

## The changing network of financial market linkages: The Asian experience<sup>☆</sup>

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### ABSTRACT

We investigate the changing integration of Asian financial markets within the global financial network from 1995 to 2016, incorporating the direction of links between markets, the significance of these links, and their strength. Emphasis is placed on the transition of the networks before and after the Asian financial crisis of 1997–1998 and the global financial crisis of 2008–2009. The results reveal a general deepening of the connections of the Asian market with the rest of the world over the past two decades. The analysis demonstrates the increase in interconnectedness during periods of stress and the fall in the number of links in post-crisis periods. Moreover, many of these markets have transitioned from being primarily linked to the global markets via key bridge markets (such as Hong Kong) and over time developed stronger direct links with external markets. These findings highlight the potential importance of key geographical nodes in allowing emerging markets access to the international financial network.

### 1. Introduction

Since the Asian financial crisis of 1997–1998, Asian markets have become more central in global output production and investment, shifting the center of the financial world steadily eastward (Quah, 2011). In the Bank for International Settlements' (BIS) April 2013 Triennial Central Bank Survey, transactions between the Chinese yuan and US dollar alone accounted for 2.1% of recorded foreign exchange transactions - up from a nonexistent presence in a 1998 survey. In 2016, one-third of the top-15 equity markets by market capitalization were in Asia: in order, Japan; China; Hong Kong; India; and Australia. This growing international presence and market development in Asia suggests considerable change in the international network of financial linkages between countries and regions. This paper examines the development of the Asian markets using new methods of analyzing the changing financial interconnectedness through network finance, facilitating a clearer understanding of how financial stress transmits between markets. The advantage of network analysis lies in its ability to

better understand the mechanisms underlying the transmission of financial stress between markets, to help identify and monitor network nodes that act as critical links between regions and can therefore facilitate the transmission of shocks. More generally, it can help authorities design appropriate policy responses and targeted interventions to promote financial stability and resilience.

The paper focuses on a 21-year period from 1995 to 2016 covering both the global financial and the Asian financial crises (GFC and AFC), and examines the transmission of shocks to market returns between 42 equity markets, divided into 5 regions (Africa, Asia and the Pacific, Europe, Latin America, and North America, see Table 1 for more detail).<sup>1</sup> By extracting the changing contribution of shocks emanating from the intertwined network of financial markets we contribute to the deepening understanding of how emerging markets operate during periods of stress and calm. In order to achieve this task, we conduct an empirical analysis to effectively model the changing network of financial markets within and between Asia and the rest of the world to capture its evolution through six time periods over the last two

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<sup>1</sup> The Asian markets include Australia; Hong Kong; India; Indonesia; Japan; Malaysia; New Zealand; Pakistan; China; the Philippines; the Republic of Korea; Singapore; Sri Lanka; Taiwan; and Thailand.

**Table 1**  
Markets grouped by region.

Europe	Asia and the Pacific	Africa	North America	Latin America
Austria	Australia	Egypt	Canada	Argentina
Belgium	China	South Africa	United States	Brazil
Czech Republic	Japan			Chile
Denmark	India			Mexico
Finland	Indonesia			
France	Hong Kong			
Germany	Malaysia			
Greece	New Zealand			
Hungary	Pakistan			
Ireland	Philippines			
Italy	Singapore			
Netherlands	Republic of Korea			
Poland	Sri Lanka			
Portugal	Taiwan			
Spain	Thailand			
Sweden				
Switzerland				
Turkey				
United Kingdom				

decades—before, during, and after the AFC and GFC, respectively.<sup>2</sup> We test both the statistical significance of the potentially changing linkages between the markets in each of the 6 phases, their direction, and how they change across periods.

The paper draws on the methodological approaches developed in [Dungey, Harvey, and Volkov \(2018\)](#) in developing a network of financial linkages between nodes (represented by country index equity market data) where the links between them (edges) are determined by an adjacency matrix, which includes both the direction and strength of those links and a measure of their statistical significance. Our application uses data from equity markets. The use of data on equity rather than bank liabilities (utilized more frequently in other studies, see [Dungey et al. \(2018\)](#)) was due in part to its ability to more accurately reflect market sentiment; and to the concern that concentrating analysis and reforms on one sector could create shocks that transmit through other markets. The results show the developing profile of Asian financial markets in a global network over a 20-year period containing two important periods of crisis. The analyses of crisis periods demonstrate the increase in interconnectedness during periods of stress. However, at times the countervailing influences of changes in strength and changes in number of links mean that statistics such as the completeness of the network may weaken while the number of links increases. The results reveal a general deepening of the connections of the Asian market with the rest of the world markets over the past two decades. They also reveal that in developing its financial markets, many Asian markets have gone through a transition of being primarily linked to developed non-Asian markets via key bridge markets (such as Hong Kong and Singapore, or the ASEAN block of markets) before developing

<sup>2</sup> We divide the sample into six distinct periods: (i) The lead-up to the Asian financial crisis (January 3, 1995 to July 1, 1997), (ii) the Asian financial crisis (July 2, 1997 to December 31, 1998), (iii) Post-Asian financial crisis (January 1, 1999 to December 31, 2002) (iv) the lead-up to the global financial crisis (January 1, 2003 to September 14, 2008), (v) the Global financial crisis (September 15, 2008 to March 31, 2010) and (v) Post-global financial crisis (April 1, 2010 to December 30, 2016). Note that although we are able to define the lead-up and crisis periods relatively clearly. In each case, the post-crisis period contains ongoing crises in other regions or asset markets of the world—the post-AFC period includes the dotcom crisis in the United States (US) and a number of South American problems (see [Dungey, Milunovich, & Thorp, 2010](#)), while the post-GFC period includes the significant problems in the European sovereign debt markets.

stronger direct links with these external markets by the most recent phase.

Our work focusing on the interconnectedness in the financial market has the following contributions. First our paper contributes to the existing literature on interconnectedness by using the network finance. Previous research has mainly focused on the developed market however, little attention has focused on emerging markets especially in the Asian context. To the best of our knowledge, this is the major piece of work, we know of no other that is dealing with the Asian markets or changing integration during periods of stress over such a long period. Second, we compare the evolution of the network before, during and after two different crises (East Asian in 1997–1998 and GFC in 2008–09) and provide statistical evidence based on weighted networks and Jaccard similarity coefficients to assess the impact of the crises on the increasingly interconnected Asian markets. Our focus on evidence for the changing number and strengths of links (or edges) between the nodes (equity markets) in the network differentiates the work from those which focus exclusively on the net change in the number of statistically significant links, such as [Billio, Getmansky, Lo, and Pelizzon \(2012\)](#) or solely on the strength (but not statistical significance) of the linkages, such as [Diebold and Yilmaz \(2014, 2015\)](#). We consider not only the net change in links between nodes, but also the evolution of the Jaccard similarity coefficient, which provides information on the number of links between sample periods. The changing nature of the network leads us to consider not only the degrees and centrality measures of the networks, but also to an analysis of the number and strength of links that are extinguished and those that are formed. For example, in terms of the weighted completeness of the network, a result that may at first appear as a net increase in links may in fact represent a reduction in strong linkages and proliferation of weaker links. Third, our approach embeds existing definitions of contagion within a network representation of systemic risk. In particular, when links fail between nodes during periods of stress, this is evidence of the form of contagion proposed in [Gai and Kapadia \(2010\)](#), when the breakdown of the network results from contagion due to failing counterparty arrangements. Alternatively, when new links are formed between nodes during periods of stress, this increases the number of connections, akin to the traditional [Forbes and Rigobon \(2002\)](#) definition of markets becoming more interconnected during crises. To date, the literature finds evidence of both of these contagion routes but does not effectively reconcile them into a single framework.

Overall, our results show that there are clear networks within the Asian region, and between the Asian region and other regional cluster and these networks are both complex and changing over time. In this way, the results mirror those of [Wang, Xie, and Stanley \(2018\)](#), which examine a correlation-based network between 57 international equity markets and find distinct evidence of regions. [Wang et al. \(2018\)](#) find evidence of critical linkages between Asia and the rest of the world's equity markets; consequently, the second half of this paper shifts the focus to the role of markets that act as critical bridges between the region and the rest of the world, and how this has evolved over time. The role of the bridge market may be critical to the development of emerging markets, although we show that not all markets choose to go this way. The empirical evidence from the past 20 years provides instances of markets which seem to have benefited from a relationship with a regional bridge market, those which have chosen not to use a regional bridge but to concentrate on directly accessing the global network, those which have chosen to become a bridge market, and what takes place in each of these scenarios during periods of financial stress. Clear advantages exist to protecting emerging markets from crises if they are sheltered behind a regional node, as policy makers can concentrate on protecting that critical link to international markets. Disadvantages to this model may also exist, such as managing the transition to direct integration, and the potential cost to the bridge node of being caught in a crisis not of its own making. Policy makers in each market and region need to weigh the relative risks of each strategy.

The remainder of the paper proceeds as follows. Section 2 examines the literature on financial market integration and network applications in finance. Section 3 outlines the methodologies used in the construction of the financial networks. Section 4 describes the data used in this paper with some stylized facts. Section 5 presents the main findings of this network study. Section 6 discusses the role of the financial network in shaping policy reforms, and Section 7 concludes.

## 2. Literature review

This paper contributes to efforts to improve our understanding of interconnections in the financial system, where they stem from, and how they can be evaluated and monitored. Interconnections between financial markets play a dual role. On the one hand, they can absorb shocks and lead to greater robustness. They can also propagate shocks and create greater fragility. The finance literature has been traditionally focusing on interconnectedness as measured through direct exposures, which is constrained by the availability of reliable granular data. A more intuitive way is to investigate the empirical correlation of assets and the resulting implied network structure. This network helps describe the financial system, its systemic structure, and possible contagious effects. The network can provide important insights into system-level effects and help uncover changes in market microstructure, bubble formation, and changes in business models as some market participants withdraw from certain activities and others take their place.

Our work relates to a rapidly expanding line of research applying network analysis tools to analyze financial linkages in global markets and their implications for the emergence and management of risk contagion. This literature draws on the seminal work of Allen and Gale (2000), who use network theory to model financial interconnectedness and draw implications for system stability. The present research relates to network as a source of shocks propagation in the financial system. The notion of financial institutions being more interconnected is one of the channels through which financial stress propagates in the financial system. More recent research focus on the structure of financial network of a given economy. For example, Gai and Kapadia (2010) show that shocks are transmitted more by interconnected institutions. This implies that the probability of contagion is higher in more interconnected entities. Minoiu and Reyes (2013) find evidence that financial interconnectedness would help predict systemic risk in banking institutions. They show that increase within a country's interconnection and decrease in interconnections with others would signify a high chance of banking crisis which would result in financial instability.

Our work closely follows the connectedness measures that have been recently proposed. Billio et al. (2012) introduce Granger causality tests to measure the extent to which financial institutions are interconnected. This measure has been applied in many existing researches. For example, Zhang and Broadstock (2018) uses it for robustness checks and find that the connectedness in the global commodity prices rising following the global financial crisis. On the other hand, Cimini (2015) investigate the network density among the Eurozone entities and find that the overall interconnection of both financial and non-financial entities reduced after the global financial crisis. Pradhan, Arvin, and Ghoshray (2015) investigates the dynamics of the different macroeconomic variables from the G-20 countries and find that there is long-run economic relationship between these macroeconomic variables. In short-run, they find a complex network causal relationship.

Another widely used measure of connectedness in the financial system is the one proposed by Diebold and Yilmaz (2009) in their seminal paper. It has been widely accepted and applied in various studies. For example, Mensi, Boubaker, Al-Yahyaee, and Kang (2018) investigate volatility and connectedness among the global and regional markets and find an increased spillover to be more intensified at the beginning of the global financial crisis. They also find that the United States is a shock transmitter while the rest of the economies are

receivers. Ji, Bouri, and Roubaud (2018) in investigating net spillover across the oil and gas markets find that the total connectedness has volatile characteristics. Zhang (2017) uses this approach to study relationship between oil shocks and six stock market indexes and finds that the global stock markets affect oil price movements especially during periods of financial stress. Other work by Luo and Ji (2018) also studies the connectedness of the realized volatility of the USA crude oil and the Chinese agricultural commodity and finds that transmission in volatility has a leverage effect across markets. Ji, Bouri, Lau et al. (2018), Ji, Bouri, and Roubaud (2018), and Ji, Geng et al. (2018) investigate connectedness among the eight cryptocurrencies and find that their connectedness shows rising trend towards the end of 2016. While Ji, Geng, and Tiwari (2018) also investigate connectedness via return and volatility spillovers across six largest cryptocurrencies, they find each cryptocurrency return and volatility connectedness is not necessarily related to a market size.

