_contagion.html.

[2] It is important to note that this definition of contagion is not universally accepted. Some economists argue that contagion occurs whenever a shock to one country is transmitted to another country, even if there is no significant change in cross-market relationships. Others argue that it is impossible to define contagion based on changes in cross-market linkages. Instead, they argue that it is necessary to identify exactly how a shock is propagated across countries, and only certain types of transmission mechanisms (no matter what the magnitude) constitute contagion.

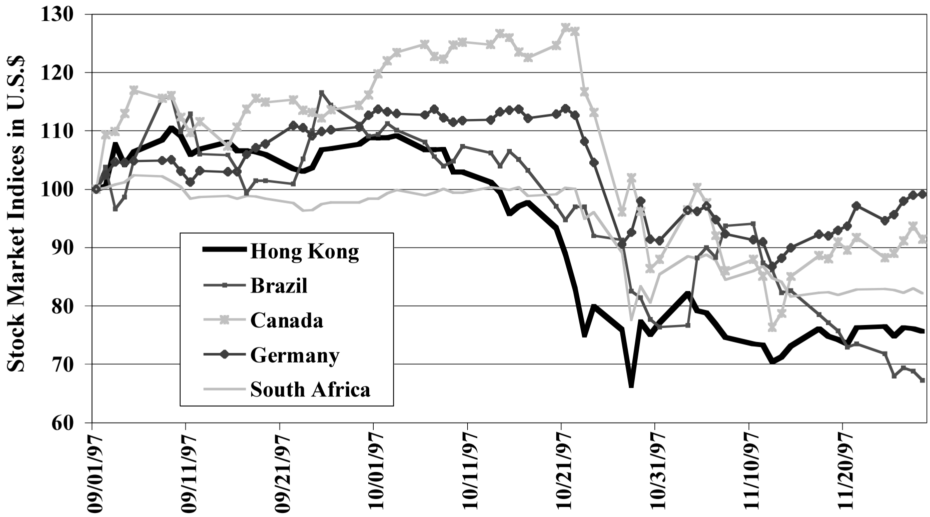

Figure 1. Stock market indices during the 1997 Hong Kong crash. This figure graphs stock market indices for five countries around the time of the October 1997 crash in the Hong Kong market. Indices are set to 100 on September 1, 1997, and are based on U.S. dollar values.

this definition, if two markets show a high degree of comovement during periods of stability, even if the markets continue to be highly correlated after a shock to one market, this may not constitute contagion. According to this paper's definition, it is only contagion if cross-market comovement increases significantly after the shock. If the comovement does not increase significantly, then any continued high level of market correlation suggests strong linkages between the two economies that exist in all states of the world. This paper uses the term *interdependence* to refer to this situation.

Although this definition of contagion is restrictive, it has two important advantages. First, it provides a straightforward framework for testing if contagion occurs. Simply compare linkages between two markets (such as cross-market correlation coefficients) during a relatively stable period (generally measured as a historic average) with linkages directly after a shock or crisis. Contagion is a significant increase in cross-market linkages after the shock. This intuitive test for contagion formed the basis of this literature until the financial crises of the late 1990s.

A second benefit of this definition is that it provides a straightforward method of distinguishing between alternative explanations of how crises are transmitted across markets. There is an extensive theoretical literature on the international propagation of shocks.[3] Many theories assume that investors behave differently after a crisis. Other theories argue that most shocks

[3] For reviews of this literature, see Claessens, Dornbusch, and Park (2001) and Forbes and Rigobon (2001).

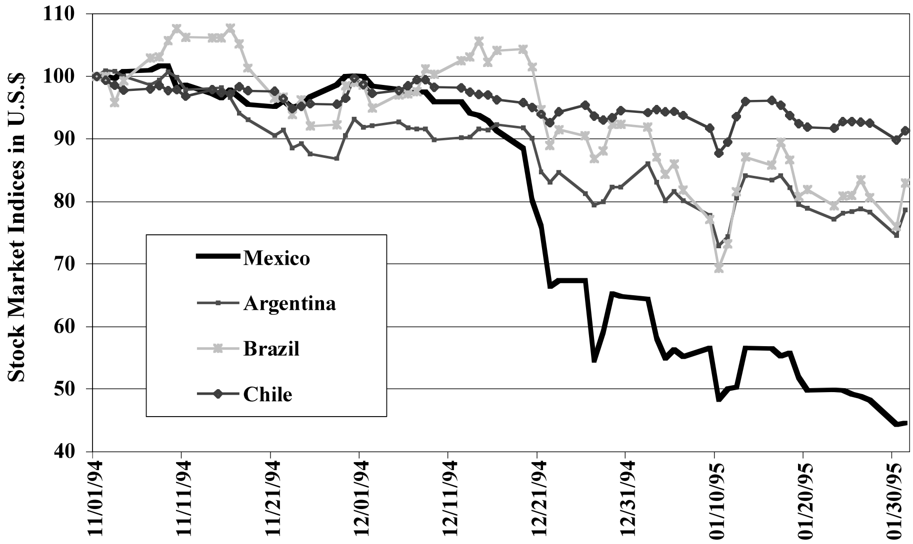

Figure 2. Stock market indices during the 1994 Mexican crisis. This figure graphs stock market indices for four Latin American countries around the time of the December 1994 crash in the Mexican market. Indices are set to 100 on November 1, 1994, and are based on U.S. dollar values.

are propagated through stable real linkages between countries, such as trade. It is extremely difficult to measure these various transmission mechanisms directly. By defining contagion as a significant increase in cross-market linkages, this paper avoids having to directly measure and differentiate between these various propagation mechanisms. Instead, this testing strategy can provide evidence on which group of theories—those predicting a change in cross-country linkages after a shock versus those based on a continuation of the same cross-country linkages that exist in all states of the world—were most important during recent crises.

Even this narrow definition of contagion can incorporate a number of different types of cross-market linkages. For example, linkages could be measured through the correlation in asset returns or the probability of a speculative attack. This paper focuses only on tests for contagion based on cross-market correlation coefficients in order to show clearly that these tests are biased and inaccurate due to heteroskedasticity. Cross-market correlation coefficients are conditional on market volatility. Therefore, during crises when markets are more volatile, estimates of correlation coefficients tend to increase and be biased upward. When tests do not adjust for this bias in the correlation coefficient, they traditionally find evidence of contagion. This paper shows that under certain assumptions (no endogeneity or omitted variables), it is possible to specify the magnitude of this bias and correct for it. When this correction is made, tests based on the unconditional correlation

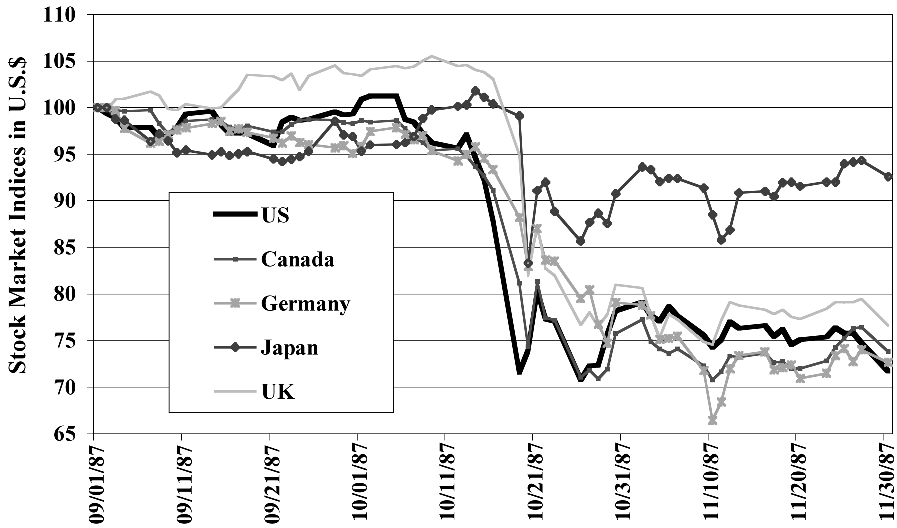

Figure 3. Stock market indices during the 1987 U.S. crash. This figure graphs stock market indices for five countries around the time of the October 1987 crash in the U.S. market. Indices are set to 100 on September 1, 1987, and are based on U.S. dollar values.

coefficients find no significant increase in cross-market correlations during recent financial crises. According to this paper's definition, this can be interpreted as evidence that contagion did not occur during these periods.

The remainder of this paper is as follows. Section I briefly reviews the relevant empirical literature. Section II discusses the conventional technique of using correlation coefficients to test for contagion and uses a numerical example, formal proof, and graphical example to show how heteroskedasticity can bias these tests. This section also proposes one method of adjusting for this bias under certain conditions. The remainder of the paper applies these concepts in empirical tests for stock market contagion.[4] Section III discusses the model and data. Sections IV through VI test for stock market contagion during the 1997 East Asian crisis, 1994 Mexican peso devaluation, and 1987 U.S. market decline, respectively. Each section shows that when correlation coefficients are adjusted to correct for heteroskedasticity, virtually all evidence of contagion disappears. This suggests that high cross-market correlations during these periods are a continuation of strong linkages that exist in all states of the world (interdependence), rather than an increase in these linkages (contagion). The final section of the paper presents several important caveats to these results as well as suggestions for future research.

[4] Although this paper only focuses on stock markets, it is straightforward to apply the methodology to test for contagion based on correlation coefficients in other markets, such as bond and currency markets.

I. Empirical Evidence on International Transmission Mechanisms

As discussed above and shown in Figures 1–3, stock markets of very different sizes, structures, and geographic locations can exhibit a high degree of comovement after a shock to one market. Since stock markets differ greatly across countries, this high degree of comovement suggests the existence of mechanisms through which domestic shocks are transmitted internationally. The empirical literature testing how shocks are propagated and if contagion exists is extensive.[5] Much of this empirical literature uses the same definition of contagion as in this paper, although some of the more recent work has used a broader definition. Four different methodologies have been utilized to measure how shocks are transmitted internationally: cross-market correlation coefficients, ARCH and GARCH models, cointegration techniques, and direct estimation of specific transmission mechanisms. Many of these papers do not explicitly test for contagion, but virtually all papers which do test for its existence conclude that contagion—no matter how defined—occurred during the crisis under investigation.

The first methodology uses cross-market correlation coefficients and is the most straightforward approach to test for contagion. These tests measure the correlation in returns between two markets during a stable period and then test for a significant increase in this correlation coefficient after a shock. If the correlation coefficient increases significantly, this suggests that the transmission mechanism between the two markets strengthened after the shock and contagion occurred. In the first major paper using this approach, King and Wadhwani (1990) test for an increase in stock market correlations between the United States, the United Kingdom, and Japan and find that cross-market correlations increased significantly after the U.S. market crash in 1987. Lee and Kim (1993) extend this analysis to 12 major markets and find further evidence of contagion; average weekly cross-market correlations increased from 0.23 before the 1987 U.S. crash to 0.39 afterward. Calvo and Reinhart (1996) use this approach to test for contagion in stock prices and Brady bonds after the 1994 Mexican peso crisis. They find that cross-market correlations increased for many emerging markets during the crisis. To summarize, each of these tests based on cross-market correlation coefficients reaches the same general conclusion: There was a statistically significant increase in cross-market correlation coefficients during the relevant crisis and, therefore, contagion occurred.[6]

[5] For an excellent survey of this empirical literature, see Claessens et al. (2001). For a number of recent empirical papers on this subject, see Claessens and Forbes (2001).

[6] For further applications and extensions of this general approach, see Bertero and Mayer (1990) for a study of why the transmission of the U.S. stock market crash differed across countries, Karolyi and Stulz (1996) for an analysis of comovements between the U.S. and Japanese markets, Pindyck and Rotemberg (1993) for a study of comovements between individual stock prices within the United States, and Pindyck and Rotemberg (1990) for an analysis of comovements in commodity prices.

A second approach for analyzing market comovement is to use an ARCH or GARCH framework to estimate the variance–covariance transmission mechanisms between countries. Hamao, Masulis, and Ng (1990) use this procedure to examine stock markets around the 1987 U.S. stock market crash and find evidence of significant price-volatility spillovers from New York to London and Tokyo, and from London to Tokyo. Edwards (1998) examines linkages between bond markets after the Mexican peso crisis and shows that there were significant spillovers from Mexico to Argentina, but not from Mexico to Chile. Both of these papers, along with most other studies based on ARCH and GARCH models, show that market volatility is transmitted across countries. They do not, however, explicitly test if this transmission changes significantly after the relevant shock or crisis. Therefore, although these papers provide important evidence that volatility is transmitted across markets, most do not explicitly test for contagion as defined in this paper.

A third method of examining cross-market linkages tests for changes in the cointegrating vector between markets over long periods of time. For example, Longin and Solnik (1995) consider seven OECD countries from 1960 to 1990 and report that average correlations in stock market returns between the United States and other countries rose by about 0.36 over this 30-year period.[7] This approach does not specifically test for contagion, however, since cross-market relationships over such long periods could increase for a number of reasons, such as greater trade integration or higher capital mobility. Moreover, this testing strategy could miss periods of contagion when cross-market relationships only increase briefly after a crisis.

A final series of papers examining international transmission mechanisms attempts to directly measure how different factors affect a country's vulnerability to financial crises. This literature is extensive and incorporates a range of testing strategies. In one of the earliest papers based on this approach, Eichengreen, Rose, and Wyplosz (1996) use a binary-probit model to predict the probability of a crisis occurring in a set of industrial countries between 1959 and 1993. They find that this probability is correlated with the occurrence of a speculative attack in other countries at the same time. Using a very different testing strategy, Forbes (2000) estimates the impact of the Asian and Russian crises on stock returns for a sample of over 10,000 companies around the world. She finds that trade linkages (which she divides into competitiveness and income effects) are important predictors of firms' stock returns and, therefore, of country vulnerability to these crises. Many of these papers measuring specific cross-country transmission channels avoid the debate on how to define contagion and do not explicitly test for its existence.

Although the empirical literature examining how crises are transmitted across markets has used this wide range of methodologies, the remainder of

[7] For further examples of tests based on cointegration, see Chou, Ng, and Pi (1994) or Cashin, Kumar, and McDermott (1995).

this paper focuses only on the first approach: tests based on correlation coefficients. Not only was this approach utilized in the majority of previous work explicitly testing for contagion, but it also provides the most straightforward framework to test for its existence. Moreover, despite the range of countries and time periods investigated, papers based on this approach arrive at a consistent conclusion; there is a statistically significant increase in cross-market correlation coefficients after the relevant crisis and therefore contagion occurred during the time period under investigation.

II. Bias in the Correlation Coefficient

This section shows that tests for contagion based on correlation coefficients are biased and inaccurate due to heteroskedasticity in market returns. It begins with a short numerical example to develop the intuition behind this bias. Then it uses a simple model (which assumes no omitted variables or endogeneity between stock markets) to specify the magnitude of this bias and how to correct for it. The section closes with a graphical example suggesting that this bias could be important in tests for contagion.

This discussion of how changes in market volatility can bias correlation coefficients was motivated by Ronn (1998), which addresses this issue in the estimation of intra-market correlations in stocks and bonds.[8] Ronn, however, uses more restrictive assumptions about the distribution of the residuals in his proof of the bias and does not consider how this bias affects cross-market correlations or the measurement of contagion. More recently, a series of papers has begun to investigate this bias in more detail, as well as broader problems with measuring contagion. Boyer, Gibson, and Loretan (1999) and Loretan and English (2000) use a different statistical framework to document this bias. They propose an adjustment to the correlation coefficient, which, after some algebraic manipulation, is the same as the correction proposed in this paper.[9]

[8] Ronn (1998) indicates that this result was first proposed by Rob Stambaugh in a discussion of Karolyi and Stulz (1995) at an NBER Conference on Financial Risk Assessment and Management.

[9] More specifically, Loretan and English propose the following adjustment to the correlation coefficient:

$$\rho_A = \frac{\rho}{\sqrt{\rho^2 + (1-\rho^2)\dfrac{\mathrm{Var}(x)}{\mathrm{Var}(x|x \in A)}}}.$$

Using the event definitions in this paper, the relative variances are defined as: $\mathrm{Var}(x|x \in A) = (1+\delta)\mathrm{Var}(x)$. If this definition is substituted into the equation for ρ_x, this formula to adjust the correlation coefficient is the same as that derived in this paper (equation (11)).

Table I

A Simulated Example: Heteroskedasticity and Cross-Market Correlations

This table shows that even though underlying linkages between two stock markets remain constant, changes in market volatility (i.e., heteroskedasticity) will affect estimates of cross-market covariances and correlations. In the low volatility scenario, the return on the Nasdaq is assumed to be a uniformly distributed, random number ranging from −1 to 1 percent. In the high volatility scenario, the return on the Nasdaq is multiplied by 10 and therefore ranges from −10 to 10 percent. The return on the Mexican market is calculated as the value of a Mexican domestic shock (which is a uniformly distributed, random number ranging from −2 to 2 percent), plus 20 percent of the return on the Nasdaq for the same period.

	Low Volatility Scenario	High Volatility Scenario
Variance of domestic Mexican innovations	1.33	1.33
Variance of Nasdaq innovations	0.33	33.33
Variance of the Mexican stock market	1.35	2.67
Variance of the Nasdaq	0.33	33.33
Covariance between the two markets	0.07	6.67
Estimated cross-market correlation	10%	71%

A. A Numerical Example: Bias in the Correlation Coefficient

This section presents a simple numerical example to show how heteroskedasticity can bias cross-market correlation coefficients.[10] The assumptions and statistics underlying this example are summarized in Table I. Assume that during normal periods, the daily return on the Nasdaq is a uniformly distributed, random number between −1 percent and 1 percent. During periods of heightened interest in the Internet, however, the Nasdaq becomes more volatile and the impact of the same news on the market return is magnified 10-fold (so that the market return is now a uniformly distributed, random number between −10 and 10 percent). Also assume that the return on the Mexican stock market is comprised of two parts. One part results from domestic shocks to Mexico, which will cause the market return to range from −2 to 2 percent (and is also a uniformly distributed, random variable). The other part is based on events in the United States and is equal to 20 percent of the return in the Nasdaq for the same day.

Therefore, during normal periods when volatility in the Nasdaq is fairly low, most of the variation in the Mexican market is driven by its own idiosyncratic shocks. More specifically, in this example, the variance in Mexico is four times greater than the variance in the Nasdaq. Movement in the Nasdaq explains only 0.04 of the volatility in the Mexican market. As a result, the correlation in returns between Mexico and the Nasdaq is only 10 percent.

[10] For another intuitive example of how heteroskedasticity affects the correlation coefficient, see Forbes and Rigobon (2001). They develop a number of coin-tossing examples to clarify this point.

On the other hand, during periods when the volatility of the Nasdaq increases, the proportion of the variation in the Mexican market driven by movements in the Nasdaq increases significantly. More specifically, in the example when shocks to the Nasdaq are uniformly distributed from -10 to 10, the variance of these shocks is 25 times the variance of the domestic shocks to the Mexican market. As a result, movements in the Nasdaq explain about 50 percent of the variance in the Mexican stock market, and the correlation between these two markets increases to over 70 percent.

This example clearly shows how an increase in market volatility can affect estimates of cross-market correlation coefficients.[11] Even though the transmission mechanism from the Nasdaq to the Mexican market remains constant at 20 percent in both states of the world, estimates of the cross-market correlation coefficient increase from 10 percent during the normal period to 70 percent during the volatile period. Heteroskedasticity in returns (i.e., the increased volatility in the Nasdaq) will affect estimates of cross-market correlation coefficients, even when the underlying cross-market linkages remain constant.

B. Proof of the Bias and a Proposed Correction

This section presents an informal proof of how heteroskedasticity biases the cross-market correlation coefficient. Appendix A presents a more formal proof.[12] For simplicity, the following discussion focuses on the two-market case. Assume x and y are stochastic variables which represent stock market returns (in different markets), and these returns are related according to the equation:

$$y_t = \alpha + \beta x_t + \epsilon_t, \tag{1}$$

where

$$E[\epsilon_t] = 0, \tag{2}$$

$$E[\epsilon_t^2] = c < \infty \tag{3}$$

[11] This simple example can be extended to its limiting values to emphasize the key point. The two markets continue to be linked through the same mechanisms: 20 percent of the Nasdaq return is transmitted to the Mexican market. Now assume that the variance of the Nasdaq falls to zero. Then the covariance and correlation between the two stock markets will be zero. In the other extreme, assume that the variance of the Nasdaq goes to infinity (or that the variance becomes so large that innovations in the Mexican market are negligible by comparison). Then all the movement in the Mexican market is explained by movement in the Nasdaq, so that the correlation between the two markets increases to one. In each case, the true cross-market linkage remains constant (at 0.20), but the estimated correlation coefficient will move from 0 to 1.

[12] Both of these proofs build on Ronn (1998). Ronn, however, uses more restrictive assumptions about the distribution of the residuals.

(where c is a constant), and

$$E[x_t \epsilon_t] = 0. \tag{4}$$

Note that it is not necessary to make any further assumptions about the distribution of the residuals. Divide the sample into two groups, so that the variance of x_t is lower in one group (l) and higher in the second group (h). In terms of our definition of contagion, the low-variance group is the period of relative market stability and the high-variance group is the period of market turmoil directly after the shock or crisis. In the context of the example with Mexico and the Nasdaq discussed above, the low-variance group is the normal period and the high-variance group is the period of heightened interest in the Internet, so that $\alpha = 0$ and $\beta = 0.20$ for both periods.

Next, since $\mathrm{E}[x_t \epsilon_t] = 0$ by assumption in equation (4), OLS estimates of equation (1) are consistent for both groups and $\beta^h = \beta^l$. By construction, we know that $\sigma_{xx}^h > \sigma_{xx}^l$, which, when combined with the standard definition of β:

$$\beta^h = \frac{\sigma_{xy}^h}{\sigma_{xx}^h} = \frac{\sigma_{xy}^l}{\sigma_{xx}^l} = \beta^l, \tag{5}$$

implies that $\sigma_{xy}^h > \sigma_{xy}^l$. In other words, the cross-market covariance is higher in the second group. This increase in the cross-market covariance from that in the first group is directly proportional to the increase in the variance of x.

Meanwhile, according to equation (1), the variance of y is

$$\sigma_{yy} = \beta^2 \sigma_{xx} + \sigma_{ee}. \tag{6}$$

Since the variance of the residual is positive, the increase in the variance of y across groups is less than proportional to the increase in the variance of x. In other words, since the variance of the residuals is assumed to remain constant over the entire sample, this implies that the increase in the variance of y across groups is less than proportional to the increase in the variance of x. Therefore,

$$\left(\frac{\sigma_{xx}}{\sigma_{yy}}\right)^h > \left(\frac{\sigma_{xx}}{\sigma_{yy}}\right)^l. \tag{7}$$

Finally, substitute equation (5) into the standard definition of the correlation coefficient:

$$\rho = \frac{\sigma_{xy}}{\sigma_x \sigma_y} = \beta \frac{\sigma_x}{\sigma_y}, \tag{8}$$

and, when combined with equation (7), this implies that $\rho^h > \rho^l$.

As a result, the estimated correlation between x and y increases when the variance of x increases—even if the true relationship (β) between x and y is constant. Therefore, tests for a change in cross-market transmission mechanisms based on the correlation coefficient can be misleading. Estimates of the correlation coefficient are biased and conditional on the variance of x.

The formal proof presented in Appendix A shows that it is possible to quantify the extent of this bias. More specifically, if we continue to assume the absence of endogeneity (equation (4)) and omitted variables (equation (2)), the conditional correlation can be written as

$$\rho^* = \rho\sqrt{\frac{1+\delta}{1+\delta\rho^2}}, \tag{9}$$

where ρ^* is the conditional correlation coefficient, ρ is the unconditional correlation coefficient, and δ is the relative increase in the variance of x:

$$\delta \equiv \frac{\sigma_{xx}^h}{\sigma_{xx}^l} - 1. \tag{10}$$

Equation (9) clearly shows that the estimated correlation coefficient is increasing in δ. Therefore, during periods of high volatility in market x, the estimated correlation (i.e., the conditional correlation) between markets y and x will be greater than the unconditional correlation. In other words, even if the unconditional correlation coefficient remains constant during a stable period and volatile period, the conditional correlation coefficient will be greater during the more volatile period.