Our empirical framework relies on the network approach developed by Diebold and Yilmaz (2014, 2015) to measure financial asset connectedness, based on the variance decomposition of the h-step-ahead forecasts from a VAR model as well as an innovative causality modeling approach introduced by Billio et al. (2012). Both frameworks are able to identify and accurately measure the degree of interconnectedness and the stress transmission effects among the examined economies and markets. However, our work differs from the existing literature in examining the changing nature of the networks of interconnections over different phases, thus controlling for different volatility regimes (an advance on De Bruyckere, Gerhardt, Schepens, & Vander Vennet, 2013) and includes a weighted directed network, improving on the unweighted approach of Billio et al. (2012) and the weighted approach of Diebold and Yilmaz (2014, 2015) which includes insignificant linkages.

Our paper extends previous studies to investigate how the connectedness among the Asian market have changed over time. Although there is increasing number of studies that investigate how markets are interconnected, there need to investigate the behavior of financial networks. Given the continuous rising of interconnections after the global financial crisis, there is still a need to study the nature of these interconnections especially in the most recent periods. Little attention has focused on emerging markets especially in the Asian context. Thus, our paper aims to fill the gap by focusing on the Asian markets who are becoming more significant markets in propagating financial shocks. It focuses on studying the changing network among the Asian economies. The paper aims at identifying the important links that were removed or formed in different periods.

## 3. Network measures

This paper proposes a new way of examining the changes in financial networks over time. We test for changes in the existence, number and strength of links between financial markets. Our analysis draws on the approaches developed in Dungey et al. (2018), Diebold and Yilmaz (2014, 2015), and Billio et al. (2012), primarily to document changes in the characteristics of financial network: changes in the number and strength of links between financial markets in the network.<sup>3</sup> We further consider the evolution of the Jaccard similarity coefficient which provides information on the number of retained links between sample periods. For example, in terms of the weighted completeness of the network, a result which may at first appear as a net increase in links, may in fact represent a reduction in strong linkages and proliferation of weaker links.

<sup>3</sup> While net pairwise connectedness measure of Diebold and Yilmaz (2009) can be used to identify linkages between the countries it does not permit capturing bi-directional relationships between the countries. This is important difference between our methodology and DY approach.

To derive a comprehensive network representation, two main steps are applied using vector autoregression (VAR) models. First, a VAR considers the relationships between all of the asset markets. Within that framework, nested Granger Causality tests determine which links are statistically significant. Second, the relative strength of the links is identified following Diebold and Yilmaz (2014, 2015). These network states allow for a detailed analysis of Asiana financial network and how it has evolved.

### 3.1. Methodology

#### 3.1.1. Establishing network edges via Granger causality

To measure the connectedness between entities, we identify statistically significant relations by applying Granger causality tests to establish the edges and their direction. Granger causality tests suggest causality if past values of one-time series,  $Y_i$ , stock return series in our case, contain information that help forecast another return series,  $Y_s$ .

These causality links can be assessed using a VAR

$$Y_t = c + \sum_{j=1}^k \Phi_j Y_{t-j} + \varepsilon_t, \tag{1}$$

where  $k$  is the number of lags,<sup>4</sup> and  $\Phi_j$  and  $c$  are parameters of the model. The Wald statistic to test for Granger causality between stock returns has the form:

$$WT = [e \text{vec}(\widehat{\Pi})]' [e(V \otimes (\widehat{Y}Y)^{-1})e']^{-1} [e \text{vec}(\widehat{\Pi})], \tag{2}$$

in which  $Y$  is the matrix of independent variables from Eq. (1),  $\text{vec}(\widehat{\Pi})$  denotes the row vectorised coefficients of  $\widehat{\Pi} = [\Phi_1, \dots, \Phi_k]$ ,  $\widehat{V} = T^{-1} \sum_{t=1}^T \widehat{\varepsilon}_t \widehat{\varepsilon}_t'$  and  $e$  is the  $k \times 2(2k + 1)$  selection matrix defined as

$$e = \begin{bmatrix} 0 & 1 & 0 & 0 & \dots & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & \dots & 0 & 0 & \dots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 1 & \dots & 0 & 0 & \dots & 0 & 0 & 0 \end{bmatrix} \tag{3}$$

Each row of  $e$  picks one of the coefficients to set to zero under the non-causal hypothesis  $Y_t \rightarrow Y_s$ . Then, Granger causality test results can be summarized as binary entries of matrix

$$A = [a_{ij}] \tag{4}$$

where,

$$a_{ij} = \begin{cases} 0, & \text{if return in country } i \text{ does not Granger cause return in country } j, \\ 1, & \text{if return in country } i \text{ Granger causes return in country } j. \end{cases} \tag{5}$$

Eqs. (4) and (5) permit establishing network edges.

#### 3.1.2. Network connectedness

The second aspect is the strength of the links, which we examine by assigning weights,  $W_{ij}$ , to each of the significant relationships existing in the network. We use the Diebold and Yilmaz (2009) framework of a generalized variance decomposition to obtain these weights and to obtain the weight matrix  $W_{ij} = [w_{ij}]$ . The spillover measure is based on forecast error variance decompositions. The contribution of shocks to variable  $j$  to the  $H$  step ahead generalized forecast error variance of entity  $i$ ,  $\theta_{ij}^g(H)$ , is represented by

$$\theta_{ij}^g(H) = \frac{V_{jj}^{-1} \sum_{h=0}^{H-1} (e'_i B_h V e_j)^2}{\sum_{h=0}^{H-1} (e'_i B_h V B'_h e_i)}, \tag{6}$$

where,  $H = 1, 2, 3, \dots$ , and  $V$  is the variance covariance matrix for the error term  $\varepsilon_t$ ,  $V_{jj}$  is the standard deviation of the  $j$ th error term and  $e_i$  is

<sup>4</sup> In the empirical section the choice of  $k$  is based on AIC information criteria. According to this criteria  $k = 2$ .

the selection vector with one as the  $i$ th element and zero otherwise.<sup>5</sup> The coefficient matrices,  $B_i$ , obey the recursion  $B_i = \phi_1 B_{i-1} + \phi_2 B_{i-2} + \dots + \phi_k B_{i-k}$  with  $B_0$  an  $n \times n$  identity matrix and  $B_i = 0$  for  $i < 0$ . Each entry of the generalized variance decomposition is normalized by the row sum as

$$w_{ij} = \frac{\theta_{ij}^g(H)}{\sum_{j=1}^n \theta_{ij}^g(H)}, \tag{7}$$

where  $\sum_{j=1}^n w_{ij} = 1$  and  $\sum_{ij=1}^n = n$ . We denote the values defined in Eq. (7) as DY weights.

The structure of the weighted network is defined by combining matrices  $A$  and  $W$  resulting in the adjacency matrix  $\widetilde{A}$  defined as

$$\widetilde{A} = A \odot W, \tag{8}$$

where  $\odot$  is the Hadamard product.<sup>6</sup> Elements of adjacency matrix  $\widetilde{A}$  capture the connectedness between entities conditional on significant causal linkages between them. Henceforth, we will call them *GDY* weights. The system-wide completeness of the network is measured as

$$C = \frac{\sum_{i,j=1; i \neq j}^n \widetilde{a}_{ij}}{\sum_{i,j=1; i \neq j}^n w_{ij}} \tag{9}$$

This paper concerned with the changing nature of the network over the sample period. The adjacency matrix may change due to changes in the weight matrix,  $W$ , and/or the significant entries in the matrix  $A$ . The changes in the  $A$  matrix link the specification directly to the literature assessing links during crises; for example Granger, Huang, and Yang (2000) assess changing Granger causality links in the Asian markets between 1986 and 1998. To illustrate how this may apply in the current framework, consider the example of linkages between a pair of assets in a 2-node example (we stress that this is for illustrative purposes—the Granger causality relationships used in the empirical application are drawn from the VAR Model of the entire system with a Wald test approach as outlined in Eqs. (2) to (3)). Consider a bivariate vector autoregression with one lag between  $Y_{1t}$  and  $Y_{2t}$

$$Y_{1t} = c_1 + \vartheta_{11} Y_{1t-1} + \vartheta_{12} Y_{2t-1} + \varepsilon_{1t} \tag{10}$$

$$Y_{2t} = c_2 + \vartheta_{21} Y_{1t-1} + \vartheta_{22} Y_{2t-1} + \varepsilon_{2t} \tag{11}$$

which can be compactly written in matrix form as

$$Y_t = c + \Theta Y_{t-1} + \varepsilon_t, \tag{12}$$

where  $Y_t$  is the vector  $[Y_{1t} \ Y_{2t}]'$ ,  $c$  is the  $2 \times 1$  vector of constants,  $\Theta$  is the  $2 \times 2$  matrix of coefficients and  $\varepsilon_t$  is the  $2 \times 1$  vector of residuals.

The Granger causality test is essentially a test of significance of the off-diagonal elements of the coefficient matrix in Eq. (12). That is, whether  $\vartheta_{12}$  and/or  $\vartheta_{21}$  are non-zero. To extend this to evidence for contagion and the changing nature of networks, we may consider comparing these coefficients across two sample periods. If, in period 1,  $\vartheta_{12}$  is statistically significant, but in period 2 it is not, then the link has been lost between the two periods—consistent with contagion through breakdown of linkages as per Gai and Kapadia (2010). Alternatively, if the link  $\vartheta_{12}$  is insignificant in period 1, but significant in period 2, then the evidence is consistent with contagion through the formation of new linkages, such as in the Forbes and Rigobon (2002) approach.

#### 3.1.3. Similarity of networks

We use the Jaccard similarity coefficient to examine just how many

<sup>5</sup> In the empirical section the forecast horizon  $H$  is chosen to be 10, which is consistent with other studies dealing with daily equity returns (see Diebold & Yilmaz, 2014, 2015). However, we also check robustness of our results to different values of  $H$  (see Section 5.5).

<sup>6</sup> A detailed discussion of the relation between Granger causality and variance decompositions can be found in Dufour and Renault (1998) and Dufour and Tassier (1993).



of the edges identified in each subsample are retained between samples. Papers such as [Billio et al. \(2012\)](#) are concerned only with the net formation of new links, but we find that it is important to consider the gross movements to obtain a clearer picture. The Jaccard similarity coefficient considers what portion of the edges in two networks are formed by the same edges, and is formed as a ratio of the intersection of the sets of links in two networks,  $Q$  and  $R$ , to the union of the sets of links in two networks as follows:

$$J(Q,R) = \frac{n(Q \cap R)}{n(Q \cup R)} = \frac{n(Q \cap R)}{n(Q) + n(R) - n(Q \cap R)} \quad (13)$$

When the statistically significant links in  $A$  are weighted by DY weights, it is possible that the  $W$  matrix may change between periods. In this way the completeness of the network (as per Eq. (9)) may change, either due to changes in the number of links, and/or changes in the relative strength of those links. As we will show, this effect seems to be important in distinguishing the nature of the evolving network and seems to be particularly the case in understanding the transition from the build up to a crisis and the crisis itself.

#### 4. Data and stylized facts

The dataset includes 15 Asian daily equity market indices (in local currencies) for 1995–2016 from Thompson Reuters Datastream. These are augmented by the daily (closing) equity market indices for 27 other countries, all listed by region in [Table 1](#). We chose our sample of markets based on the availability of the following data: (i) closing values, (ii) closing hours, and (iii) changes in closing prices. Our analysis of equity return spillovers is based on local currencies because we did not want to blur the extent of market co-movements with fluctuations in the foreign exchange market ([Mink, 2015](#)).<sup>7</sup> Unit root tests reveal the usual characteristics of stationary returns in each series. The analysis is conducted using demeaned returns (as the mean is usually extremely close to zero and, as we are focused on variance decompositions, this assumption is innocuous). Analysis of the complete network, consisting of 42 nodes, forms the initial benchmark for the study.

To construct our network, we use the data with its recorded local closing time date. The choice of time zone treatment can have dramatic effects; no one choice is dominant due to the complications of wanting to test for two-way causality. Other researchers have used the dates as provided with the data ([Wang et al., 2018](#)), averaged data over consecutive days ([Forbes & Rigobon, 2002](#)) or used time-matched data series ([Kleimeier, Lehnert, & Verschoor, 2008](#)). Although the last of these is arguably the most appropriate, it is difficult to obtain this data for the markets examined here and to control for problems associated with out-of-local trading time liquidity effects (most markets have different price-impact effects during local and nonlocal trading). The averaging procedure used by [Forbes and Rigobon \(2002\)](#) introduces a moving average bias into the problem, and, with Granger-causality testing, produces additional problems with the performance of the statistic. And the use of lagged or non-lagged samples is dogged by argument as to whether this introduces or reduces noise in the process. Sensitivity analysis to different choices of date-lagging produced important differences; the most pronounced of these is that when US data are lagged there is virtually no evidence of transmission from the US to Asia, which seems at odds with our understanding of international financial markets and the transmission of shocks. Consequently, this

<sup>7</sup> We study 42 stock markets that fall into three categories; developed, emerging, and frontier markets. We extend the previous research that primarily focused on a few developed or emerging markets (see, e.g., the G7 stock markets investigated by [Apostolakis and Papadopoulos \(2014\)](#), the 10 developed and 11 emerging markets in Asia studied by [Yarovaya, Brzeszczyński, and Lau \(2016\)](#), and Asian markets examined by [Narayan, Narayan, and Prabheesh \(2014\)](#) and that does not take into full consideration all possible interconnectedness across different stock markets.

paper uses the convention of actual day dating in its analysis.