This result has direct implications for tests for contagion based on cross-market correlation coefficients. Markets tend to be more volatile after a shock or crisis. Therefore, the conditional correlation coefficient will tend to increase after a crisis, even if the unconditional correlation coefficient (the underlying cross-market relationship) is the same as during more stable periods. In other words, heteroskedasticity in market returns can cause estimates of cross-market correlation coefficients to be biased upward after a crisis. Formal tests for contagion could find a significant increase in the estimated, conditional correlation coefficients after a crisis. Without adjusting for the bias, however, it is impossible to deduce if this increase in the conditional correlation represents an increase in the unconditional correlation or simply an increase in market volatility. According to our definition, only an increase in the unconditional correlation coefficient would constitute contagion.

Under the assumptions discussed above, it is straightforward to adjust for this bias. Simple manipulation of equations (9) and (10) to solve for the unconditional correlation coefficient yields

$$\rho = \frac{\rho^*}{\sqrt{1+\delta[1-(\rho^*)^2]}}. \tag{11}$$

One potential problem with this adjustment for heteroskedasticity is that it assumes there are no omitted variables or endogeneity between markets (written as equations (2) and (4)). In other words, the proof of this bias and the adjustment is only valid if there are no exogenous global shocks and no feedback from stock market y to x. These assumptions are clearly a simplification, but there does not currently exist any procedure that can adjust the correlation coefficient without making these two assumptions. Appendix B analyzes the impact of relaxing these two assumptions. This appendix shows that the correlation coefficient is still biased in the presence of heteroskedasticity and omitted variables or endogeneity. It also shows that without making additional assumptions, it is impossible to estimate the extent of this bias and, therefore, impossible to make any sort of simple adjustment to calculate the unconditional correlation coefficient.

On a more positive note, however, Appendix B also shows that the adjustment in equation (11) is a relatively good approximation of the unconditional correlation coefficient if the change in the variance is large and it is possible to identify the country where the shock originates. The intuition behind these findings is based on what the simultaneous-equations literature calls near identification. More specifically, assume that there are two countries whose returns are simultaneously determined and both affected by the same aggregate shock as well as their own idiosyncratic shocks. If the idiosyncratic shock affecting one country is much larger than the aggregate shock, then the adjustment to the correlation coefficient proposed in equation (11) is fairly accurate.

In the empirical implementation below, we ascertain that these criteria for near identification are valid when deciding which pairs of correlations to calculate and test for contagion. The three criteria are: a major shift in market volatility, clear identification of which country generates this shift in volatility, and inclusion of the relevant country as one market in the estimated correlation. The data suggests that these criteria are satisfied during the crisis periods investigated in this paper. During the three relevant periods, the variance of returns in the crisis countries increased by over 10 times, and the source of the shock is clear (the United States in 1987, Mexico in 1994, and Hong Kong in October, 1997). We only test for contagion from the country where the shock originates to other countries in the sample. For example, during December 1994, there was a large increase in market volatility caused mainly by events in Mexico. Therefore, it is only valid to use this framework and the adjustment in equation (11) to analyze cross-market correlations between Mexico and each of the other countries in the sample during this period. (It is not valid to use this framework, for example, to test for contagion from Chile to Argentina during this period.)

C. A Graphical Example: The Bias in Tests for Contagion

To clarify the intuition behind this bias in the cross-market correlation coefficient and its potential importance in tests for contagion, Figure 4 graphs the correlation in stock market returns between Hong Kong and the Philip-

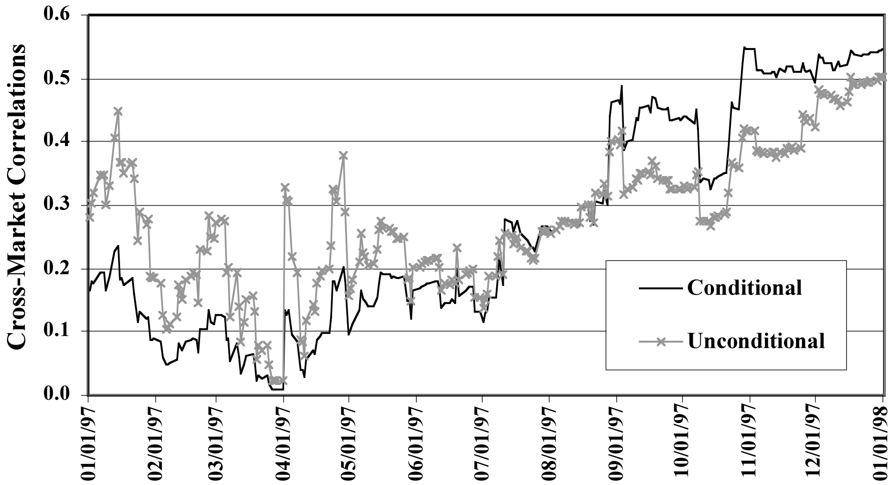

Figure 4. Cross-market correlations: Hong Kong and the Philippines. This figure graphs the conditional and unconditional correlations in stock market returns between Hong Kong and the Philippines during 1997. Correlations are calculated as quarterly-moving averages based on U.S. dollar returns. The unconditional correlation is calculated using the adjustment specified in equation (11).

pines during 1997.[13] The dark line is the conditional correlation in daily returns (ρ_t^*), which has traditionally been used in tests for contagion. The line marked with x's is the unconditional correlation (ρ_t), adjusted for heteroskedasticity as specified in equation (11), and represents the underlying relationship between the two stock markets.

While the two lines in Figure 4 tend to move together, the bias generated by heteroskedasticity is clearly significant. During the relatively stable period in the first half of 1997, the conditional correlation is slightly lower than the unconditional correlation. On the other hand, during the more volatile period of the fourth quarter, the conditional correlation is substantially greater than the unconditional correlation. Despite the upward trend visible in the chart, tests for contagion based on the conditional correlation coefficients find a significant increase in cross-market correlations in the fourth quarter. Tests for contagion based on the unconditional correlations do not find a significant increase in cross-market correlations. As a result, tests based on the conditional correlation coefficient conclude that contagion occurred from Hong Kong to the Philippines during this period, while tests based on the unconditional correlations conclude that contagion did not occur. These conflicting conclusions are generated solely by the bias in the cross-market correlation coefficient generated by heteroskedasticity in market returns.

[13] Correlations are calculated as quarterly moving averages. The exact procedure, definitions, and data source used to estimate this graph are described in detail in Section III.

III. The Base Model and the Data

Before formally analyzing how heteroskedasticity biases tests for contagion during recent financial crises, this section briefly discusses our model specification and data set. To adjust for the fact that stock markets are open during different hours, as well as to control for serial correlation in stock returns and any exogenous global shocks, we utilize a VAR framework to estimate cross-market correlations. More specifically, the base specification is:

$$X_t = \phi(L)X_t + \Phi(L)I_t + \eta_t \tag{12}$$

$$X_t \equiv \{x_t^C, x_t^j\}' \tag{13}$$

$$I_t \equiv \{i_t^C, i_t^{US}, i_t^j\}', \tag{14}$$

where x_t^C is the stock market return in the crisis country; x_t^j is the stock market return in another market j; X_t is a transposed vector of returns in the same two stock markets; $\phi(L)$ and $\Phi(L)$ are vectors of lags; i_t^C, i_t^{US}, and i_t^j are short-term interest rates for the crisis country, the United States, and country j, respectively; and η_t is a vector of reduced-form disturbances. For each series of tests, we first use the VAR model in equations (12) through (14) to estimate the variance–covariance matrices for each pair of countries during the stable period, turmoil period, and full period. Then we use the estimated variance–covariance matrices to calculate the cross-market correlation coefficients (and their asymptotic distributions) for each set of countries and periods.

Stock market returns are calculated as rolling-average, two-day returns based on each country's aggregate stock market index.[14] We utilize average two-day returns to control for the fact that markets in different countries are not open during the same hours. We calculate returns based on U.S. dollars as well as local currency, but focus on U.S. dollar returns since these were most frequently used in past work on contagion. We utilize five lags for $\phi(L)$ and $\Phi(L)$ in order to control for serial correlation and any within-week variation in trading patterns. We include interest rates in order to control for any aggregate shocks and/or monetary policy coordination.[15] All of the data is from Datastream. An extensive set of sensitivity tests (many of which are reported below), show that changing the model specification has no significant impact on results. For example, using daily or weekly returns, local currency returns, greater or fewer lags, and/or varying the interest rate controls does not change our central findings. Moreover, the sensitivity analy-

[14] Daily returns are also adjusted for weekends and holidays.

[15] Although interest rates are an imperfect measure of aggregate shocks, they are a good proxy for global shifts in real economic variables and/or policies that affect stock market performance.

Table II

Stock Market Characteristics

This table shows the total market capitalization and annual value traded of each stock market in the sample. All statistics are reported as millions of U.S. dollars as of year-end 1996. Data source is International Finance Corporation (1997).

Region	Country	Total Market Capitalization	Total Value Traded
East Asia	Hong Kong	449,381	166,419
	Indonesia	91,016	32,142
	Japan	3,088,850	1,251,998
	Korea	138,817	177,266
	Malaysia	307,179	173,568
	Philippines	80,649	25,519
	Singapore	150,215	42,739
	Taiwan	273,608	470,193
	Thailand	99,828	44,365
Latin America	Argentina	44,679	n.a.
	Brazil	261,990	112,108
	Chile	65,940	8,460
	Mexico	106,540	43,040
OECD	Australia	311,988	145,482
	Belgium	119,831	26,120
	Canada	486,268	265,360
	France	591,123	277,100
	Germany	670,997	768,745
	Italy	258,160	102,351
	Netherlands	378,721	339,500
	Spain	242,779	249,128
	Sweden	247,217	136,898
	Switzerland	402,104	392,783
	United Kingdom	1,740,246	578,471
	United States	8,484,433	7,121,487
Other emerging markets	China	113,755	256,008
	India	122,605	109,448
	Russia	37,230	n.a.
	South Africa	241,571	27,202

sis also shows that focusing only on the cross-market correlation coefficient—with daily returns, no lags, and no interest rate controls—actually strengthens our central results.

For our analysis of the East Asian crisis and Mexican peso crisis, the sample of countries includes 28 markets: the 24 largest markets (as ranked by market capitalization at the end of 1996), plus Argentina, Chile, the Philippines, and Russia. Table II lists these countries with total stock market capitalization and average market volume. It also defines the regions utilized throughout this paper. For our analysis of the 1987 U.S. stock market crash, however, many of these 28 markets were highly illiquid (or not even in existence). Therefore, during this earlier period we only include the 10 largest markets.

IV. Contagion from Hong Kong during the 1997 East Asian Crisis

As our first empirical analysis of how heteroskedasticity biases tests for contagion based on the correlation coefficient, we consider the East Asian crisis of 1997. One difficulty in testing for contagion during this period is that no single event acts as a clear catalyst behind this turmoil. For example, the Thai market declined sharply in June, the Indonesian market fell in August, and the Hong Kong market crashed in mid-October. A review of American and British newspapers and periodicals during this period, however, shows an interesting pattern. The press in these countries paid little attention to the earlier movements in the Thai and Indonesian markets until the sharp decline in the Hong Kong market in mid-October. After this, events in Asia became headline news, and an avid discussion quickly began on the East Asian "crisis" and the possibility of "contagion" to the rest of the world.

Therefore, for our base analysis, we focus on tests for contagion from Hong Kong to the rest of the world during the volatile period directly after the Hong Kong crash. It is obviously possible that contagion occurred during other periods of time, or from the combined impact of turmoil in a group of East Asian markets instead of in a single country. We test for these various types of contagion in the sensitivity analysis and show that using these different contagion sources has no significant impact on key results.[16] Using the October decline in the Hong Kong market as the base for our contagion tests, we define our "turmoil" period as the month starting on October 17, 1997 (the start of this visible Hong Kong crash). We define the "stable" period as January 1, 1996, to the start of the turmoil period.[17]

Then we estimate the VAR model specified in equations (12) through (14) with Hong Kong as the crisis country (c). Using the variance–covariance estimates from this model, we calculate the cross-market correlation coefficients between Hong Kong and each of the other countries in the sample during the stable period, turmoil period, and full period. Then we use these coefficients to perform the standard test for contagion described at the start of Section I. These are based on the conditional correlation coefficients and are not adjusted for heteroskedasticity. Finally, we use t-tests to evaluate if

[16] Many papers date the start of the Asian crisis as the Thai devaluation in July 1997. The sensitivity analysis shows, however, that there were few cases of contagion after the Thai devaluation (based on the conditional correlation coefficients), and since markets were less volatile during this earlier period, the bias in tests for contagion is less problematic. Therefore, for the purpose of this paper, the Hong Kong crisis provides a cleaner example of how heteroskedasticity can bias tests for contagion.

[17] A sensitivity analysis shows that period definition does not affect the central results. We do not utilize a longer length of time for the stable period in our base estimates due to the fact that any structural change in markets over this period would invalidate the tests for contagion.

there is a significant increase in any of these correlation coefficients during the turmoil period.[18] If ρ is the correlation during the full period and ρ_t^h is the correlation during the turmoil (high volatility) period, the test hypotheses are

$$\begin{aligned} &H_0 : \rho > \rho_t^h \\ &H_1 : \rho \leq \rho_t^h. \end{aligned} \tag{15}$$

The estimated, conditional correlation coefficients for the stable, turmoil, and full period are shown in Table III. The critical value for the *t*-test at the five percent level is 1.65, so any test statistic greater than this critical value indicates contagion (C), while any statistic less than or equal to this value indicates no contagion (N). Test statistics and results are reported on the right of the table.

Several patterns are immediately apparent. First, cross-market correlations during the relatively stable period are not surprising. Hong Kong is highly correlated with Australia and many of the East Asian economies, and much less correlated with Latin American markets. Second, cross-market correlations between Hong Kong and most of the other countries in the sample increase during the turmoil period. This is a prerequisite for contagion to occur. This change is especially notable in many of the OECD markets, where the average correlation with Hong Kong increases from 0.22 during the stable period to 0.68 during the turmoil period. In one extreme example, the correlation between Hong Kong and Belgium increases from 0.14 in the stable period to 0.71 in the turmoil period. Third, the *t*-tests indicate a significant increase in this conditional correlation coefficient during the turmoil period for 15 countries. According to the standard interpretation in this literature, this implies that contagion occurred from the October crash of the Hong Kong market to Australia, Belgium, Chile, France, Germany, Indonesia, Italy, Korea, the Netherlands, the Philippines, Russia, South Africa, Spain, Sweden, and Switzerland.

As discussed above, however, these tests for contagion may be inaccurate due to the bias in the correlation coefficient resulting from heteroskedasticity. The estimated increases in the conditional correlation coefficient could reflect either an increase in cross-market linkages and/or increased market volatility. To test how any bias in the correlation coefficient affects our tests for contagion, we repeat this analysis but use the correction in equation (11) to adjust for this bias. In other words, we repeat the above analysis using the unconditional instead of the conditional correlation coefficients. Unconditional correlation coefficients and test results are shown in Table IV.

[18] We have also experimented with a number of other tests, such as two-sided tests and/or comparing the correlation coefficient during the turmoil period with that during the stable period (instead of the full period). In each case, test specification has no significant impact on results.

Table III

1997 East Asian Crisis: Conditional Correlation Coefficients

This table reports conditional (unadjusted) cross-market correlation coefficients and standard deviations for Hong Kong and each country in the sample. The stable period is defined as January 1, 1996, through October 16, 1997. The turmoil period is defined as one month starting on October 17, 1997. The full period is the stable period plus the turmoil period. The test statistics are for one-sided t-tests examining if the cross-market correlation coefficient during the full period is significantly greater than during the turmoil (high volatility) period. "C" in the final column indicates that the test statistic is greater than the critical value and therefore contagion occurred. "N" in the final column indicates that the test statistic was less than or equal to the critical value and therefore no contagion occurred.

		Stable		Turmoil		Full Period		Test	
Region	Country	ρ	σ	ρ	σ	ρ	σ	Statistic	Contagion?
East Asia	Indonesia	0.381	0.040	0.749	0.146	0.428	0.037	1.75	C
	Japan	0.231	0.044	0.559	0.229	0.263	0.042	1.09	N
	Korea	0.092	0.046	0.683	0.178	0.173	0.044	2.30	C
	Malaysia	0.280	0.043	0.465	0.261	0.288	0.041	0.58	N
	Philippines	0.294	0.042	0.705	0.168	0.323	0.041	1.83	C
	Singapore	0.341	0.041	0.493	0.252	0.348	0.040	0.50	N
	Taiwan	0.010	0.046	0.149	0.326	0.028	0.046	0.33	N
	Thailand	0.046	0.046	0.402	0.279	0.082	0.045	0.99	N
Latin America	Argentina	0.030	0.046	−0.144	0.326	0.004	0.046	−0.40	N
	Brazil	0.105	0.046	−0.593	0.332	0.080	0.045	−0.37	N
	Chile	0.144	0.045	0.619	0.206	0.197	0.044	1.69	C
	Mexico	0.238	0.044	0.241	0.314	0.238	0.043	0.01	N
OECD	Australia	0.356	0.040	0.865	0.084	0.431	0.037	3.59	C
	Belgium	0.140	0.045	0.714	0.163	0.178	0.044	2.58	C
	Canada	0.145	0.045	0.378	0.286	0.170	0.044	0.63	N
	France	0.227	0.044	0.886	0.072	0.299	0.042	5.19	C
	Germany	0.383	0.039	0.902	0.062	0.450	0.036	4.60	C
	Italy	0.175	0.045	0.896	0.066	0.236	0.043	6.05	C
	Netherlands	0.319	0.042	0.742	0.150	0.347	0.040	2.08	C
	Spain	0.191	0.045	0.878	0.076	0.269	0.042	5.14	C
	Sweden	0.233	0.044	0.796	0.122	0.298	0.042	3.04	C
	Switzerland	0.183	0.045	0.842	0.097	0.232	0.043	4.34	C
	U.K.	0.255	0.043	0.615	0.201	0.280	0.042	1.34	N
	U.S.	0.021	0.046	−0.390	0.285	−0.027	0.046	−1.11	N
Other emerging markets	India	0.097	0.046	0.024	0.333	0.089	0.045	−0.17	N
	Russia	0.026	0.043	0.866	0.084	0.365	0.040	4.07	C
	S. Africa	0.368	0.040	0.052	0.092	0.455	0.036	3.10	C

It is immediately apparent that adjusting for heteroskedasticity has a significant impact on estimated cross-market correlations and the resulting tests for contagion. In each country, the unconditional correlation is substantially smaller (in absolute value) than the conditional correlation during the turmoil period and is slightly greater in the stable period. For example, during the turmoil period, the average conditional correlation for the entire

Table IV

1997 East Asian Crisis: Unconditional Correlation Coefficients

This table reports unconditional cross-market correlation coefficients and standard deviations for Hong Kong and each country in the sample. The correlation coefficients have been adjusted for heteroskedasticity using equation (11). The stable period is defined as January 1, 1996, through October 16, 1997. The turmoil period is defined as one month starting on October 17, 1997. The full period is the stable period plus the turmoil period. The test statistics are for one-sided t-tests examining if the cross-market correlation coefficient during the full period is significantly greater than during the turmoil (high volatility) period. "C" in the final column indicates that the test statistic is greater than the critical value and therefore contagion occurred. "N" in the final column indicates that the test statistic was less than or equal to the critical value and therefore no contagion occurred.

		Stable		Turmoil		Full Period			
Region	Country	ρ	σ	ρ	σ	ρ	σ	Test Statistic	Contagion?
East Asia	Indonesia	0.413	0.042	0.399	0.244	0.428	0.037	−0.10	N
	Japan	0.252	0.045	0.255	0.290	0.263	0.042	−0.02	N
	Korea	0.098	0.046	0.380	0.257	0.173	0.044	0.69	N
	Malaysia	0.305	0.044	0.200	0.304	0.288	0.042	−0.26	N
	Philippines	0.315	0.044	0.388	0.253	0.323	0.041	0.22	N
	Singapore	0.348	0.043	0.343	0.288	0.348	0.040	−0.02	N
	Taiwan	0.010	0.046	0.058	0.331	0.028	0.046	0.08	N
	Thailand	0.051	0.046	0.171	0.312	0.082	0.045	0.25	N
Latin America	Argentina	0.033	0.046	−0.059	0.331	0.004	0.046	−0.17	N
	Brazil	0.113	0.046	−0.025	0.333	0.080	0.045	−0.28	N
	Chile	0.157	0.046	0.302	0.277	0.197	0.044	0.33	N
	Mexico	0.256	0.045	0.102	0.326	0.238	0.043	−0.37	N
OECD	Australia	0.385	0.042	0.561	0.191	0.431	0.037	0.57	N
	Belgium	0.153	0.046	0.371	0.254	0.178	0.044	0.65	N
	Canada	0.159	0.046	0.156	0.315	0.170	0.044	−0.04	N
	France	0.248	0.045	0.596	0.177	0.299	0.042	1.35	N
	Germany	0.412	0.042	0.642	0.162	0.450	0.036	0.97	N
	Italy	0.191	0.045	0.818	0.170	0.236	0.043	1.79	C
	Netherlands	0.346	0.043	0.397	0.246	0.347	0.040	0.18	N
	Spain	0.209	0.045	0.584	0.182	0.269	0.042	1.40	N
	Sweden	0.255	0.045	0.454	0.226	0.298	0.042	0.58	N
	Switzerland	0.200	0.045	0.519	0.205	0.232	0.043	1.16	N
	U.K.	0.278	0.044	0.292	0.279	0.280	0.042	0.04	N
	U.S.	0.023	0.046	−0.169	0.313	−0.027	0.046	−0.40	N
Other emerging markets	India	0.101	0.046	0.009	0.333	0.089	0.045	−0.21	N
	Russia	0.285	0.044	0.569	0.188	0.365	0.040	0.89	N
	S. Africa	0.389	0.042	0.592	0.186	0.455	0.036	0.62	N

sample is 0.53, while the average unconditional correlation is 0.32. During the stable period, the average conditional correlation is 0.20 while the average unconditional correlation is 0.22. In many cases, the unconditional correlation coefficient is still greater during the turmoil period than the full period, but this increase is substantially smaller than that reported in Table III.

For example, the conditional correlation between Hong Kong and the Netherlands jumps from 0.35 during the full period to 0.74 during the turmoil period, while the unconditional correlation only increases from 0.35 to 0.40. Moreover, when tests for contagion are performed on these unconditional correlations, only one coefficient (for Italy) increases significantly during the turmoil period. In other words, according to this testing methodology, there is only evidence of contagion from the Hong Kong crash to one other country in the sample (versus 15 cases of contagion when tests are based on the conditional correlations).

Moreover, these results highlight exactly how this testing methodology defines contagion. Many stock markets are highly correlated with Hong Kong's market during this volatile period in October and November of 1997. For example, during this period, the unconditional correlation between Hong Kong and Australia is 0.56 and that between Hong Kong and the Philippines is 0.39. These high cross-market correlations do not qualify as contagion, however, because these markets are correlated to a similar high degree during more stable periods. These stock markets are highly interdependent in all states of the world. Therefore, according to the assumptions and simple tests performed above, this interdependence does not change significantly during October and November of 1997.

A. Sensitivity Tests

Since this adjustment to the correlation coefficient has such a significant impact on our analysis, we perform an extensive series of sensitivity tests. In the following section, we test for the impact of modifying the period definitions, the source of contagion, the frequency of returns, the lag structure, the interest rate controls, and the currency denomination. In each case (as well as others not reported below), the central results do not change. Tests based on the conditional correlation coefficients find some evidence of contagion, while tests based on the unconditional coefficients (adjusted according to equation (11)) find virtually no evidence of contagion. Due to the repetition of these tests, we only report a selection of summary results for each analysis.[19]

As a first set of robustness tests, we modify definitions for the stable and turmoil periods. In the base analysis, we define the stable period as January 1, 1996, through October 16, 1997, and the turmoil period as the month starting on October 17, 1997. We begin by defining the turmoil period as starting at an earlier date, such as on June 1, 1997 (when the Thai market first dropped) or on August 7, 1997 (when the Indonesian and Thai markets began their simultaneous decline). Next we extend the turmoil period to end on March 1, 1998. Then we extend the length of the stable period by defining it to begin on January 1, 1993, or January 1, 1995. A selection of these

[19] Complete results are available from the authors.

results is reported near the top of Table V. The base case is reported in bold italics in the first row of the table.