We first examine the evolution of the weighted networks over the sample period and then augment this analysis with scenarios based around alternative clusterings of markets, as per the Asian Development Bank member countries and the role of regional groupings including the Association of Southeast Asian Nations (ASEAN) with other regions across the globe.

#### 5. Results and analysis

Panel A of [Fig. 1](#) shows the statistically significant links between each of the country nodes in the sample using just the Granger causality test results over the entire sample period (1995–2016). It immediately points to the complexity of the relationships between nodes - there are 1722 (= 42! / 40!) possible connections between the nodes. It is evident that the markets involved are heavily interconnected, but it is difficult analytically to say more from this diagram.<sup>8</sup> The outcome of all the results in these paper is based on the VAR(2) model (based on Akaike information criterion (AIC) which is the most standard selection of the true lag in VAR models). In [Fig. 1](#) panel A, the unweighted network is represented with the Granger Causality results grouped regionally (using the groupings in [Table 1](#)). The primary focus of this paper is the Asian economies, which are represented in light green, grouped in the center of each figure. The sizes of each node reflect the number of links to and from of that node - for example, it is evident that the United States has many connections over the sample period.

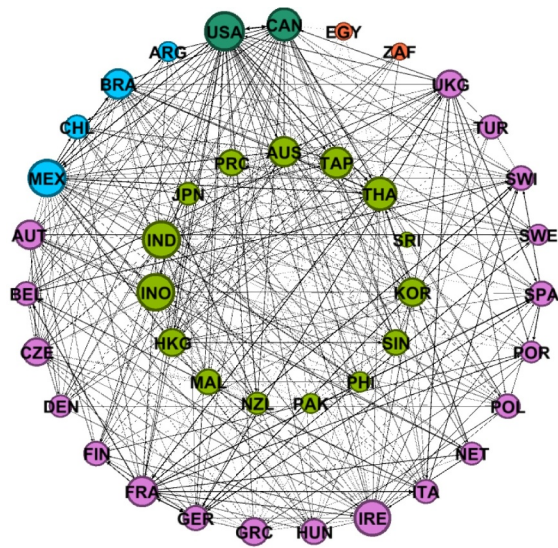
We augment these simple directional graphs with weights drawn from the DY method to obtain a weighted directional network of the nodes in Panel B of [Fig. 1](#). It identifies both the nodes with the largest connections and with statistically significant links. Some nodes are relatively isolated in this picture, Pakistan is a relatively isolated node, while Sri Lanka is an end node (that is, it is joined by only a few edges to other nodes in the system). The diagram also illustrates the clear, relatively strong significance of the relationships between the European markets (colored magenta) in the sample, particularly those which are members of the euro area. The linkages between the markets are also directional, as given by the arrows at the ends of each edge—while some are double-ended, implying Granger causality in both directions (such as Hong Kong and Singapore), others are not (the link between Thailand and Malaysia is shown running in one direction only).

The thickness of the lines in panel B indicates the relative strength as well as statistical significance of the links. Thus, it is immediately evident that the US and France are strongly connected to others (a similar role for France is found in [Wang et al. \(2018\)](#)). Within the Asian focus of this paper there are clearly strong links between Hong Kong and the United States, and slightly less so for Hong Kong and Canada. Hong Kong is also strongly linked to Malaysia and Singapore, as well as slightly less strongly to a raft of other economies. Other distinctly strong linkages occur between European countries such as Finland and Sweden, the UK and Italy and so on. The links between the European countries are stronger (in DY weights) than those detected for most of the Asian economies, which is probably unsurprising as many of them were members of a common currency union for a large part of the sample period.

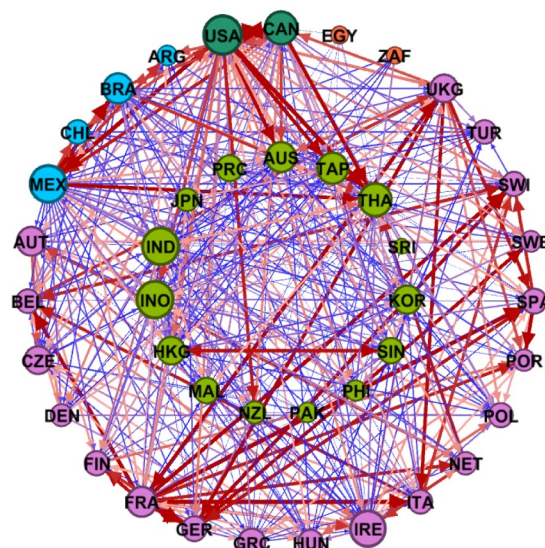
A distinct disadvantage of [Fig. 1](#) is the span of the sample covered. There have been many changes in world financial markets in this period—including the introduction of the euro; the float of many Asian currencies; increasing financialization of emerging markets in Asia, Africa and South America; more liberated international capital markets; and capital deepening in many areas. In addition, there have been several financial crises. We consequently divide our sample into six subsample periods. Each panel (A to F) in [Figs. 2–4](#) represents the

<sup>8</sup> We discuss the descriptive statistics of the network at each phase in [Appendix A.1](#).

**A. Unweighted with Regions indicated**



**B. Weighted with regions indicated**



**Fig. 1.** Evolution of network plots for entire sample.

Notes: Sample period: 1 March 1995 to 30 December 2016. Regions are color-coded as Asia (light green), Europe (magenta), North America (dark green), South America (blue), Africa (orange), as defined in Table 1. The figure displays the returns-based network of 42 equity markets. Edges were calculated using bivariate Granger causality tests between markets at the 5% level of significance. Edge in A is unweighted and is allocated equal weights. Edge thickness in B is proportional to the intensity of the edge strength and is set as: red (strongest), orange (medium) and blue (weakest). Node color shows the regional grouping while the node size is proportional to its degree. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

network in each of these six phases. The phases are selected based primarily on a desire to examine how the network of Asian markets has changed over the sample period. The sample periods are divided as represented in Table 2.

To avoid complications in naming our choice of periods in the literature, particularly for choosing end points of each sample, we refer to each of these subperiods simply as phases within the total sample. In Table 2 the total number of observations in the whole sample is 5738; in each subsample, the number of observations varies. Phase 1 represents the period in the lead-up to the Asian crisis of 1997–1998 and Phase 2 covers the generally accepted duration of that crisis (see Dungey, Fry, & Martin, 2006). Phase 4 covers the recognized lead-up to the global financial crisis pre-2008, and Phase 5 the usual period of the global financial crisis itself (see Dungey, Milunovich, Thorp, & Yang, 2015). Consequently, Phases 1 and 4 both represent periods of lead-up to crisis, Phases 2 and 5 are periods of crisis, and Phases 3 and 6 are to some extent recovery periods, although this is clouded by the dotcom crisis in 2001 in Phase 3 and the stress in sovereign debt markets post-2010. Our area of interest is to examine not only the networks in those periods, but also the transitions which occur in these networks between the different phases. In this way, we will generalize about the number of characteristics of networks as they enter and exit crisis conditions. Our findings are reinforced by those for the large network (107 nodes) of credit default swaps (CDS) issuers examined in Dungey et al. (2018), even though market coverage in that paper was more specifically geared towards individual financial institutions and sovereign issuers rather than the equity market indicators used here.

**5.1. Changing network links over time**

Fig. 2 illustrates the changing nature of the weighted financial network over the six phases defined in the previous section. Table 3 provides the associated network statistics. The first impression from panels A to B in Fig. 3 is that the density of the network has changed substantially over time. The figures give the impression of becoming darker and thicker - that is, more connected, in a similar manner to the

changes noted by Billio et al. (2012) and Merton et al. (2013) for several forms of financial intermediaries in the US and European markets. However, Table 3 reveals that the number of statistically significant edges in the network has grown less monotonically than the panels may suggest. In Phase 1, 210 of the possible 1722 linkages were statistically significant. This is only 12.2% of all the possible linkages. However, this number grew dramatically, by 45% to 305 links in Phase 2, before returning to close to the pre-crisis period numbers in Phase 3. In Phase 4, the build-up to the global financial crisis, the number of links increased in the system, up by 10%, but in Phase 5 the number of links jumped dramatically to 389, an increase of almost 65%. After that period, the links decreased again but remained at about the same level in Phase 6, as was evident in the crisis of 1997–1998.

The Jaccard statistics, which compare the networks in a phase to that in the previous phase, summarize one aspect of the changing numbers of linkages (Table 4). The first row of Table 4 indicates the proportion of links that existed in the earlier period which were removed in the transition to the next period. The second row indicates the proportion of links which formed between the two phases as a proportion of the latest phase's links. In this way, we can see the composition of the elements of the Jaccard statistic listed in the third row of the column. The Jaccard statistics are low; that is, relatively few links are common between two phases. This is partly because the network is growing significantly in number of links over the sample period, with 45% more links in Phase 6 than Phase 1, and this growth results in a reduction in the Jaccard statistic by construction. The first two rows show that, in general, the network exhibits greater stability, in terms of the retention of edges, as time progresses. Setting aside the post-crisis period of Phase 6, it is apparent that the proportion of links lost during each of the sample shifts is falling, from 80% to 65%. The edges are becoming more likely to be retained over the sample period. The growth of the network is still apparent, however, in that the drop of the number of new links as a proportion of the total in each phase remains relatively more stable, at or over 75% of each phase. The transitions around the global financial crisis period, involving Phase 5, paint a picture complementary to the analysis above. During Phase 5 a



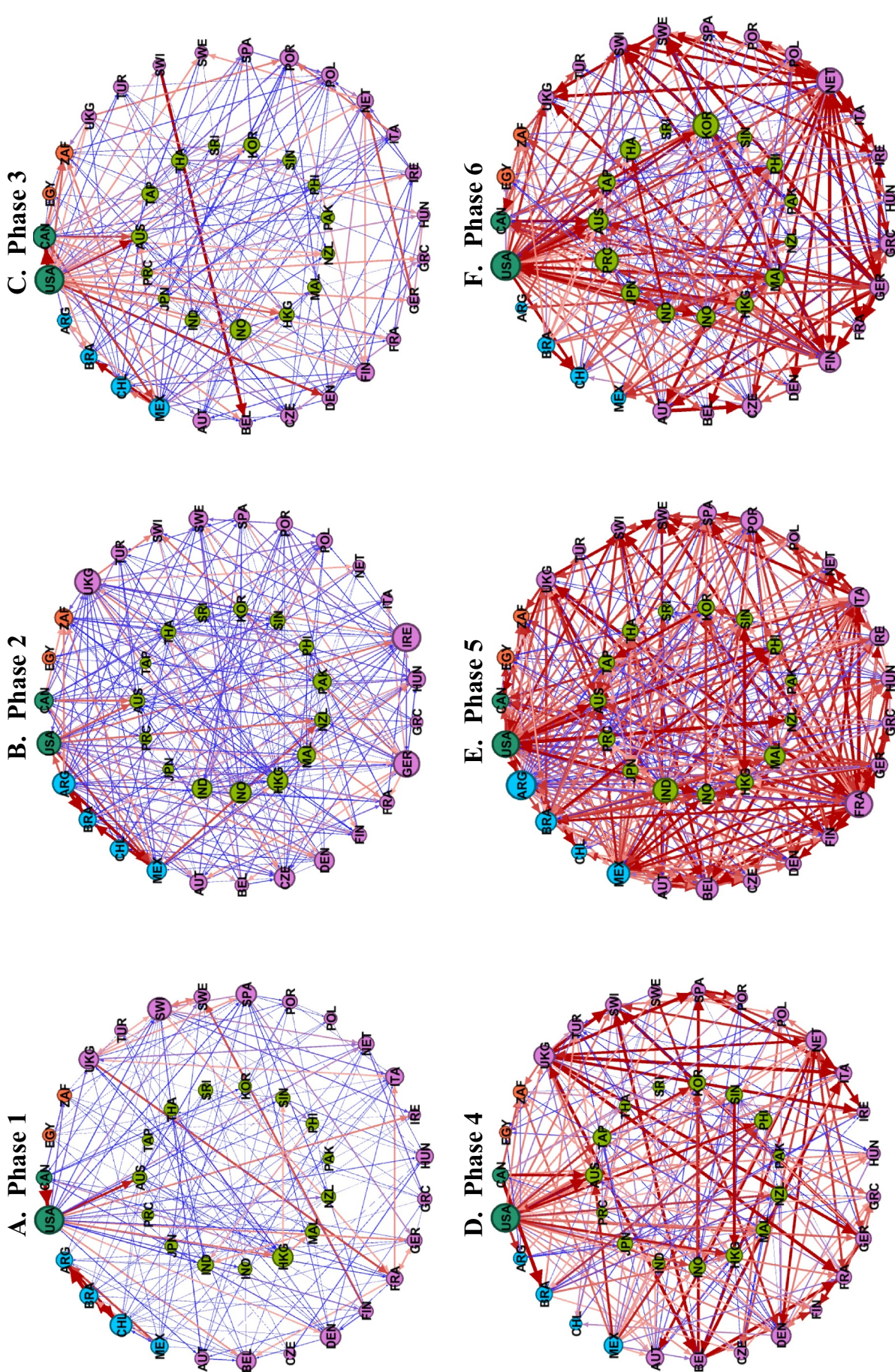


Fig. 2. Evolution of weighted networks with regional groupings. Notes: Sample period: 1 March 1995 to 30 December 2016. Regions are color-coded as Asia (light green), Europe (magenta), North America (dark green), South America (blue), Africa (orange), as defined in Table 1. The figure displays the returns-based network of 42 equity markets. Edges were calculated using bivariate Granger causality tests between markets at the 5% level of significance. Edge thickness is proportional to the intensity of the edge strength and is set as: red (strongest), orange (medium) and blue (weakest). Node color shows the regional grouping while the node size is proportional to its degree.