For a second set of sensitivity tests, we examine how altering the defined source of contagion can impact results. As discussed above, one difficulty in testing for contagion during the East Asian crisis is that there is no single event acting as a clear catalyst driving this turmoil. We begin by testing for contagion from single East Asian markets (other than Hong Kong) after a significant downturn in those markets: from Thailand after its June decline; from Thailand or Indonesia after their August losses; or from Korea for the two-months after its crash that started in late October. Next, since contagion may occur from the combined impact of movements in several East Asian markets, we construct several East Asian indices.[20] We test for contagion from Thailand and Indonesia after the August crashes in both of these markets; from Hong Kong and Korea during several tumultuous periods in these markets; and from Hong Kong, Indonesia, Korea, Malaysia, and Thailand (a five-country index) during several different periods. Summary results for a selection of these tests are reported in the middle of Table V.

As a third series of robustness tests, we adjust the frequency of returns and/or lag structure. In our base analysis, we focus on rolling-average, two-day returns in order to control for the fact that different stock markets are open during different hours. We also include five lags of the cross-market correlations (X_t) and the vector of interest rates (I_t). We repeat this analysis using daily returns and weekly returns. We also combine each of these return calculations with zero, one, or five lags (as possible) of X_t and I_t.[21] A selection of results is reported near the bottom of Table V.

For a final series of sensitivity tests, we vary the interest rate controls and currency denomination. First, we include no interest rates in the model or only include interest rates in the United States or the crisis country. Then we repeat the analysis with local-currency returns with a variety of lag and return structures. A sample of these results is reported at the bottom of Table V. It is worth noting that the results reported in the last row of the table—with daily returns, no lags, and no interest rate controls—is a test for contagion in the simple theoretical model (developed in Section II) before adding the additional controls and extensions in Section III.

This series of sensitivity tests reported in Table V suggests that a wide range of modifications to our base model do not affect the central results. When tests for a significant change in cross-market relationships are based on the conditional correlation coefficients, there is evidence of contagion in

[20] To calculate each index, we weight each country by total market capitalization at the end of 1996, as reported in Table II.

[21] Note that in each case, estimates are only consistent if there are at least as many lags (minus one) as the number of days averaged to calculate the returns. Lags are required because we utilize a moving average to measure returns. Therefore, by construction, observations at time t are correlated with those at $t - 1$, $t - 2$, and so forth. Also note that we do not use more than five lags due to the short length of the turmoil period.

Table V

1997 East Asian Crisis: Robustness Tests

This table summarizes test results for a series of sensitivity tests and extensions to the analysis performed in Tables III and IV. The base analysis is reported in bold italics in the first row. In every other row, modifications to the base analysis are printed in bold. The final two columns report the total number of cases of contagion indicated from one-sided t-tests using the conditional and unconditional cross-market correlation coefficients.

Source of Contagion	Turmoil Period	Start of Stable Period	Return Frequency	Lags Included	Interest Rate Controls	Currency of Returns	Cases of Contagion based on	
							Conditional ρ	Unconditional ρ
Hong Kong	***10/17/97–11/16/97***	***01/01/96***	***2-day avg.***	***5***	$\boldsymbol{i^{HK}, i^{US}, i^{j}}$	***U.S. $***	***15***	***1***
Hong Kong	**06/01/97–11/16/97**	01/01/96	2-day avg.	5	i^{HK}, i^{US}, i^{j}	U.S. $	2	0
Hong Kong	**10/17/97–03/01/98**	01/01/96	2-day avg.	5	i^{HK}, i^{US}, i^{j}	U.S. $	16	0
Hong Kong	10/17/97–11/16/97	**01/01/95**	2-day avg.	5	i^{HK}, i^{US}, i^{j}	U.S. $	15	1
Thailand	**06/01/97–06/30/97**	01/01/96	2-day avg.	5	i^{HK}, i^{US}, i^{j}	U.S. $	0	0
Indonesia	**08/07/97–09/06/97**	01/01/96	2-day avg.	5	i^{HK}, i^{US}, i^{j}	U.S. $	5	0
Korea	**10/23/97–12/22/97**	01/01/96	2-day avg.	5	i^{HK}, i^{US}, i^{j}	U.S. $	0	0
Hong Kong, Korea	**10/17/97–12/23/97**	01/01/96	2-day avg.	5	i^{HK}, i^{US}, i^{j}	U.S. $	12	0
5-country index	**10/17/97–12/23/97**	01/01/96	2-day avg.	5	i^{HK}, i^{US}, i^{j}	U.S. $	6	0
5-country index	**08/07/97–03/01/98**	01/01/96	2-day avg.	5	i^{HK}, i^{US}, i^{j}	U.S. $	7	0
Hong Kong	10/17/97–11/16/97	01/01/96	**Daily**	**0**	i^{HK}, i^{US}, i^{j}	U.S. $	17	0
Hong Kong	10/17/97–11/16/97	01/01/96	**Weekly**	5	i^{HK}, i^{US}, i^{j}	U.S. $	13	2
Hong Kong	10/17/97–11/16/97	01/01/96	2-day avg.	5	**None**	U.S. $	15	0
Hong Kong	10/17/97–11/16/97	01/01/96	2-day avg.	5	$\boldsymbol{i^{US}}$	U.S. $	15	0
Hong Kong	10/17/97–11/16/97	01/01/96	2-day avg.	5	i^{HK}, i^{US}, i^{j}	**Local**	14	2
Hong Kong	10/17/97–11/16/97	01/01/96	**Daily**	**1**	i^{HK}, i^{US}, i^{j}	**Local**	14	0
Hong Kong	10/17/97–11/16/97	01/01/96	**Daily**	**0**	**None**	U.S. $	16	0

about half the sample (with the number of cases highly dependent on the specification estimated). When tests are based on the unconditional correlation coefficients, there is virtually no evidence of a significant increase in cross-market linkages.

V. Contagion during the 1994 Mexican Peso Crisis

As our second analysis of how bias in the correlation coefficient can affect tests for contagion, we compare cross-market correlations before and after the Mexican peso crisis of 1994. In December 1994, the Mexican government suffered a balance of payments crisis, leading to a devaluation of the peso and a precipitous decline in the Mexican stock market. This crisis generated fears that contagion could quickly lead to crises in other emerging markets and especially in the rest of Latin America. This analysis is more straightforward than that of the East Asian crisis due to the existence of one clear catalyst driving any contagion.

For our base test, we define the turmoil period in the Mexican market as lasting from December 19, 1994 (the day the exchange rate regime was abandoned) through December 31, 1994. We define the entire period as January 1, 1993 through December 31, 1995 (with the stable period including all days except the turmoil period). Next, we estimate the same system of equations (12) through (14) with Mexico as the crisis country (c). We repeat the standard test for stock market contagion: test for a significant increase in cross-market correlations during the turmoil period. Estimates of the conditional correlation coefficients (which have not been adjusted for heteroskedasticity) and test results are shown in Table VI.

These conditional correlation coefficients show many patterns similar to the East Asian case. First, during the relatively stable period, the Mexican market tends to be more highly correlated with markets in the same region. Second, cross-market correlations between Mexico and most countries in the sample increase during the turmoil period. This is a prerequisite for contagion to occur. Many developed countries that are not highly correlated with Mexico during the stable period become highly correlated during the turmoil period. Third, the t-tests indicate that there is a significant increase (at the five percent level) in the correlation coefficient during the turmoil period for six countries. According to the interpretation used in previous empirical work, this indicates that contagion occurred from the Mexican stock market in December 1994 to Argentina, Belgium, Brazil, Korea, the Netherlands, and South Africa.

As discovered above, however, this evidence of contagion could result from heteroskedasticity biasing estimates of cross-market correlations. Therefore, we repeat these tests using equation (11) to adjust for this bias (again under the assumptions of no omitted variables or endogeneity). Estimated unconditional correlation coefficients and test results are shown in Table VII. Once again, this adjustment has a significant impact on estimated correlations and the resulting tests for contagion. In each country, the unconditional

Table VI

1994 Mexican Peso Crisis: Conditional Correlations in Stock Market Returns

This table reports conditional (unadjusted) cross-market correlation coefficients and standard deviations for Mexico and each country in the sample. The turmoil period is defined as December 19, 1994, through December 31, 1994. The stable period is defined as January 1, 1993, through December 31, 1995 (excluding the turmoil period). The full period is the stable period plus the turmoil period. The test statistics are for one-sided t-tests examining if the cross-market correlation coefficient during the full period is significantly greater than during the turmoil (high volatility) period. "C" in the final column indicates that the test statistic is greater than the critical value and therefore contagion occurred. "N" in the final column indicates that the test statistic was less than or equal to the critical value and therefore no contagion occurred.

		Stable		Turmoil		Full Period			
Region	Country	ρ	σ	ρ	σ	ρ	σ	Test Statistic	Contagion?
East Asia	Hong Kong	0.055	0.037	0.467	0.391	0.070	0.036	0.93	N
	Indonesia	0.042	0.037	0.194	0.481	0.049	0.036	0.28	N
	Japan	0.028	0.037	0.426	0.409	0.036	0.036	0.87	N
	Korea	0.035	0.037	0.721	0.240	0.058	0.036	2.40	C
	Malaysia	0.048	0.037	−0.064	0.498	0.042	0.036	−0.20	N
	Philippines	0.066	0.037	−0.067	0.498	0.061	0.036	−0.24	N
	Singapore	0.068	0.037	0.194	0.481	0.070	0.036	0.24	N
	Taiwan	0.092	0.036	0.526	0.362	0.097	0.036	1.08	N
	Thailand	0.047	0.037	0.101	0.495	0.045	0.036	0.10	N
Latin America	Argentina	0.382	0.031	0.859	0.131	0.401	0.031	2.84	C
	Brazil	0.384	0.031	0.791	0.187	0.402	0.031	1.79	C
	Chile	0.309	0.033	0.426	0.409	0.298	0.033	0.29	N
OECD	Australia	0.078	0.036	0.565	0.340	0.092	0.036	1.26	N
	Belgium	0.039	0.037	0.636	0.298	0.052	0.036	1.75	C
	Canada	0.136	0.036	0.333	0.444	0.135	0.036	0.41	N
	France	0.097	0.036	0.139	0.490	0.093	0.036	0.09	N
	Germany	0.001	0.037	0.332	0.444	0.011	0.036	0.67	N
	Italy	−0.002	0.037	−0.504	0.373	−0.016	0.036	−1.19	N
	Netherlands	0.044	0.037	0.652	0.288	0.054	0.036	1.84	C
	Spain	0.139	0.036	0.120	0.492	0.134	0.036	−0.03	N
	Sweden	0.105	0.036	−0.213	0.477	0.095	0.036	−0.60	N
	Switzerland	0.005	0.037	0.182	0.483	0.010	0.036	0.33	N
	U.K.	0.097	0.036	0.284	0.460	0.096	0.036	0.38	N
	U.S.	0.207	0.035	0.118	0.493	0.196	0.035	−0.15	N
Other emerging markets	India	0.013	0.037	−0.017	0.500	0.012	0.036	−0.05	N
	Russia	−0.009	0.037	0.077	0.497	−0.008	0.036	0.16	N
	S. Africa	0.062	0.037	0.710	0.248	0.073	0.036	2.24	C

correlation is substantially smaller (in absolute value) than the conditional correlation during the turmoil period. In many cases, the unconditional correlation coefficient is still greater during the turmoil period, but this increase is significantly diminished from that found in Table VI. For example, the cross-market correlation between Mexico and Argentina is 0.40 for the

Table VII

1994 Mexican Peso Crisis: Unconditional Correlations in Stock Market Returns

This table reports unconditional cross-market correlation coefficients and standard deviations for Mexico and each country in the sample. The correlation coefficients have been adjusted for heteroskedasticity using equation (11). The turmoil period is defined as December 19, 1994, through December 31, 1994. The stable period is defined as January 1, 1993, through December 31, 1995 (excluding the turmoil period). The full period is the stable period plus the turmoil period. The test statistics are for one-sided t-tests examining if the cross-market correlation coefficient during the full period is significantly greater than during the turmoil (high volatility) period. "C" in the final column indicates that the test statistic is greater than the critical value and therefore contagion occurred. "N" in the final column indicates that the test statistic was less than or equal to the critical value and therefore no contagion occurred.

		Stable		Turmoil		Full Period			
Region	Country	ρ	σ	ρ	σ	ρ	σ	Test Statistic	Contagion?
East Asia	Hong Kong	0.058	0.037	0.172	0.460	0.070	0.036	0.21	N
	Indonesia	0.044	0.037	0.065	0.493	0.049	0.036	0.03	N
	Japan	0.029	0.037	0.154	0.467	0.036	0.036	0.24	N
	Korea	0.037	0.037	0.339	0.387	0.058	0.036	0.66	N
	Malaysia	0.051	0.037	−0.021	0.499	0.042	0.036	−0.12	N
	Philippines	0.070	0.037	−0.022	0.499	0.061	0.036	−0.15	N
	Singapore	0.072	0.037	0.067	0.493	0.070	0.036	−0.01	N
	Taiwan	0.097	0.037	0.200	0.448	0.097	0.036	0.21	N
	Thailand	0.049	0.037	0.034	0.498	0.045	0.036	−0.02	N
Latin America	Argentina	0.398	0.033	0.500	0.307	0.401	0.031	0.29	N
	Brazil	0.403	0.033	0.390	0.358	0.402	0.031	−0.03	N
	Chile	0.325	0.034	0.151	0.467	0.298	0.033	−0.29	N
OECD	Australia	0.082	0.037	0.223	0.438	0.092	0.036	0.28	N
	Belgium	0.041	0.037	0.260	0.420	0.052	0.036	0.46	N
	Canada	0.143	0.036	0.116	0.480	0.134	0.036	−0.04	N
	France	0.103	0.036	0.046	0.497	0.093	0.036	−0.09	N
	Germany	0.001	0.037	0.113	0.481	0.011	0.036	0.20	N
	Italy	−0.002	0.037	−0.189	0.453	−0.016	0.036	−0.35	N
	Netherlands	0.046	0.037	0.273	0.414	0.054	0.036	0.49	N
	Spain	0.146	0.036	0.040	0.498	0.134	0.036	−0.17	N
	Sweden	0.111	0.036	−0.071	0.492	0.095	0.036	−0.31	N
	Switzerland	0.005	0.037	0.061	0.494	0.010	0.036	0.09	N
	U.K.	0.102	0.036	0.097	0.486	0.096	0.036	0.00	N
	U.S.	0.218	0.036	0.039	0.498	0.196	0.035	−0.29	N
Other emerging markets	India	0.015	0.037	−0.006	0.500	0.012	0.036	−0.03	N
	Russia	−0.010	0.037	0.026	0.499	−0.008	0.036	0.06	N
	S. Africa	0.065	0.037	0.314	0.394	0.073	0.036	0.56	N

full period. In the turmoil period the conditional correlation jumps to 0.86, while the unconditional correlation only increases to 0.50. When tests for contagion are performed on these unconditional correlations, there is not one case in which the correlation coefficient increases significantly during the turmoil period. In other words, according to this testing methodology, there is no longer evidence of a significant change in the magnitude of the propagation mechanism from Mexico to any other country in the sample.

An extensive set of sensitivity tests supports these results. We modify period definitions, adjust the frequency of returns and lag structure, vary the interest rate controls, and/or estimate local currency returns. In the series of tests based on the conditional correlation coefficient, there are between zero and seven cases of contagion. Whenever the statistics are adjusted for heteroskedasticity and tests are based on the unconditional correlation coefficients, however, there is virtually no evidence of contagion.[22] In other words, there are virtually no cases where the unconditional correlation coefficient between Mexico and any other country in the sample increases significantly during the peso crisis.

VI. Contagion during the 1987 U.S. Stock Market Crash

Before the East Asian crisis and Mexican devaluation, another period of stock market turmoil when investors feared contagion was after the U.S. stock market crash in October 1987. To test for contagion during this period, we repeat the test procedure described above. We define the turmoil period as October 17, 1987 (the date the crash began) through December 4, 1987 (the nadir of the U.S. market) and define the stable period as January 1, 1986, through October 17, 1987. Since many of the smaller stock markets in our sample of 28 countries were not in existence or were highly regulated at this time, we focus only on the 10 largest stock markets (including the United States). Once again, we focus on two-day, rolling-average, U.S. dollar returns and control for five lags of returns and interest rates. Results based on the conditional and unconditional correlation coefficients are reported in Tables VIII and IX. We also perform an extensive set of sensitivity tests in which we modify period definitions, adjust the frequency of returns and lag structure, vary the interest rate controls, and utilize local currency returns. Results are virtually identical to those reported in Tables VIII and IX.

Most patterns are similar to those found after the 1997 East Asian crisis and the 1994 Mexican devaluation. Tests for a significant increase in cross-market correlations based on the conditional correlation coefficients show a substantial amount of contagion—usually in about one-third to one-half the sample. This agrees with the findings of earlier work testing for contagion after the 1987 U.S. stock market crash (and discussed at the start of Section I). None of this work using correlation coefficients, however, attempted to correct for heteroskedasticity and estimate the unconditional correlations

[22] In all of these tests based on the unconditional coefficients, there are never more than two cases of contagion. These cases only occur when returns are measured in local currency, and often occur in countries that are geographically distant from the source of contagion, such as India and South Africa.

Table VIII

1987 U.S. Stock Market Crash: Conditional Correlation Coefficients

This table reports conditional (unadjusted) cross-market correlation coefficients and standard deviations for the United States and each country in the sample. The stable period is defined as January 1, 1986, through October 16, 1987. The turmoil period is defined as October 17, 1987, through December 4, 1987. The full period is the stable period plus the turmoil period. The test statistics are for one-sided *t*-tests examining if the cross-market correlation coefficient during the full period is significantly greater than during the turmoil (high volatility) period. "C" in the final column indicates that the test statistic is greater than the critical value and therefore contagion occurred. "N" in the final column indicates that the test statistic was less than or equal to the critical value and therefore no contagion occurred.

	Stable		Turmoil		Full Period			
Country	ρ	σ	ρ	σ	ρ	σ	Test Statistic	Contagion?
Australia	−0.199	0.045	−0.106	0.202	−0.180	0.044	0.30	N
Canada	0.515	0.034	0.635	0.122	0.531	0.032	0.68	N
France	0.169	0.045	0.610	0.128	0.256	0.042	2.08	C
Germany	0.105	0.046	0.492	0.155	0.172	0.044	1.61	N
Hong Kong	0.154	0.045	0.091	0.202	0.139	0.044	−0.20	N
Japan	−0.015	0.046	0.167	0.198	0.005	0.044	0.67	N
Netherlands	0.246	0.044	0.662	0.115	0.325	0.040	2.18	C
Switzerland	0.160	0.045	0.552	0.142	0.221	0.043	1.79	C
U.K.	0.145	0.045	0.645	0.119	0.212	0.043	2.67	C

in tests for contagion.[23] As shown in Table IX, when the correlation coefficients are adjusted for changes in market volatility, there is virtually no evidence of contagion.[24] In other words, when the cross-market correlation coefficients are adjusted for heteroskedasticity, there is no longer evidence of a significant increase in these correlations after the 1987 U.S. stock market crash.

VII. Caveats and Conclusions

The key point of this paper is that tests for contagion based on cross-market correlation coefficient are problematic due to the bias introduced by changing volatility in market returns (i.e., heteroskedasticity). The paper focuses on a definition of contagion traditionally used in this literature: a

[23] It is worth noting, however, that several papers using ARCH or GARCH frameworks to test for contagion incorporated heteroskedasticity in their models. These papers continue to find evidence of a strong contemporaneous relationship across stock markets during crises, but generally do not define contagion as a shift in these cross-country linkages during crises. For example, see Hamao et al. (1990).

[24] In the series of sensitivity tests, there are usually zero cases of contagion. In a few specifications, there is one case of contagion (and never more).

Table IX

1987 U.S. Stock Market Crash: Unconditional Correlation Coefficients

This table reports unconditional cross-market correlation coefficients and standard deviations for the United States and each country in the sample. The correlation coefficients have been adjusted for heteroskedasticity using equation (11). The stable period is defined as January 1, 1986, through October 16, 1987. The turmoil period is defined as October 17, 1987, through December 4, 1987. The full period is the stable period plus the turmoil period. The test statistics are for one-sided t-tests examining if the cross-market correlation coefficient during the full period is significantly greater than during the turmoil (high volatility) period. "C" in the final column indicates that the test statistic is greater than the critical value and therefore contagion occurred. "N" in the final column indicates that the test statistic was less than or equal to the critical value and therefore no contagion occurred.

	Stability		Turmoil		Full Period			
Country	ρ	σ	ρ	σ	ρ	σ	Test Statistic	Contagion?
Australia	−0.209	0.045	−0.007	0.203	−0.180	0.044	0.46	N
Canada	0.528	0.038	0.497	0.152	0.531	0.032	−0.18	N
France	0.176	0.046	0.441	0.159	0.256	0.042	0.92	N
Germany	0.110	0.046	0.352	0.176	0.172	0.044	0.82	N
Hong Kong	0.162	0.046	0.057	0.203	0.139	0.044	−0.33	N
Japan	−0.015	0.046	0.107	0.201	0.005	0.044	0.42	N
Netherlands	0.256	0.045	0.500	0.149	0.325	0.040	0.93	N
Switzerland	0.165	0.046	0.431	0.165	0.221	0.043	1.01	N
U.K.	0.150	0.046	0.502	0.150	0.212	0.043	1.50	N

significant increase in cross-market linkages after a shock to one country (or group of countries). It also focuses on a conventional method of testing for contagion: analyze if cross-market correlation coefficients increase significantly after a crisis. If the cross-market correlations increase, this is interpreted as evidence of contagion. The paper shows, however, that the correlation coefficient underlying these tests is actually conditional on market volatility over the time period under consideration. As a result, during a crisis when stock market volatility increases, estimates of cross-market correlations will be biased upward.

The paper also presents one method of correcting for this heteroskedasticity and calculating unconditional cross-market correlation coefficients. This adjustment is based on the assumption of no omitted variables or endogeneity. When this unconditional correlation coefficient is used in tests for contagion, there is virtually no evidence of a significant increase in cross-market correlation coefficients during the 1997 East Asian crisis, 1994 Mexican peso devaluation, and 1987 U.S. stock market crash. These results can be interpreted as evidence that there was no contagion during these three periods. It is critical to mention, however, that these results do not suggest that markets were not closely linked during recent crises. Instead, the estimates show a high level of market comovement during all states of the world (during crises as well as more stable periods), which we call interdependence.

This paper only focuses on adjusting for one problem with the cross-market correlation coefficient: heteroskedasticity. While the proposed adjustment for heteroskedasticity is clearly an improvement over past work, it is only a first step. The adjustment can change in the presence of endogeneity and/or omitted variables. As shown in Appendix B, it is impossible to predict the extent of this bias in the conditional correlation coefficient when heteroskedasticity is combined with either of these problems. Future work needs to examine how endogeneity and omitted variables, especially when combined with heteroskedasticity, can affect cross-market correlation coefficients and tests for contagion.

Finally, the main objective of this paper and its extensive series of tests is to show that inferences based on the conditional correlation coefficient can be extremely misleading. A simple adjustment for heteroskedasticity can reverse what appear to be straightforward conclusions about the existence of contagion during recent currency crises.