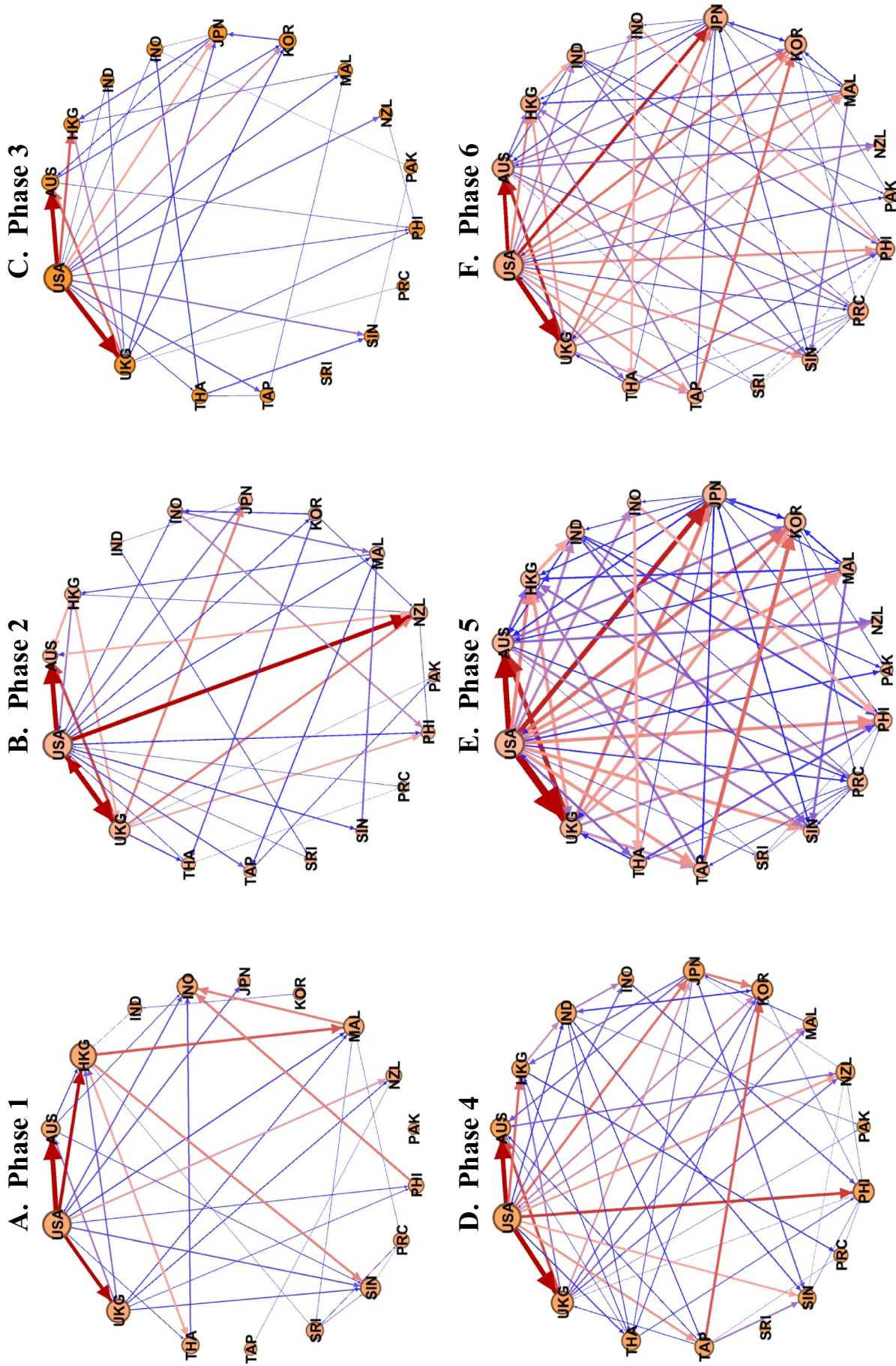
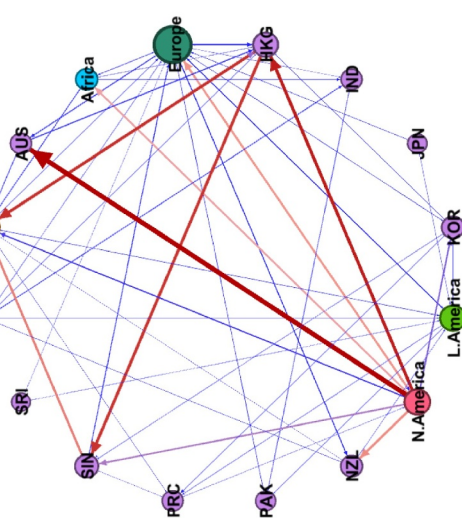


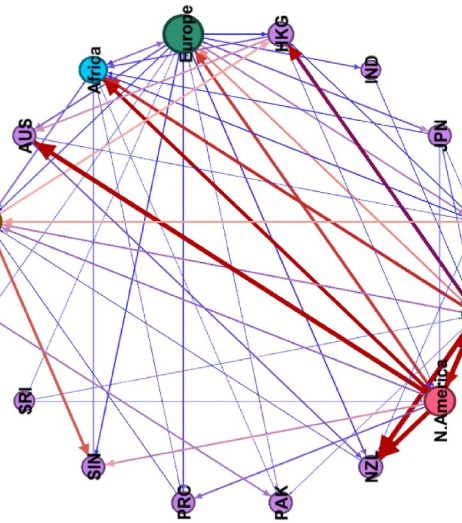
Fig. 3. Evolution of Weighted Networks with Asian markets, the US and the UK. Notes: The figure displays the returns-based network of 42 equity markets from 1 March 1995 to 30 December 2016. Edges were calculated using bivariate Granger causality tests between markets at the 5% level of significance. The thickness of the lines indicates the average relative strength of each market (or regional grouping) and is set as: red (strongest), orange (medium) and blue (weakest). The size of the nodes increases with the number of inward and outward links of each respective market (or regional grouping). Regional groupings are defined in Table 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



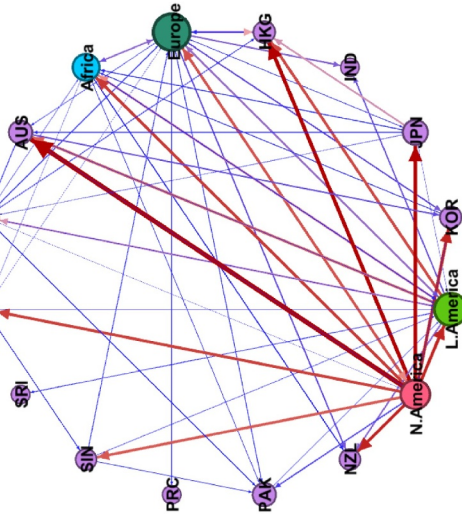
### A. Phase 1



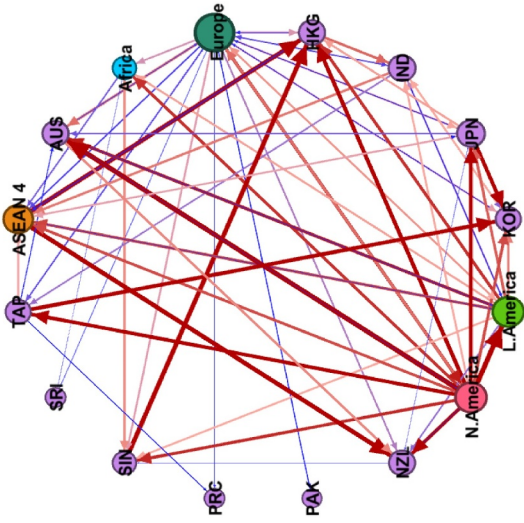
### B. Phase 2



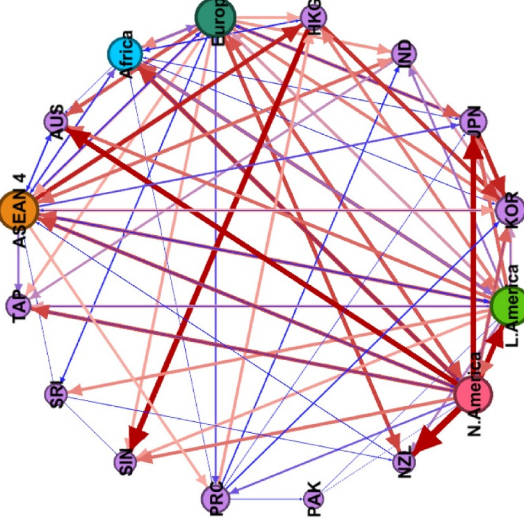
### C. Phase 3



### D. Phase 4



### E. Phase 5



### F. Phase 6

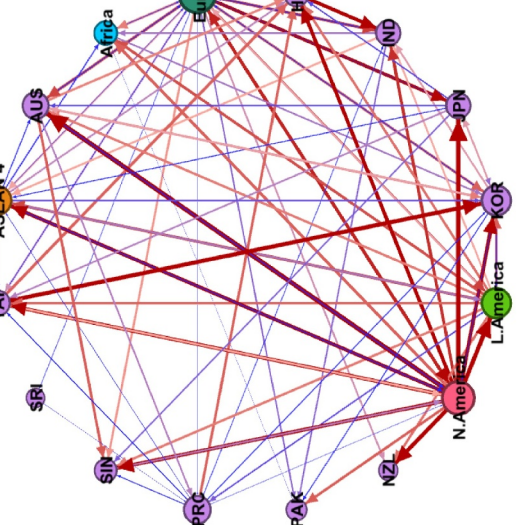


Fig. 4. Evolution of weighted networks with regional groupings highlighting ASEAN and Asian markets.

ASEAN4 = Association of Southeast Asian Nations (Indonesia, Malaysia, Philippines, and Thailand).

Notes: The figure displays the returns-based network of 42 equity markets from 1 March 1995 to 30 December 2016. Edges were calculated using bivariate Granger causality tests between markets at the 5% level of significance. The thickness of the lines indicates the average relative strength of each market (or regional grouping) and is set as: red (strongest), orange (medium) and blue (weakest). The size of the nodes increases with the number of inward and outward links of each respective market (or regional grouping). Regional groupings are defined in Table 1.

relatively lower proportion of existing links in Phase 4 have been retained, and the many that are formed during the crisis period are subsequently not retained in Phase 6. Thus, the crisis period sees an increase in density consistent with the high degree of net formation of new links, consistent with the dominance of the [Forbes and Rigobon \(2002\)](#) form of contagion.

The result of examining the transition from the build-up in pre-crisis to crisis period is that there is a rapid increase in the number of statistically significant edges in the network—supporting the idea that during periods of stress the markets become more interconnected. This is consistent with the literature finding considerable evidence of contagion.<sup>9</sup>

The average link is weaker in the crisis period than the lead-up to crisis period. Panel B of [Table 3](#) shows how this evolves. The top part of the panel describes the mechanism of formation of edges between each of the phases and the bottom section describes the edges removed. A relatively large number, on average, of weaker edges were formed (264 edges formed of average strength 0.0194) while a smaller number of stronger edges were removed (169 edges removed of average strength 0.0206). [Dungey et al. \(2018\)](#) observe declines in the average strength of the links between the periods leading up to crisis and the crisis periods themselves for CDS markets.

A similar pattern is observed in the transition between the pre-GFC period and the crisis itself in comparing the results for Phases 4 and 5. In this case, there were 306 links formed between Phase 4 and 5 and 154 links removed. That is, the number of links formed outweighs the number of links removed (and note that the total number of links recorded in Phase 5 was 389, so that a full 64% of the links in Phase 4 were removed in Phase 5). The Jaccard statistic for Phase 5 compared with Phase 4 is 11.74% ([Table 4](#)). In both of these cases slightly fewer links were removed and slightly fewer formed than in the adjacent periods otherwise covered in the table. This suggests that in periods of stress some links do not thrive, but they return during non-stress periods. Ongoing work is examining in detail the corporate characteristics of these markets within countries, but to our knowledge none has yet been undertaken on a macro fundamental country basis, although these results certainly provide a motivation to do so.