Appendix A: Proof of the Bias in the Conditional Correlation Coefficient

Assume x and y are two stochastic variables that have the following relationship:

$$y_t = \alpha + \beta x_t + \epsilon_t, \tag{A1}$$

where

$$E[\epsilon_t] = 0, \tag{A2}$$

$$E[\epsilon_t^2] = c < \infty \tag{A3}$$

(where c is a constant), and

$$E[x_t \epsilon_t] = 0. \tag{A4}$$

Note that these assumptions assume that there is no endogeneity or omitted variables. Other than these assumptions, it is not necessary to make any further restrictions on the distribution of the residuals. Divide the sample into two sets so that the variance of x_t is lower in the first group (l) and higher in the second group (h). Since $\mathrm{E}[x_t \epsilon_t] = 0$ by assumption, OLS estimates of the above equation are consistent and efficient for both groups, so that $\beta^h = \beta^l$.

Next, define

$$1 + \delta \equiv \frac{\sigma_{xx}^h}{\sigma_{xx}^l}. \tag{A5}$$

Then

$$
\begin{aligned}
\sigma_{yy}^{h} &= \beta^{2}\sigma_{xx}^{h} + \sigma_{ee} \\
&= \beta^{2}(1+\delta)\sigma_{xx}^{l} + \sigma_{ee} \\
&= (\beta^{2}\sigma_{xx}^{l} + \sigma_{ee}) + \delta\beta^{2}\sigma_{xx}^{l} \\
&= \sigma_{yy}^{l} + \delta\beta^{2}\sigma_{xx}^{l} \\
&= \sigma_{yy}^{l}\left(1 + \delta\beta^{2}\frac{\sigma_{xx}^{l}}{\sigma_{yy}^{l}}\right),
\end{aligned}
\tag{A6}
$$

and when this is combined with

$$
\rho = \frac{\sigma_{xy}}{\sigma_{x}\sigma_{y}} = \beta\frac{\sigma_{x}}{\sigma_{y}} \tag{A7}
$$

then

$$
\sigma_{yy}^{h} = \sigma_{yy}^{l}(1 + \delta[\rho^{l}]^{2}). \tag{A8}
$$

Therefore,

$$
\begin{aligned}
\rho^{h} &= \frac{\sigma_{xy}^{h}}{\sigma_{x}^{h}\sigma_{y}^{h}} \\
&= \frac{(1+\delta)\sigma_{xy}^{l}}{(1+\delta)^{1/2}\sigma_{x}^{l}(1+\delta[\rho^{l}]^{2})^{1/2}\sigma_{y}^{l}} \\
&= \rho^{l}\sqrt{\frac{1+\delta}{1+\delta[\rho^{l}]^{2}}}.
\end{aligned}
\tag{A9}
$$

The correlation coefficient is clearly an increasing function of δ.

Appendix B: Misspecification Due to Omitted Variables and Endogeneity

In the main text, we use the simple, stylized model in equations (1) through (11) to highlight the properties of the conditional correlation coefficient. We show that correlation coefficients can be biased in the presence of heteroskedasticity. The model assumes that there are no omitted variables or endogeneity. These two assumptions are clearly simplifications, and this appendix explores their importance.

More specifically, this appendix has two objectives. First, it uses two models with less restrictive assumptions to show that conditional correlation coefficients continue to be biased in the presence of heteroskedasticity and either omitted variables or endogeneity. Second, it evaluates the performance of the proposed adjustment to the correlation coefficient (equation (11)) in the presence of omitted variables and endogeneity. It performs a number of simulations to estimate when this adjustment overcorrects or undercorrects for heteroskedasticity. It also estimates the range of parameter values for which the proposed adjustment to the correlation coefficient is fairly accurate.

A. Omitted Variables

This section extends the model developed in equations (1) through (11) to allow for omitted variables. Assume that the returns in two countries (x_t and y_t) are described by

$$\begin{aligned} y_t &= \beta x_t + \gamma z_t + \epsilon_t \\ x_t &= z_t + \eta_t, \end{aligned} \tag{B1}$$

where z_t is any unobservable variable. This could represent a global liquidity shock, a change in investors' risk preferences, or any factor common to both stock markets.

Next, we calibrate the model to produce unconditional correlation coefficients similar to those found in the data ($\rho = 0.20$). The variable γ is assumed to be equal to 0.50, and the variances of η_t and z_t are set equal to one. Thus, the variance of ϵ_t is computed to obtain the desired unconditional correlation for a given β and γ. Finally, β is allowed to vary from 0 to 1.

Then, following the proof developed in Section II, we divide the sample into two periods: a high- and a low-volatility period. The high-volatility period assumes that the variance of x_t increases by 10. This is close to the average conditional change in volatilities in the three crises studied in the paper. We also assume that this increase in volatility is partially explained by the common shock (z_t) and partially by the idiosyncratic shock (η_t). In other words, we are relaxing the assumption that all of the heteroskedasticity is explained by η_t. We allow this proportion of the heteroskedasticity explained by the common shock to vary from 0 to 1.

Next, we simulate the model such that for each proportion of the heteroskedasticity explained by common shocks, the changes in the variances of z_t and η_t are computed so that the variance of x_t increases by 10 times. Given these changes in the variances of both shocks, and assuming that ϵ_t is homoskedastic, we compute the variance of y_t and the covariance between x_t and y_t.

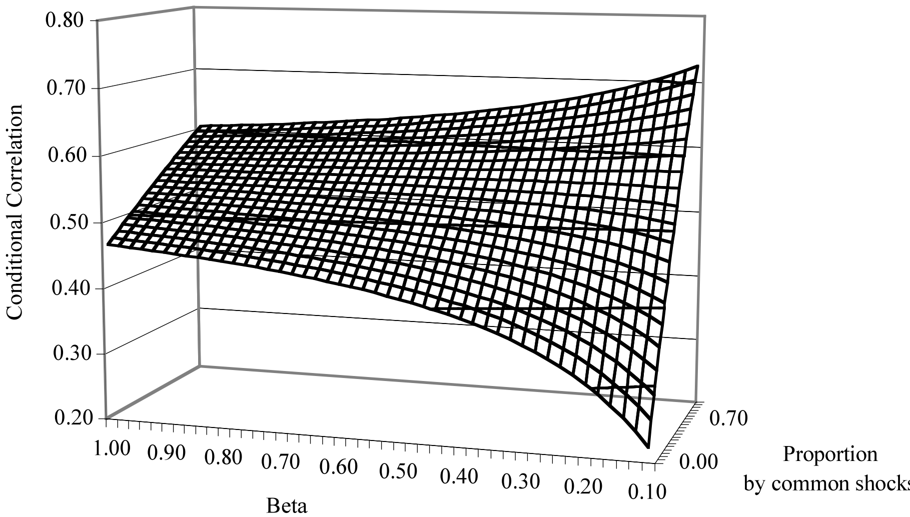

Figure A1. Simulations of the conditional correlation coefficient in the presence of omitted variables. This figure graphs the conditional correlation coefficient for different values of cross-market relationships and omitted variables. On the x-axis is beta, which is the direct impact of one market on the other and is allowed to vary from 0 to 1. On the y-axis is the proportion of the variance explained by the common shock, which is also allowed to vary from 0 to 1. In each simulation, the unconditional correlation is held constant at 0.20, but the z-axis shows the resulting estimate of the conditional correlation.

Figure A1 reports simulation results for the conditional correlation coefficient during the volatile period. The x-axis is β and is expressed as increasing from right to left (to improve the graphical representation). The y-axis is the proportion of the variance explained by the common shock, and the z-axis is the conditional correlation coefficient.

The graph shows that the resulting bias in the conditional correlation is sizable for all parameters, except when β is small and most of the shift in the variance is explained by η_t. The conditional correlation coefficient moves from the unconditional value of 20 percent to over 70 percent. Therefore, the bias in the correlation coefficient can still be a severe problem in situations with both heteroskedasticity and omitted variables.

In this situation, there is no straightforward procedure to correct for the bias in the correlation coefficient. Therefore, the relevant question is how the suggested adjustment for heteroskedasticity (equation (11) in the text) performs in the presence of omitted variables. To show if this adjustment tends to be consistent, overcorrect, or undercorrect in the presence of omitted variables, Figure A2 graphs the unconditional correlation coefficient (calculated using equation (11)) for a number of different situations.

The figure shows that the proposed adjustment for heteroskedasticity undercorrects (meaning that the adjusted correlation is greater than the unconditional correlation) when a sizable proportion of the variance is explained

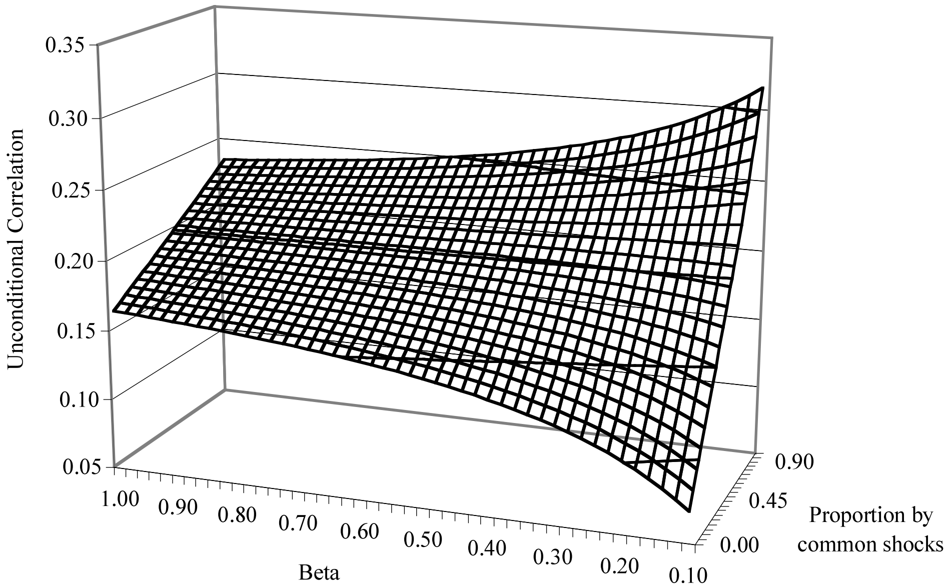

Figure A2. Simulations of the heteroskedasticity adjustment in the presence of omitted variables. This figure shows the accuracy of the adjustment for heteroskedasticity in equation (11) in the presence of omitted variables. On the x-axis is beta, which is the direct impact of one market on the other and is allowed to vary from 0 to 1. On the y-axis is the proportion of the variance explained by the common shock, which is also allowed to vary from 0 to 1. In each simulation, the unconditional correlation is held constant at 0.20, and the z-axis shows the resulting, adjusted estimate of the unconditional correlation.

by the common shock. On the other hand, the adjustment tends to overcorrect (meaning that the adjusted correlation is less than the unconditional correlation) when the proportion of the heteroskedasticity explained by the common shock is small.

A useful method for summarizing these results is to graph various situations when the adjusted estimates of the correlation coefficient are close to the unconditional value. Figure A3 performs this analysis assuming that the unconditional correlation coefficient is 20 percent. The dark areas of the graph are combinations (of β and the proportion of the variance explained by the common shock) for which the adjusted correlation coefficient is within 5 percent of the unconditional correlation coefficient (between 15 and 25 percent).[25] The light areas are coefficient combinations for which the adjusted correlation coefficient differs from the unconditional correlation coefficient by over 5 percent.

Figure A3 shows that for any magnitude of omitted variables, the adjustment for heteroskedasticity performs extremely well for large values of β. In other words, when two markets are closely connected, the adjustment for

[25] We choose five percent as the cutoff between “accurate” and “inaccurate” estimates, since five percent is close to two standard deviations for our results.