The new links formed between phase 4 and phase 5 were on average slightly stronger than those removed,<sup>10</sup> and the completeness statistics for the network increase due to both higher average strength of the link and a higher number of links. The net change in the number of edges reported is not sufficient to characterize the changing nature of the network. Edges removed are just as important as edges formed in understanding the transmission of crises—these are both forms of contagion between markets. The complications of using completeness statistics to understand the evolution of a network are also revealed—completeness may fall due to increased number of edges being outweighed by the fall in their average strength as in the Asian financial crisis example, or it may rise due to the overwhelming increase in the number of edges, which is the case for the global financial

<sup>9</sup> In our analysis, sample variances are separately controlled in the different phases, thus the changes in correlation are not a symptom of the changing variance. See [Forbes and Rigobon \(2002\)](#).

<sup>10</sup> The reason the average strength of links in panel A of [Table 3](#) is lower in Phase 5 than Phase 4, but the formed edges between Phases 4 and 5 are stronger than the removed edges in panel B is that they represent slightly different options for calculation. Panel A gives the average strength as the sum of the weighted Granger links over the possible links. Panel B gives the removed strengths as the sum of the removed links weighted by the t-1 period weights over the changed number of links (that is, an incremental Granger matrix) and the formed strengths are given as the sum of the weighted links formed, weighted with the current period weights, over the sum of the formed links (that is, an incremental Granger matrix). Thus, in panel A the results are only about time t data, whereas panel B involves weights from both the previous and current periods. This accounts for the apparent analytical differences.

**Table 2**

Time series observation in each subsample period.

Phase	Period	Represents	Observations
All phases	01.03.1995–30.12.2016		5738
Phase 1	01.03.1995–01.07.1997	Pre-AFC period	650
Phase 2	02.07.1997–31.12.1998	AFC period	391
Phase 3	01.01.1999–31.12.2002	Post-AFC	1042
Phase 4	01.01.2003–14.09.2008	Lead-up to the GFC	1287
Phase 5	15.09.2008–31.03.2010	GFC	602
Phase 6	01.04.2010–30.12.2016	Post-IMF program in Greece	1761

AFC = Asian financial crisis, GFC = global financial crisis, IMF = International monetary fund.

crisis period. Knowing which edges are removed may be critical—for example, the collapse of Bear-Stearns in 2007. Policy makers will clearly wish to understand both the possibilities for removed edges and formed edges in periods of stress and have alternative plans available for each.

The post-crisis periods in the sample also reveal interesting contrasts. Both periods also include crisis periods in other parts of the network—in Phase 3, the dotcom crisis, and in Phase 6, the European debt crisis—making it difficult to classify these two periods as clearly post-crisis conditions. However, the transitions from the main crises of focus in this analysis are instructive. From Phase 2 to Phase 3, the number of links is reduced, as it is from Phase 5 to Phase 6. That is, after our main crisis period, the number of edges falls. In the first case, from Phase 2 to Phase 3, this is achieved by reducing in the number of links (loss of 250 links and gain of only 159) and a lower average strength in the new links than those which are removed. These factors both contribute to a lower completeness statistic in Phase 3 than in the previous period. Similarly, in the transition from Phase 5 to Phase 6, more links are removed than formed. The links which are removed are stronger than those formed, contributing to a lower completeness statistic in Phase 6.

Identifying which of the links exist prior to a crisis, are lost during the crisis, and then reformed in the post-crisis period has policy implications. Were these linkage losses due to deliberate isolation of nodes or due to their vulnerability? The first evidence of this is provided in the Jaccard statistics for pre-crisis to post-crisis phases (the last two columns of [Table 4](#)). The Jaccard tests show that there are relatively few of the links in place before the crisis are in place again after the crisis. There is clearly some return of the pre-existing links, as the test statistic is larger than those between other periods, but overall the evidence suggests that the network does not return to its pre-existing state in the post-crisis period. This is consistent with the existing literature examining single instances of pre and post crisis networks. To address this question more specifically we turn to analysis of the links between nodes themselves.

## 5.2. Spreaders and absorbers

We are particularly interested in identifying four types of nodes, and whether different nodes change their role during periods of stress and calm. The four types of nodes are: super-spreaders, super-absorbers, periphery-spreaders, and periphery-absorbers. Super-spreaders are those markets which absorb shocks and distribute them to many other nodes; generally, they will have a substantially higher out-degree than in-degree. Super-absorbers are markets which are subject to many shocks but do not distribute them widely; generally, they will have a substantially lower out-degree than in-degree. A greater discrepancy between the in-degree and the out-degree of each node places it more firmly into the super-spreader or super-absorber category. Periphery-spreaders originate shocks to many markets but do not receive a great deal of in-links. They can be viewed as a specific form of the super-



**Table 3**  
Statistics used for analysis of network structures (all countries).

Panel A						
	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Average strength	0.0260	0.0235	0.0236	0.0276	0.0260	0.0225
Number of edges	210	305	214	237	389	306
Completeness	0.2570	0.2252	0.1820	0.2034	0.2734	0.1990
Panel B						
	Phase 1–Phase 2	Phase 2–Phase 3	Phase 3–Phase 4	Phase 4–Phase 5	Phase 5–Phase 6	
Edges formed						
Δ in average strength (EF)	0.0194	0.0169	0.0208	0.0225	0.0211	
Number of edges formed	264	159	180	306	233	
Δ in completeness (EF)	0.1608	0.0968	0.1163	0.1864	0.1424	
Edges removed						
Δ in average strength (ER)	0.0206	0.0196	0.0180	0.0207	0.0229	
Number of edges removed	169	250	157	154	316	
Δ in completeness (ER)	0.1640	0.1536	0.1020	0.0994	0.1957	

Note: Δ represents change EF represent edge formed while ER is edge removed. The average link strength is estimated from the connectedness of each respective network. The number of edges was calculated using bivariate Granger causality tests between network nodes (entities).

**Table 4**  
Jaccard statistics.  
Jaccard statistic for all countries in the sample (%).

	Phases							
	1–2	2–3	3–4	4–5	5–6	1–3	4–6	
Edges removed as proportion of Phase t – 1	80.48	81.97	73.96	64.98	81.23	74.29	68.35	
Edges formed as proportion of Phase t	86.56	74.30	75.95	78.66	76.14	74.77	75.49	
Jaccard statistic for all edges	8.65	11.85	14.47	15.29	11.74	14.59	16.03	

spreaders, the key difference being that the in-degree is relatively small. Periphery-absorbers are markets which absorb shocks but do not pass them on; they are a specific form of super-absorbers where the key is the very low out-degree.

The most obvious super-spreader in the sample is the US (Table 5). It routinely has more out-degrees than in-degrees. The central role of the US in global financial markets is well-documented, and here our evidence seems to strongly support the center and periphery argument of Kaminsky, Reinhart, and Vegh (2003), where developed financial markets act as a conduit for the transmission of shocks from other periphery markets. The first two columns present the out-degree and in-degree of each of the nodes for the entire sample of the network. It is evident that the greatest number of out-degrees is recorded for the US, consistent with our designation of a super-spreader. The fewest links are recorded by Sri Lanka, which, we noted previously, is an isolated node. The maximum in-degree is received by the Republic of Korea, while the minimum in-degree is recorded by Mexico.

To summarize the role of the super-spreaders, super-absorbers, and peripheral spreaders and peripheral absorbers Table 6 provides a breakdown of the markets identified in the sample. To construct this table, we used the following selection rules applied to each market:

Define:  $x = (\text{out-degree} - \text{in-degree})$

	$x < 0$	$x > 0$
Out-degree < 3	Peripheral-absorber	
In-degree < 3		Peripheral-spreader
Absolute $x > 6$	Super-absorber	Super-spreader

The cut-off points for differentiating these types of absorbers have been chosen on an ad-hoc basis in this table, based on visual analysis by the authors. Further work to examine the sensitivity and explanatory power of different variables to alternative definitions is warranted in future work.

Table 6 makes evident that over the different samples, the number of spreaders and absorbers increases - which simply represents the more connected network. Two countries particularly stand out as ones that swap roles between periods of stress and non-stress. Both Argentina and Ireland are super-spreaders in the crisis periods of Phases 2 and 5 but revert to being super-absorbers during other periods. The constant presence of the US as a super-spreader is accompanied by Japan, which is a spreader (either super or peripheral) in each period except Phase 4. (Recall that Phase 4 represents the early part of the 21st century when the Japanese economy was not synchronized with other OECD or global economies - Farrell et al. (2005) note a diminishing role for Japanese markets in this period). Distinct roles for several European markets emerge in the later parts of the sample; particularly post Phase 3 after the formal introduction of the euro area. France and Italy are each super-spreaders during the global financial crisis, but not during the surrounding phases, while Germany emerges as a super-spreader in both post-crisis periods of Phases 3 and 4. The perhaps unexpectedly different roles of the German and French markets are consistent with results in Wang et al. (2018), who attribute the centrality of the French markets within Europe as due to the presence of the World Federation of Exchanges in Paris.<sup>11</sup>

<sup>11</sup> If this hypothesis is correct, then there are significant gains to a market from co-location with an international organizational body.

**Table 5**  
Characteristics of a return based network.

Vertex	All phases		Phase 1		Phase 2		Phase 3		Phase 4		Phase 5		Phase 6	
	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In
Argentina	4	7	2	9	18	5	4	4	5	3	35	12	0	3
Australia	13	18	4	4	4	7	4	7	5	9	1	14	7	13
Austria	13	14	3	5	5	10	7	6	11	4	12	9	8	8
Belgium	7	11	6	9	6	3	1	5	7	6	17	12	0	7
Brazil	19	11	3	10	6	9	4	8	8	5	12	14	14	0
Canada	24	11	6	4	12	5	16	6	11	1	1	15	9	10
Chile	6	12	11	7	9	7	11	6	2	3	2	10	8	7
China	16	6	1	4	4	3	1	2	0	3	8	8	23	4
Czech Republic	10	15	4	1	9	11	4	9	3	6	7	9	9	10
Denmark	6	9	10	6	10	9	6	4	10	9	4	9	3	6
Egypt	7	9	7	0	3	6	2	5	0	5	10	7	9	6
Finland	7	12	6	2	2	9	5	10	1	4	5	10	13	11
France	19	10	5	6	1	10	3	5	4	7	33	9	1	5
Germany	9	11	4	5	15	14	3	2	8	4	11	5	13	5
Greece	18	7	4	4	7	1	1	4	3	6	6	7	11	10
Hong Kong	8	17	7	9	11	9	1	8	7	6	3	15	3	13
Hungary	9	12	7	5	3	13	1	5	1	7	8	10	1	5
India	6	11	3	3	0	5	0	3	5	6	4	8	10	6
Indonesia	28	15	3	7	13	6	4	5	2	4	27	9	5	11
Ireland	29	10	1	4	22	10	7	4	2	5	15	7	2	10
Italy	9	9	4	9	1	5	3	5	5	7	17	8	1	5
Japan	29	13	6	1	15	6	15	4	6	7	5	12	12	5
Malaysia	6	15	2	6	6	10	4	3	2	7	18	8	7	11
Mexico	37	5	7	5	10	8	14	4	17	0	22	8	4	5
Netherlands	7	10	4	6	0	7	4	8	16	5	0	11	23	9
New Zealand	6	9	4	4	4	8	1	5	3	10	1	4	0	5
Pakistan	5	6	1	3	13	3	3	4	0	3	2	1	1	5
Philippines	2	10	3	3	4	6	0	4	10	5	0	12	2	10
Poland	4	15	1	5	1	12	2	10	5	6	0	6	4	9
Portugal	1	13	3	6	7	6	7	8	1	5	22	8	4	6
Singapore	8	13	4	4	7	4	4	3	1	12	6	9	1	8
South Africa	7	14	3	5	4	12	5	8	2	7	5	8	3	8
Republic of Korea	9	18	2	4	6	4	4	7	2	11	2	14	21	11
Spain	7	13	9	7	5	7	4	5	3	6	9	11	3	5
Sri Lanka	0	6	8	0	7	0	1	2	0	4	3	8	1	2
Sweden	4	9	1	9	5	12	2	4	4	4	2	8	6	8
Switzerland	5	14	12	8	1	6	2	3	5	7	3	7	5	10
Taiwan	13	13	3	1	5	4	11	1	10	6	4	10	8	7
Thailand	12	16	3	5	2	9	5	6	1	3	2	12	14	7
Turkey	7	11	3	3	6	7	4	5	4	8	2	5	2	4
United Kingdom	11	14	8	7	20	8	6	3	14	7	11	11	1	11
United States	37	10	22	5	16	9	28	4	31	4	32	9	34	5

Rather than being isolated or negligible (as in the analysis of Farrell et al., 2005), the Asian region markets are clearly identifiable as a presence in the network. While Japan is evident throughout, Asian markets are more generally identified as spreaders or absorbers from Phase 3 onward - that is, in the post-Asian crisis period. The emergence of Hong Kong and Singapore as super-absorbers is particularly important (Hong Kong from Phase 3 onward, and Singapore in Phases 3 and 6). New Zealand also emerges as an absorber in this period. Interestingly, these are all some of the most developed markets in the region, although the New Zealand market is small by global standards. This role of super-absorber is evident as they form bridges between the numerous in-linkages from Asian economies and fewer out-linkages transporting the effects to the global markets.

The analysis of the changing in- and out-degree of the network considers that not only are the numbers of links in the network changing, but also that the nodes that are most connected change. The next stage in this research agenda is to explore whether these changes in out-degree and in-degree can be systematically related to characteristics of the markets involved.

### 5.3. Focus on the Asia-Pacific region

Fig. 3 (Panels A to F) illustrates the sub-network within the Asia-Pacific region with a few key non-regional source shocks included

(notably the US, UK). That is, we have cut down the information in Fig. 1 to make this analytically more tractable. The system statistics are given in Table 7 for each Phase, where we treat each 'region' as a single node in counting the in-degree and out-degree.

It is readily apparent from Fig. 3 that the United States has the greatest number of connections of each of the nodes considered (omitting all the European links from the diagram provides this clarity), and that Sri Lanka and Pakistan are relatively isolated. The dominant direction is an out-link from the US to the other markets. We proceed to the sub-sample analyses to understand more clearly the changing nature of the network within the Asia-Pacific.

Fig. 3, Panel A, reveals the network for the Phase One, prior to the Asian crisis. Here it is apparent that the network is quite sparse. The links from the United States directly to the Asian markets are dominated by the direct link to Hong Kong. This provides an evidently important conduit from Hong Kong to and from other Asian markets – Hong Kong has links to each of Malaysia, Singapore, Thailand and Australia. There are also direct links from the US to Singapore, which again provides a conduit on to other Asian markets which are not as strongly connected, such as China and Australia. Thus, both Hong Kong and Singapore are providing a bridge node for transmissions to other Asian markets. Even more evident is the role of the UK and Australia in receiving links from the US and distributing them into Asia. The Australian node transmits between Indonesia and Hong Kong, while there



**Table 6**  
Spreaders and absorbers by phase.

Vertex	Phase 1		Phase 2		Phase 3		Phase 4		Phase 5		Phase 6	
	S	A	S	A	S	A	S	A	S	A	S	A
Argentina		SA	SS						SS			PA
Australia										SA		
Belgium						PA						SA
Brazil												
Canada					SS					SA		
Chile							PA		PA			
China		PA				PA						SS
Czech Republic	PS											
Egypt	SS					PA		PA				
Finland	PS			SA				PA				
France									SS			PA
Germany					SS							SS
Greece						PA						
Hong Kong						SA				SA		SA
Hungary				SA				PA				PA
India						PA						
Indonesia				SS				PA	SS			
Ireland		PA		SS				PA	SS			SA
Italy									SS			PA
Japan	PS			SS		SS		PA				SS
Malaysia		PA							SS			
Mexico									SS			
Netherlands										SA		PA
New Zealand								SA		PA		
Pakistan		PA		SS				PA	PS			PA
Philippines										SA		SA
Poland		PA								PA		
Portugal								PA	SS			
Singapore								SA				SA
South Africa								PA				
Republic of Korea		PA						SA		SA		SS
Sri Lanka	SS			SS			PA	PA				
Sweden		SA		SA			PA	PA				
Switzerland				PA			PA					
Taiwan						SS				SA		
Thailand				SA				PA			SS	
Turkey										PA		PA
United Kingdom				SS								SS
United States	SS			SS		SS			SS			SS

Note: SS = Super-spreader, PS = Periphery-spreader, SA = Super-absorber, PA = Periphery Absorber.

is a clear expression of links from the UK into Asia-Pacific markets; evident for New Zealand, Hong Kong, Malaysia, Singapore and the Philippines. A particularly interesting facet of the network in this Phase is that Japan is connected to the US but does not provide a bridge for these shocks into Asian markets.

By Phase Two (the Asian crisis) the links from the US directly to the Asian-Pacific markets are evident for a wider range of markets than in the previous Phase. The link between the US and UK remains strong, with ongoing links to other markets, but during this crisis period, while the links to Australia and New Zealand from the US are strong, the onwards projection of shocks from these sources to other Asian markets is not as pronounced as in Phase One. However, the network does not indicate that shocks emerging from the Asian markets travel directly to the US, in this case they tend to transmit around the Asian market and then to developed markets via the conduit of regional hubs such as Hong Kong. (For example, consider a shock originating in Malaysia – one route for this to affect the developed markets of US, UK, New Zealand or Australia is via the link from Malaysia to Hong Kong and hence to the developed markets.)

Panel C of Fig. 3 shows the much-reduced network in the post-crisis period. Compared with the pre-crisis period of Phase One, more of the Asian markets are directly linked to the US. The role of the UK in providing a further conduit into Asian markets is also evident. Japan is now more integrated into the network; it is receiving shocks from all of the developed markets (bar New Zealand) directly and passing them on

to Hong Kong and Indonesia directly. China is still relatively isolated, in that it receives effects from the rest of the network only through the UK. Sri Lanka is a completely isolated node.

In the build-up to the Global Financial Crisis, in Phase Four, the network is much denser than in previous periods. In Panel D, the links directly from Asian markets to the more developed markets are becoming clear - for example Taiwan and Malaysia. Importantly, China is now connecting via an Asian bridge - the Hong Kong market, as well as directly to the UK node. The role of Japan as a means of transmitting shocks continues to grow, while it still receives shocks quite strongly from the other developed markets - and distributes them via Hong Kong and Singapore - there are also more direct links from Malaysia, to Thailand and to South Korea.

The increasing density of the Asia-Pacific network continues in the Global Financial Crisis period, Phase Five, as shown in Panel E. China in this case becomes a source of inputs to the network but is not linked directly to the shocks emanating from the US, evidence of the differences in outcomes for China and Western developed markets during this period. The role of Japan, on the other hand, continues to become more important as a bridge to Asian region markets. In contrast, the role of Hong Kong now shows primarily inward linkages from the Asian markets (it remains connected in both directions to many markets but compared with earlier Phases there is a higher degree of inward linkages) and then acting as a bridge to markets such as the US and UK. Hong Kong remains an important bridge market between the Asian

**Table 7**  
Summary statistics of various network measures for ASIA plus US and UK.

	Mean	Med	Std. dev	Min	Max
All phases					
In-degree	5.65	6.00	1.92	1.00	9.00
Out-degree	5.65	5.00	4.21	1.00	16.00
Betweenness centrality	6.94	3.95	14.67	0.00	39.94
Eigenvector centrality	0.06	0.06	0.02	0.02	0.09
Phase 1					
In-degree	2.18	2.00	1.70	0.00	5.00
Out-degree	2.18	1.00	2.72	0.00	10.00
Betweenness centrality	15.53	3.00	22.07	0.00	69.89
Eigenvector centrality	0.06	0.05	0.04	0.00	0.13
Phase 2					
In-degree	2.47	2.00	1.55	0.00	6.00
Out-degree	2.47	2.00	2.65	0.00	11.00
Betweenness centrality	13.65	3.00	32.23	0.00	134.33
Eigenvector centrality	0.06	0.06	0.03	0.01	0.14
Phase 3					
In-degree	2.06	2.00	1.14	0.00	4.00
Out-degree	2.06	1.00	3.31	0.00	13.00
Betweenness centrality	12.12	1.33	29.07	0.00	119.00
Eigenvector centrality	0.06	0.05	0.04	0.00	0.15
Phase 4					
In-degree	3.35	2.00	3.39	0.00	13.00
Out-degree	3.35	3.00	1.80	0.00	7.00
Betweenness centrality	8.24	3.43	9.97	0.00	33.79
Eigenvector centrality	0.06	0.06	0.03	0.00	0.11
Phase 5					
In-degree	4.35	4.00	2.06	0.00	7.00
Out-degree	4.35	3.00	3.71	0.00	15.00
Betweenness centrality	6.47	4.75	9.03	0.00	39.02
Eigenvector centrality	0.06	0.06	0.02	0.00	0.10
Phase 6					
In-degree	4.06	4.00	1.92	2.00	8.00
Out-degree	4.06	3.00	4.21	0.00	16.00
Betweenness centrality	8.47	2.94	14.67	0.00	60.59
Eigenvector centrality	0.06	0.06	0.02	0.02	0.10

markets and others. Singapore has a similar experience. As with the existing analyses of changing networks during the Global Financial Crisis the completeness of the network in the Global Financial Crisis increased dramatically (see Billio et al. (2012) and Merton et al. (2013)).

In Phase Six, Panel F, the density of the network decreases from the crisis period but the greater connectivity of the Asian markets from many sources remains prevalent; for example, South Korea is now receiving links from a much wider portion of the network than previously. China is clearly more connected than it has been previously, there are links outward from China to many of the Asian markets - Hong Kong, Taiwan, Thailand, South Korea, and Singapore – but it still only receives inward links from Australia and the US. Japan and Hong Kong are evident in their functioning as hubs for receiving and distributing shocks with Asian markets.

#### 5.4. Role of ASEAN<sup>12</sup> markets

Fig. 4 presents the network between the Asia and Pacific markets with the ASEAN markets aggregated to a single block to examine the evolution of the network between both ASEAN and the rest of the Asian block, as well as the rest of the world.

Fig. 4 shows the importance of the link between Hong Kong and the ASEAN markets over the whole period - each of the phase diagrams

<sup>12</sup> In this empirical exercise, ASEAN markets are Indonesia, Malaysia, Philippines, and Thailand, i.e. ASEAN4 markets.

show that this link remains prominent throughout the subsamples. These links primarily run from ASEAN markets to Hong Kong - as previously covered this reflects the role of Hong Kong (and Singapore, which is included in the ASEAN sample) in connecting Asian markets to the rest of the world.

Across the differing phases, there is a transformation of the structure of the network involving ASEAN and Asian markets, which seems to reflect the increasing development and deepening of the markets dominating the effects of crisis and non-crisis periods. Early in the sample, in Phase 1, there are noticeably fewer links to ASEAN economies than later in the sample—the links are mainly from or to developed markets rather than other developing Asian markets. Notably, Japan is not connected directly to ASEAN in this period. During Phase 2, there is a distinct change, in that inward links to ASEAN from other Asian markets begin to appear, from China and the Republic of Korea. Japan remains directly unconnected.

In Phase 3, post-Asian financial crisis, the US is clearly central to the distribution around the network. The links from other markets continue to develop, with Japan, Pakistan, and Taiwan connecting, although the Republic of Korea has dropped the association it had during the crisis period of Phase 2. China is also connecting to the network through its non-Asian links but has the role of an end node in this network, a position also occupied by Sri Lanka.

In the build-up to the global financial crisis during Phase 4, the network shows the ASEAN markets having stronger links than previously, with a similar group of markets as the previous phase. The Indian market, which was previously not directly linked with ASEAN markets, is now present; Pakistan remains relatively isolated.

During the global financial crisis, Phase 5, the network is dramatically different from the previous phase. Having subsumed the density of links between European, North American, and Latin American<sup>13</sup> markets into regional nodes, it is apparent that during this period there is an important role for the transmission of shocks from the North American markets to ASEAN through Japan, less so from Australia than previously, and not at all from New Zealand. The critical paths from the rest of the world to Asian markets have changed so that Japan has a gatekeeper role that was not evident previously. China is now more evidently directly and strongly linked to ASEAN markets and North America, so there are both direct and indirect links between Asian and Chinese markets.

In the final phase, China has continued to increase the number of evident direct links to other nodes in the network, and ASEAN markets are clearly an important hub in terms of the number of linkages coming in to the ASEAN node. There are also substantial numbers of weaker links from ASEAN to other Asian markets, such as Australia, Hong Kong, India, Japan, and the Republic of Korea. Note in this final network, ASEAN markets transition into becoming more integrated into the international network in a markedly different way from Phase 1 and the subsequent two phases. During the global financial crisis, it appears that the Asian markets matured to become more clearly interconnected with other major regions, both through the hubs of ASEAN, Hong Kong and Singapore; and more directly by links to major regions outside.

The conclusion of this analysis is that ASEAN markets are part of the bridge between the market regions of Asia, Europe, and the Americas. Consequently, there is a role here for ASEAN markets as a core for systemic risk in the Asian region, and many links are filtered through ASEAN and Hong Kong markets. Other markets are less clearly hubs for connections with the rest of the world; however, this has changed over the last phases as Asian markets have become more completely connected to other regions of world markets.

<sup>13</sup> The Latin American sample includes Argentina, Brazil, Chile and Mexico. See Table 1 for more detail on the regional groupings.



**Table 8**  
The total completeness of the Asia-Pacific network plus the US and the UK.

Horizon	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
1	<b>0.3939</b>	<b>0.6465</b>	<b>0.5675</b>	<b>0.6973</b>	<b>0.8175</b>	<b>0.7737</b>
5	<b>0.5043</b>	<b>0.7576</b>	<b>0.6592</b>	<b>0.7654</b>	<b>0.8801</b>	0.8233
6	<b>0.5055</b>	<b>0.7585</b>	0.6594	0.7655	<b>0.8802</b>	0.8233
10	0.5062	0.7593	0.6594	0.7655	0.8804	0.8233
12	0.5062	0.7593	0.6594	0.7655	0.8804	0.8233
15	0.5062	0.7593	0.6594	0.7655	0.8804	0.8233

Note: The completeness estimates for the different forecast horizons  $H$  (in days) in the different phases. Bold values represent estimates that change as you increase the forecast horizon.