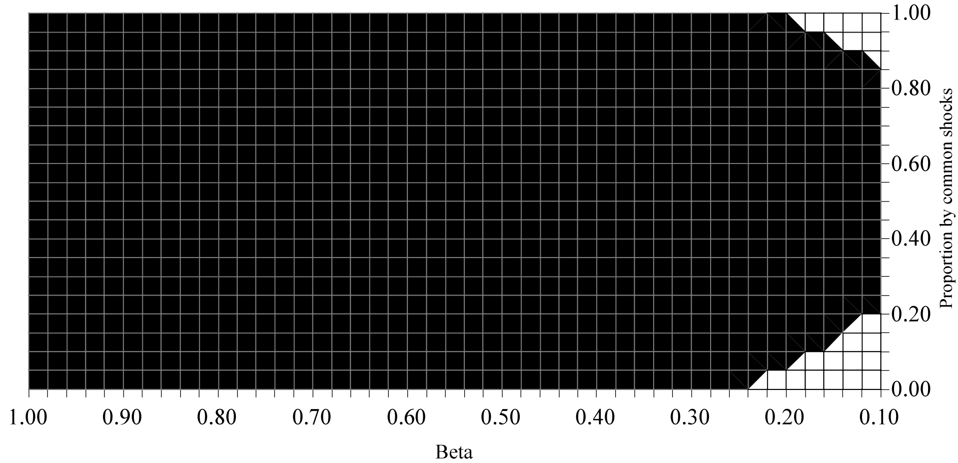

Figure A3. Accuracy of the heteroskedasticity adjustment in the presence of omitted variables. This figure summarizes the results of Figure A2 by showing when estimates of the unconditional correlation coefficient based on the adjustment in equation (11) are close to the unconditional value. The dark area of the graph is combinations of cross-market relationships (betas) and omitted variables (proportion by common shocks) for which the adjusted correlation coefficient is within five percent of the unconditional value. The white areas are coefficient combinations for which the adjusted correlation differs from the unconditional value by over five percent.

heteroskedasticity remains accurate in the presence of omitted variables. Omitted variables have a greater impact on the accuracy of this adjustment when the two markets are not closely linked, that is, on the far right-hand side of the graph. Moreover, Figure A2 shows that the adjustment is less accurate when the two markets are not closely linked and the proportion of the variance explained by the common shock is either very large (the top of the graph) or very small (the bottom of the graph). Figure A2 shows that this lower right-hand corner of Figure A3 refers to situations where the adjustment overcorrects the correlation coefficient, and the upper right-hand corner of Figure A3 refers to situations where the adjustment undercorrects. It is worth noting, however, that as long as γ is smaller than β, then the adjustment for heteroskedasticity is a good approximation. In other words, if the magnitude of any linkages between two countries is greater than the magnitude of any omitted variables, then the adjustment for heteroskedasticity proposed in equation (11) remains fairly accurate in the presence of omitted variables.

B. Endogenous Variables

This section examines how endogeneity, instead of omitted variables, affects the conditional correlation coefficient and the proposed adjustment for heteroskedasticity. We begin by extending the model developed in equations (1) through (11) to allow for endogeneity. In this more general model, the returns in two countries (x_t and y_t) are described by

$$\begin{aligned} y_t &= \beta x_t + \epsilon_t \\ x_t &= \alpha y_t + \eta_t. \end{aligned} \tag{B2}$$

We continue to calibrate the model to produce unconditional correlations equal to the average in our sample ($\rho = 0.20$). The variance of ϵ_t is assumed to be equal to one, and the variance of η_t is computed to match the unconditional correlation coefficient. The variables α and β are varied from 0 to 1.[26] The high volatility period continues to be defined as having the observed variance of x_t increase by 10. Then we estimate the shift in the variance of η_t that is consistent with this shift in the variance of x_t.

Figure A4 graphs the conditional correlation coefficient in the presence of various combinations of heteroskedasticity and endogeneity. Just as in the example with heteroskedasticity and omitted variables, the conditional correlation coefficient is always biased upward and larger than its unconditional value. The flat region of the graph, where α and β are both close to 0.15, indicates a series of coefficient combinations where the correlation between the variables is larger than 0.20 even with no variance in η_t. Therefore, the bias to the correlation coefficient continues to be a problem in the presence of endogeneity and heteroskedasticity.

Once again, there is no straightforward procedure to correct for the bias in the correlation coefficient. Therefore, the relevant question is how the suggested adjustment for heteroskedasticity (equation (11) in the text) performs in the presence of endogeneity. Figure A5 shows the unconditional correlation coefficient (adjusted using equation (11)) for a number of different situations.

Figure A5 shows that in the presence of heteroskedasticity and endogeneity, the adjustment proposed in equation (11) will always overcorrect (meaning that the adjusted correlation is less than the unconditional correlation).[27] Moreover, the degree of overcorrection tends to increase with the magnitude of the coefficients. This graph suggests an intuitive result: The adjustment for heteroskedasticity is less accurate in the presence of a high degree of endogeneity between markets. This is why the empirical tests reported in the text focus on crisis periods when there is expected to be minimal endogeneity.

As a final exercise, we estimate another summary graph to show when the estimates of the unconditional correlation coefficients (adjusted accord-

[26] It is important to note that large values of α and β would generate correlation coefficients larger than that used to calibrate the model. In practice, most of the pairs for α and β that imply real solutions to the variance problem are smaller than 0.15. Therefore, the figures in this section concentrate on this range of coefficients.

[27] Thanks to an anonymous referee for raising this point.

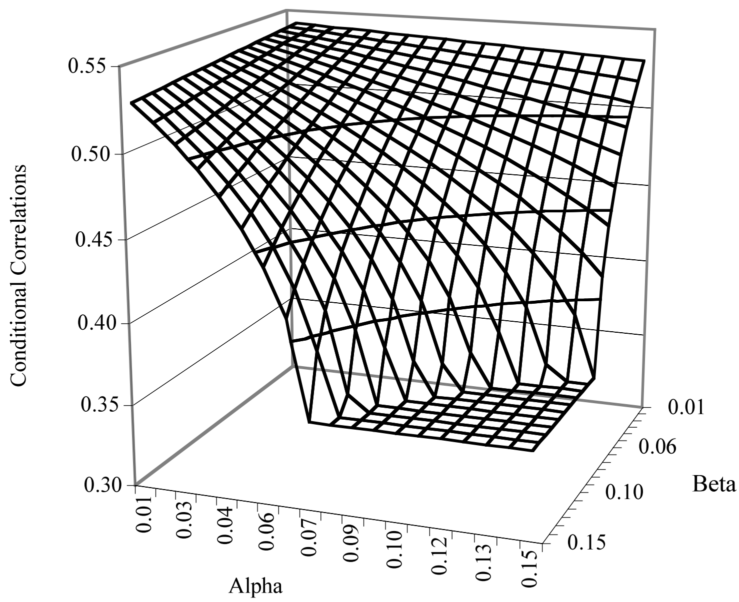

Figure A4. Simulations of the conditional correlation coefficient in the presence of endogeneity. This figure graphs the conditional correlation coefficient for different values of cross-market relationships and endogeneity. On the x-axis is alpha, which captures the impact of the first market on the second. On the y-axis is beta, which captures the impact of the second market on the first. In each simulation, the unconditional correlation is held constant at 0.20, but the z-axis shows that the resulting estimate of the conditional correlation is always greater than the unconditional correlation.

ing to equation (11)) are close to their unconditional values. Figure A6 performs this analysis assuming that the unconditional correlation coefficient is 20 percent. The dark area continues to be coefficient combinations for which the adjusted correlation coefficient is within 5 percent of the unconditional correlation coefficient (between 15 and 25 percent). The white area continues to be coefficient combinations for which the adjusted correlations differ from the unconditional correlations by over 5 percent but less than 10 percent. The gray areas are coefficient combinations for which the adjusted correlations differ from the unconditional correlations by over 10 percent.

The graph shows that the proposed adjustment for heteroskedasticity tends to overcorrect the correlation coefficient in the presence of endogeneity when both α and β are relatively large. In other words, the adjustment is less accurate if the relative variance between η_t and ϵ_t is very small. Although it is important to be aware of this limitation to the adjustment for heteroskedasticity, this is unlikely to be a serious problem in the tests for contagion described in the main section of the paper. The crisis periods examined in

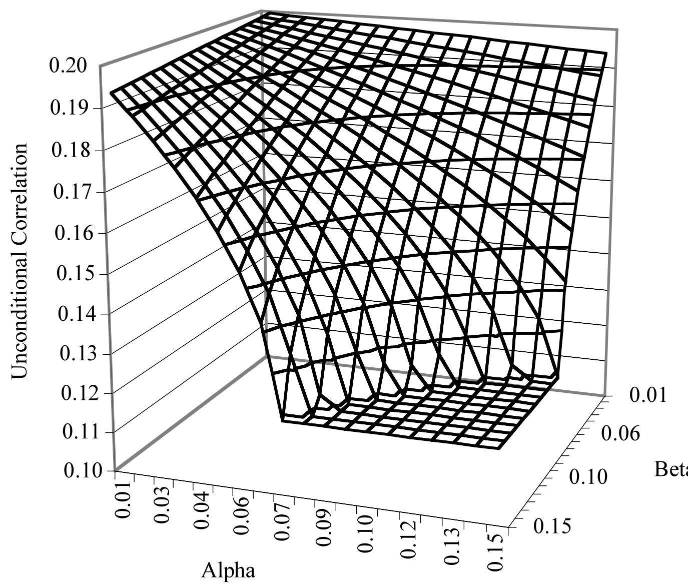

Figure A5. Simulations of the heteroskedasticity adjustment in the presence of endogeneity. This figure shows the accuracy of the adjustment for heteroskedasticity in equation (11) in the presence of endogeneity. On the x-axis and y-axis are alpha and beta, which capture the direct impact of each market on the other market. In each simulation, the unconditional correlation is held constant at 0.20, and the z-axis shows the resulting, adjusted estimate of the unconditional correlation.

the paper only include events where the feedback from the second country to the crisis country is expected to be small.[28]

C. Conclusion

In conclusion, this appendix has examined the accuracy of the adjustment for heteroskedasticity (proposed in equation (11)) in the presence of omitted variables and endogeneity. It shows that under certain circumstances, the adjustment is less accurate and should be used cautiously. For example, in situations with heteroskedasticity, positive linkages between two economies, and a large aggregate shock (omitted variable), the proposed adjustment could either over- or undercorrect the unconditional correlation coefficient. In situations with heteroskedasticity and a strong feedback effect from the second country to the crisis country (endogeneity), the proposed adjustment will tend to overcorrect the unconditional correlation coefficient. It also shows,

[28] In other situations, when the source of the crisis is less well identified and endogeneity may be more severe, it may be useful to utilize a Granger causality test to determine the extent of any feedback from each country in the sample to the initial crisis country. Granger causality tests should be used with caution, however, since serial correlation in stock returns could bias test results.

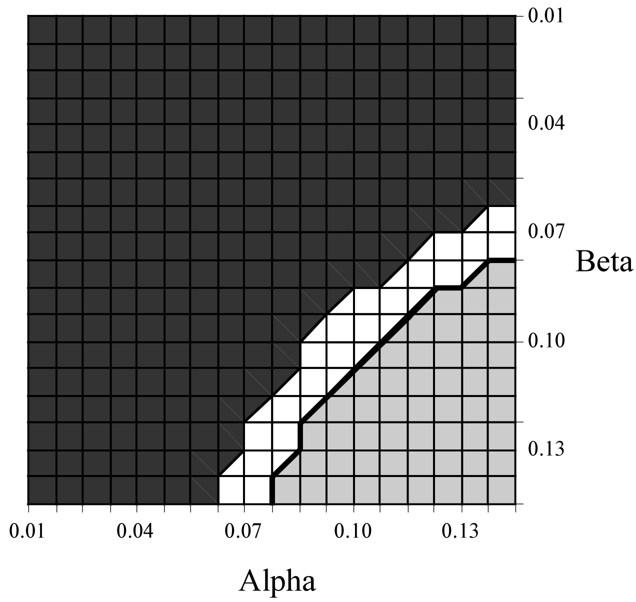

Figure A6. Accuracy of the heteroskedasticity adjustment in the presence of endogeneity. This figure summarizes the results of Figure A5 by showing when estimates of the unconditional correlation coefficient based on the adjustment in equation (11) are close to the unconditional value. The dark area of the graph is combinations of cross-market relationships (alphas and betas) for which the adjusted correlation coefficient is within 5 percent of the unconditional value. The white area is coefficient combinations for which the adjusted correlation differs from the unconditional value by over 5 percent but less than 10 percent, and the gray area in the bottom right corner is where the adjusted correlations differ from the unconditional correlations by over 10 percent.

however, that for a large set of parameter values, the adjustment for heteroskedasticity is fairly accurate (where accurate is defined as cases when the adjusted correlation is within one standard deviation of the true value). Moreover, by carefully choosing which countries and crisis periods to analyze (such as only including situations where endogeneity is expected to be minimal), the proposed adjustment to the correlation coefficient is a good approximation.

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