### 5.5. Robustness checks

Our empirical results from the previous sections are related to different parameters that include VAR lag length and a forecast horizon  $H$ . The lag length,  $k$ , is chosen to be 2 based on the Akaike information criterion (AIC). Consequently all network characteristics are obtained from VAR(2).

To inspect how sensitive our empirical results to different forecast horizons  $H$  we estimate the connectedness of the Asia-Pacific network plus the USA and the UK. We present the results for the whole sample period and for the different forecast horizons. Table 8 reports the estimates of total connectedness in the different horizons. The results show that 10-day horizon is suitable as completeness for  $H = 12$  and  $H = 15$  does not change much.

Table 9 reports the estimate of the completeness matrix for the whole sample in different horizons. We again consider the Asian region with the inclusion of both the USA and the UK markets. We consider different forecast horizons;  $H = 4$  days,  $H = 6$  days and  $H = 12$  days. From the results, we observe that the forecast horizon has little influence on the estimation of the completeness matrix.

The connectedness figures for the sub-sample periods are the same as those in Fig. 3. Based on the connection matrix of the whole sample in Table 9, we observe the continuous dominance of the USA in spreading shocks to the rest. The results also show that Pakistan and Sri Lanka don't spread shocks to the other markets but rather receive. Hong Kong receives and spreads more strong links to the rest of the world comparing to the Asia-Pacific countries. It is quite clear that the connectedness matrices are not so different for  $H = 6$  and  $H = 12$ . This implies that our results are robust to the choice of forecast horizon  $H$ .

## 6. Policy implications

Based on the results, additional analysis of the evolution of network connections for each individual country, and the observations from Raddant and Kenett (2016), we look at policy options at both a regional and country level.

### 6.1. Regional level

- i. *Supporting regional development*: A clear feature which differentiates our analysis from others is the far greater scale of Asian markets included. Although other studies find that Asian markets are relatively isolated in their networks, we find evidence of distinct regional groupings, particularly around the ASEAN markets and the bridge market of Hong Kong. Our narrative of the more peripheral markets supports the idea that in the early stages of the network many of these markets first connected to the rest of the world through the bridge of the regional cooperation organizations, such as ASEAN, which may have provided a filter for informing the rest of the world about the developments in these markets.

Bridge markets can provide a way in which second degree links are available to relatively unconnected nodes - for example, in Phase 1, Sri Lanka and Thailand connect to the US and Germany through Hong Kong. Support is provided by overcoming information asymmetries between the international markets and the domestic market. Over time, a number of markets have followed this pattern and gone on to form their own significant direct links with the rest of the world markets and are no longer primarily connecting through ASEAN, such as Indonesia and Taiwan. This points to a potentially important role for cooperation in regions to support developing markets, helping lift the participation of millions of citizens into access to international finance and thus growth opportunities.

- ii. *Regional level protection*: Regional fostering of this nature also has advantages in providing a level of protection for these markets during periods of crisis. If there is a bridge market that is critical in connecting a region to international markets, then it is much easier to sever that one link or a limited number of links and protect a large part of the regional system than if all components are individually linked. Most likely this relates to the stage of development of the market, because as markets reach a greater stage of maturity and form more direct relationships with the rest of the global markets, they will increasingly need to have more sophisticated regulatory oversight and tools.
- iii. *Concentration of market power*: A disadvantage of encouraging a regional approach to development may be the concentration of market power in the bridge market. Although this is a possibility, as there are clear advantages to the bridge market in mediating between asymmetric information situations (where the rest of the world is less informed about the developing market) as markets develop, this should be naturally eroded by the incentives to develop direct relationships to avoid these costs.

### 6.2. Individual country level

Individual countries face several options in accessing international financial markets to foster growth, while still being wary of protecting themselves during periods of stress.

- i. *Align with a regional bridge node (or nodes)*. Recommended for markets in early stages of development, this strategy allows a market to connect with the international financial markets supported by a known node which can mediate the information asymmetry between the developing node and the international market. The advantage of this approach for the developing market is that it reduces the initial costs of overcoming the information asymmetry - only one node needs to be educated about the developing node to access their connections to the rest of the world. One such strategy could be to attach to a super-spreader node. Choosing the node with which to establish such a relationship is not trivial. In the data, a couple of strategies are evident. One is to form regional groupings to act as bridges, such as ASEAN markets. This clearly has advantages in terms of regional cooperation and potentially better understanding and alignment of the information asymmetries; and could be seen as typified by the actions of markets such as the Republic of Korea in the dataset.
- ii. *Form a bridge with a dominant super-spreader market directly*. This type of relationship is typified by the two fastest-growing large economies, India and China. India developed relationships with the international network initially through its relationships with the UK (reflecting historical associations). China has tended to foster its connections outside the Asian region as a matter of priority prior to building the relationships with the Asian nodes. An observation from the data is that this seems to be a relatively slower way in which to integrate with the world network directly - although slower integration may itself also be a policy choice.

**Table 9**  
Robustness of completeness matrix for the whole sample period based on different forecast horizons H.

From		UK	US	AUS	PRS	IND	INO	JPN	HKG	MAL	NZL	PAK	PHI	SIN	KOR	SRI	THA	TAP	
<b>H = 4 days</b>																			
UK	0	0.20961	0	0	0	0	0.01736	0.02625	0	0	0	0	0	0	0	0	0	0	0
US	0	0	0.16974	0	0	0	0.00667	0.04388	0.06158	0	0	0	0	0	0.01785	0	0	0	0
AUS	0.1224	0	0	0.02763	0	0	0	0	0	0.00941	0	0	0	0	0	0	0	0.02142	0.02654
PRS	0.0099	0.00829	0.01271	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IND	0	0.04136	0.03246	0	0	0	0.02125	0.02032	0.06178	0	0	0	0	0	0.03139	0	0	0	0
INO	0	0.04289	0.03254	0	0	0	0.0374	0	0.06071	0	0	0	0	0	0.0274	0	0	0.06302	0.02426
JPN	0.09242	0.12276	0.0554	0	0	0	0.04473	0	0	0	0	0	0	0.0547	0	0	0	0	0
HKG	0.06886	0.08566	0.05712	0.01935	0	0	0.04634	0.04581	0	0	0	0	0	0.11725	0.04083	0	0.04721	0.03422	0
MAL	0	0.04238	0	0.00213	0	0	0.05375	0.01559	0	0.00941	0	0	0	0	0	0	0.05142	0	0
NZL	0.05868	0.10573	0	0	0	0	0.02016	0.01113	0.00811	0	0.00169	0	0.01587	0	0	0	0	0	0
PAK	0	0.00952	0	0	0	0	0	0	0	0.02598	0	0	0	0	0	0	0.00646	0	0
PHI	0.06133	0.07767	0	0	0	0	0.05787	0.015	0	0	0	0	0	0.06157	0.02194	0	0.04982	0	0.03755
SIN	0	0.06685	0.05157	0.00669	0	0	0.05848	0.03707	0.11975	0	0	0	0	0	0	0	0	0	0
KOR	0.05556	0.06695	0.03848	0	0	0	0	0.04422	0.05905	0.01838	0.00897	0	0	0	0	0	0.04095	0	0
SRI	0	0.00887	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
THA	0	0.04047	0	0.00538	0	0	0.06087	0.01994	0.06886	0	0	0	0	0	0.0405	0	0	0	0
TAP	0.04285	0.06942	0.03913	0	0.02729	0	0.02714	0	0	0.01919	0	0	0	0.06345	0	0	0	0	0
<b>H = 6 days</b>																			
UK	0	0.20966	0	0	0	0	0.01741	0.02631	0	0	0	0	0	0	0	0	0	0	0
US	0	0	0.16985	0	0	0	0.0067	0.04389	0.06156	0	0	0	0	0	0.01785	0	0	0	0
AUS	0.1225	0	0	0.02769	0	0	0	0	0	0.00941	0	0	0	0	0	0	0	0.0214	0.02658
PRS	0.00998	0.00843	0.01271	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IND	0	0.04139	0.03245	0	0	0	0.02126	0.02037	0.06177	0	0	0	0	0	0.03138	0	0	0	0
INO	0	0.04302	0.03252	0	0	0	0.03738	0	0.06067	0	0	0	0	0	0.02741	0	0	0.06302	0.02426
JPN	0.09245	0.12274	0.05543	0	0	0	0.02479	0	0	0	0	0	0	0.05467	0.0409	0	0.04725	0.0343	0
HKG	0.06885	0.08568	0.05715	0.01936	0	0	0.04651	0.04577	0	0	0	0	0	0.11714	0.0409	0	0.0514	0	0
MAL	0	0.04285	0	0.00215	0	0	0.0537	0.01564	0	0.00941	0	0	0.01586	0	0	0	0	0	0
NZL	0.05878	0.10591	0	0	0	0	0.02017	0.01131	0.00817	0	0.00171	0	0	0	0	0	0.00651	0	0
PAK	0	0.00976	0	0	0	0	0	0	0	0.02599	0	0	0	0.06154	0.02199	0	0.04997	0	0.0376
PHI	0.06131	0.07762	0	0	0	0	0.05809	0.015	0	0	0	0	0	0	0	0	0	0	0
SIN	0	0.06683	0.05156	0.00671	0	0	0.05853	0.03707	0.11974	0	0	0	0	0	0	0	0.04104	0	0
KOR	0.0556	0.06692	0.03852	0	0	0	0.04419	0.04419	0.05909	0.01839	0.00896	0	0	0	0	0	0	0	0
SRI	0	0.00932	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
THA	0	0.04079	0	0.00539	0	0	0.06084	0.01993	0.06881	0	0	0	0	0.06342	0.04051	0	0	0	0
TAP	0.04295	0.06939	0.03911	0	0.02737	0	0.02726	0	0	0.01918	0	0	0	0	0	0	0	0	0
<b>H = 12 days</b>																			
UK	0	0.20965	0	0	0	0	0.01742	0.02631	0	0	0	0	0	0	0	0	0	0	0
US	0	0	0.16985	0	0	0	0.0067	0.04389	0.06155	0	0	0	0	0	0.01785	0	0	0.0214	0.02658
AUS	0.1225	0	0	0.0277	0	0	0	0	0	0.00941	0	0	0	0	0	0	0	0	0
PRS	0.00998	0.00843	0.01271	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IND	0	0.04138	0.03245	0	0	0	0.02126	0.02037	0.06177	0	0	0	0	0	0.03138	0	0	0.06302	0.02426
INO	0	0.04302	0.03252	0	0	0	0.03738	0	0.06067	0	0	0	0	0	0.02741	0	0	0	0
JPN	0.09245	0.12274	0.05543	0	0	0	0.04651	0.04576	0	0	0	0	0	0.05467	0.04089	0	0.04725	0.0343	0
HKG	0.06886	0.08569	0.05715	0.01936	0	0	0.04651	0.04576	0	0.00941	0	0	0	0.11714	0.04089	0	0.05141	0	0
MAL	0	0.04285	0	0.00215	0	0	0.05371	0.01564	0	0	0	0	0.01587	0	0	0	0	0	0
NZL	0.05878	0.10592	0	0	0	0	0.02017	0.01131	0.0082	0.00941	0.00171	0	0	0	0	0	0.00652	0	0
PAK	0	0.00982	0	0	0	0	0	0	0.0082	0	0.00171	0	0	0	0	0	0	0	0
PHI	0.06131	0.07763	0	0	0	0	0.05809	0.015	0	0.02599	0	0	0	0.06154	0.02199	0	0.04996	0	0
SIN	0	0.06683	0.05156	0.00671	0	0	0.05853	0.03707	0.11973	0	0	0	0	0	0	0	0	0	0

(continued on next page)

Table 9 (continued)

From																	
To	UK	US	AUS	PRS	IND	INO	JPN	HKG	MAL	NZL	PAK	PHI	SIN	KOR	SRI	THA	TAP
KOR	0.0556	0.06693	0.03852	0	0	0	0.04419	0.05908	0.01839	0.00896	0	0	0	0	0	0.04104	0
SRI	0	0.00933	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
THA	0	0.0408	0	0.00539	0	0.06085	0.01993	0.06881	0	0	0	0	0	0.04052	0	0	0
TAP	0.04295	0.06939	0.03911	0	0.02738	0.02726	0	0	0.01918	0	0	0	0.06342	0	0	0	0

Note: The completeness matrix for the different forecast horizons  $H$  (in days) for the whole sample. Estimates using  $H = 4$  show high variability as compared to using more horizons. The bold values show estimate that change (by more than  $10^{-5}$ ) moving from  $H = 6$  to  $H = 12$ . The estimates do not change for  $H = 12$  or greater.

- iii. *Playing the role of a bridge*: A market may have the opportunity to play the role of a bridge between developing nodes and the rest of the global network. This has advantages in that there are premia to be made from exploiting the information asymmetry between the global markets and the more isolated node. It will contribute to the global importance of the bridge market in the network, presumably increasing turnover and influence. The disadvantage seems to be that if the node itself is involved in a crisis, a consequent loss of trust may be very damaging to the future formation of such relationships. A key illustration of this seems to be in the reduction in connectedness of the Hong Kong market as a bridge after the Hong Kong crisis in 1998.
  - iv. *Avoid becoming a bridge*: Some markets may also choose not to engage in the risk of acting as a bridge node, but to wait until other market nodes are more fully engaged with the entirety of the network before establishing links. This seems to be the nature of the relationship between Japan and the other Asian markets. Such an approach protects a node from the possibility that it may become a conduit for the transmission of crises originating in emerging markets to the rest of the world, and subsequently inflict loss on its local economic agents.
  - v. *Isolating markets*: An advantage of aligning with a bridge node is that during periods of stress it is simpler to cut off these bridge relationships to protect the domestic market. The greater the degree of relationships between a market and other world markets the more difficult it is to isolate during periods of stress. There are costs and benefits from being able to isolate the market node. A case in point is the Malaysian experience, where, pre-Asian financial crisis, the degree of connectedness for Malaysia was relatively high for an Asian market at that time. However, the actions to protect Malaysia during the Asian crisis seemed to result in considerable contraction in its connectedness with the rest of the world markets for several more phases (particularly until these restrictions were lifted and relationships re-established). It may be damaging to ongoing relationships to disconnect during periods of stress - although it is hard to quantify the relative costs and benefits of these actions.
- Informing these choices, we observe the following characteristics of the behavior of markets within the network during periods of crisis, both originating elsewhere and in their home environment. The perceived probability of undergoing either a homegrown policy or political crisis are critical inputs in how a market chooses to engage with the rest of the network, and what choices are offered by the existing nodes on how it may engage (that is, which markets may be willing or not willing to engage as bridge markets for a developing node).
- vi. *Growing despite crisis*: If a node is not itself directly involved in a crisis, a market may simply continue to grow its network steadily, despite chaos surrounding it. In this way, being off to the side of the network can result in being protected, and in fact may allow a market to benefit from others' difficulties in establishing direct linkages, as in Taiwan and Republic of Korea during the global financial crisis.
  - vii. *Weathering a home-grown crisis*: Just as crises come in many forms, the outcomes following the responses to crises seem to come in different forms for the nodes involved. For example, in the case of Thailand, which was relatively well-connected for an Asian market pre-Asian financial crisis, the subsequent period was characterized by a contraction in its network relationships, which took time to rebuild. On the other hand, the Republic of Korea—which arguably was not an instigator of the crisis in 1998 but was a victim of the various forms of contagion which affected it at the time—was forced into significant market liberalization by the terms of the International Monetary Fund programs it was involved in and has continuously grown its integration into world markets ever since. This is clearly not a predetermined path, however, as Indonesia had a very different experience (probably mitigated by point vi).



viii. *The role of domestic political stress:* Part of the reason for information asymmetry and uncertainty can revolve around political or civil stress in an economy. This is evident for Sri Lanka and Thailand. The timing of political unrest coincides with a reduced rate of formation of relationships between these nodes and the rest of the markets. Forming international financial connections may not be a resource priority during these periods, while the investment risk may also simply be too high for international investors.

The overall aim of economic policy making bodies is to increase the welfare of citizens. While we generally assume that greater integration into international financial markets will help to achieve this, it does expose the domestic economy to financial crises originating elsewhere. The choice to seek either a relationship with a bridge node, or indeed to become a bridge node, is one that can be mutually beneficial, but the data suggests it is not clearly so. Some markets have chosen this route while others have chosen only to connect only after sufficient development of either their own markets or other nodes, thereby initially avoiding regional bridges. The variables which influence this choice seem likely to be related to: risk aversion of the individual markets, stage of development, current rate of economic growth, appetite for capital, economic size and perhaps political uncertainty. Casual analysis suggests that (relatively) small emerging markets with lower than potential rates of growth and unmet capital needs will benefit from forming an alliance with a regional bridge as a conduit to greater capital integration. Those which choose to take on the role of bridge markets benefit from the opportunity for increased growth and exploitation of the information asymmetry. Economic geography implies that for many that the ability to exploit information asymmetry is likely to lie within regions. And the formation of bridge nodes through a group of markets, such as ASEAN markets, seems a reasonable means of groups of nodes sharing the risk of crises originating from the developing markets. A formal theoretical model of these relationships, and the determining factors for the emergence of the alternative paths evident in the data is scope for ongoing work.

## 7. Conclusion

The evolution of the financial network between the 42 countries examined here clearly indicates the growing internationalization and interconnectedness of Asian markets. We highlight instances where this has occurred through the interaction of markets with local or regional core or gatekeeper nodes, particularly Hong Kong, Singapore, and the ASEAN economies. Over time the linkages between Asian markets and other major regions have become increasingly direct. We hypothesize that the support (or existence) of geographically localized hubs or centers help establish the role of an emerging market within the global markets. On the other hand, there is also evidence of large markets, such as India, emerging to become more interconnected with global markets without significant use of a geographically based hub - in the Indian case this may be a consequence of strong historical links to British institutional structures.

The contribution of the gateway or core markets within a region to the development of emerging markets is a strong argument against plans to reduce complexity and increase the randomness of financial networks. Doing so may have detrimental effects on the development and deepening of emerging markets, which appear to “grow” into maturity by establishing their own direct links with non-regional markets through the legitimacy of first connecting via regional hubs. This is critical for regions with significant untapped financial deepening and may limit opportunities for emerging markets. A core of markets to support regional financial development may be aided by the formal economic cooperation of strategic players. For example, the results show that while Singapore and Hong Kong played important roles as gatekeepers for many Asian markets, when the ASEAN economies are aggregated, their developing role in the world financial markets, and as a gatekeeper group of markets, is clear.

Considering the role of core groups in a region in assisting the development of emerging members is a strong policy recommendation when developing interventions to protect (or even form) regional cores, and for policy actions to inoculate those cores during crisis periods, thus protecting a substantial part of the network. Akin to arguments surrounding the vulnerability of economies undergoing a transition from fixed to floating exchange rate regimes to currency crises, the period of developing financial market deepening in other financial assets may also be accompanied by vulnerabilities that require extra vigilance on the part not only of the individual economies involved, but also on the regional and international financial community. We have shown that examining net links, and changes in net links, omits valuable information about the sustainability of individual links and the changing importance of individual nodes. A few critical nodes (in our data, Argentina and Ireland) play the unusual role of switching between super-spreader during periods of stress and a super-absorber during periods of calm. Markets with these properties deserve to be watched carefully, with inoculation plans in place for adapting to changing circumstances (for example, restrictions on flows to and from those markets).

There are also markets which seem to be reliably either super-spreaders (the US) or super-absorbers. Super-absorbers are valuable allies in the bid to reduce the transmission of shocks between markets. These markets are also those that perhaps deserve particular attention, because if they were to break down, the system might become disproportionately less stable as shocks propagate through the more expansive routes (this is a form of the robust-but-fragile nature of the network). All this points to the complexity of the financial networks in place, and indeed their evolution. However, it does not necessarily support means to reduce this complexity. Instead, the complexity reveals a rich tapestry of relationships that underpin the development of financial markets and the distribution of shocks. We propose that the first step is to understand this complexity.

The disadvantages of reducing complexity (that is, trying to enact policies that force a more random structure on the network) include that this may restrict or reduce the potential for emerging markets to develop in the shortest possible time frame. The role of a regional hub in developing financial markets appears to be important. The results in this paper support the development of policies aimed at inoculation of important nodes. Indeed, there is a significant danger that constraining the form of one network through regulation may simply lead to the unwanted transmissions through another network that connects economies. For example, increased capital requirements on banks tie banking networks and sovereign bond networks more closely together and increased equity requirements have the potential to do the same for banking networks and equity markets. This also raises the somewhat more difficult proposition of policy coordination across different arms of the policy making community, to ensure the coordination of financial regulation with monetary and fiscal policy making.

The financial links between economies are certainly more complex than those established simply through equity markets. The challenge to researchers and policy makers is to develop analytically tractable tools that reveal the complexity of the multiple layers of financial interconnectedness between economies through different asset markets and potentially different players. Sovereign bond networks will differ from equity market networks (see [Dungey et al. \(2018\)](#)). Real economy networks such as trade networks, or input-output production networks as in [Pesaran and Yang \(2016\)](#), will be tied to financial networks, but the weights on the nodes are likely to be quite different, and may involve nodes which are not included in all layers. In the future understanding the roles of nodes in different layers of the network may help to understand how effective policy interventions may be targeted at nodes that play critical roles in transmitting between layers to contain crisis events (or even to spread crisis events in a way that reduces their impact on individual layers and/or nodes). A recent step in this direction can be found in the multi-country, multi-market network analysis of [Magkonis and Tsopanakis \(2018\)](#).

## Appendix A

### A.1. Changing involvement of nodes over time

As shown in Table A.1, not only does the net number of linkages between nodes change between subperiods, but this also masks changes in the existence of specific linkages. Table A.1 provides descriptive statistics of the form of the network in each phase. The first statistics are the degree of the network-in-degree is the number of links which directionally point towards each node, out-degree is the number of links pointing away from each node.

The average in-degree and out-degree for the network over the entire sample period is given in the first panel of Table A.1 and shows that the means are identical. However, the median in-degree for the network exceeds the median out-degree and has a much lower standard deviation - the range of the out-degree for each node is far higher. While for the entire sample every node has an in-degree of at least 5, meaning that each node receives transmissions from at least 5 other nodes, directly, the maximum in-degree is 18. In contrast, not all nodes transmit shocks (a minimum out-degree of zero).

To consider the changing nature of the in-degree and out-degree, Fig. A1 provides a bar chart of the numbers of nodes with out and in-degree respectively, by 5-degree intervals for each phase. The light blue section of each column of Fig. A1 is the number of nodes recording 5 or fewer edges (including zero) in that phase, with subsequent categories rising in increments of 5. It is immediately apparent that in-degree by phase has lower numbers of nodes with fewer connections than out-degree by phase. This is marked during the crisis Phases 2 and 5, which have the fewest nodes registering low in-degree or out-degree. This means that the nodes which are connected during the periods of stress have links to more other nodes than those connected during periods of less stress. The in-degree for any node involved in the system is never above 15, indicating that each node receives shocks from sources which are specific, and perhaps identifiable, paths. However, the out-degree for each phase is more diverse. Table A.1 shows that the maximum out-degree generally rises over the sample, but the figures reveal the extent to which the distribution of higher connected nodes increases in times of stress. In Phases 2 and 5 there are discernibly more nodes involved with a higher out-degree. That is, they are involved in transmitting shocks to (more) other nodes. However, this does not necessarily mean that they are source nodes for the shocks.

Table A.1  
Summary statistics of various network measures (all countries).

	Mean	Med	Std. dev	Min	Max
All phases (01.03.1995–30.12.2016)					
In-degree	11.52	11.00	3.27	5.00	18.00
Out-degree	11.52	8.00	9.18	0.00	37.00
Betweenness centrality	21.00	12.84	21.18	1.32	90.41
Eigenvector centrality	0.02	0.02	0.01	0.01	0.04
Phase 1 (01.03.1995–01.07.1997)					
In-degree	5.00	5.00	2.55	0.00	10.00
Out-degree	5.00	4.00	3.85	1.00	22.00
Betweenness centrality	36.71	22.88	43.35	3.78	227.12
Eigenvector centrality	0.02	0.02	0.01	0.01	0.06
Phase 2 (02.07.1997–31.12.1998)					
In-degree	7.26	7.00	3.19	0.00	14.00
Out-degree	7.26	6.00	5.52	0.00	22.00
Betweenness centrality	28.48	19.59	27.28	1.90	105.77
Eigenvector centrality	0.02	0.02	0.01	0.01	0.04
Phase 3 (01.01.1999–31.12.2002)					
In-degree	5.10	5.00	2.18	1.00	10.00
Out-degree	5.10	4.00	5.28	0.00	28.00
Betweenness centrality	36.19	17.42	53.48	0.00	307.61
Eigenvector centrality	0.02	0.02	0.01	0.00	0.06
Phase 4 (01.01.2003–14.09.2008)					
In-degree	5.64	6.00	2.43	0.00	12.00
Out-degree	5.64	4.00	5.91	0.00	31.00
Betweenness centrality	33.43	21.29	43.67	0.00	263.65
Eigenvector centrality	0.02	0.02	0.01	0.01	0.06
Phase 5 (15.09.2008–31.03.2010)					
In-degree	9.26	9.00	2.96	1.00	15.00
Out-degree	9.26	5.50	9.49	0.00	35.00
Betweenness centrality	24.71	10.56	38.47	0.52	196.03
Eigenvector centrality	0.02	0.02	0.01	0.00	0.05
Phase 6 (01.04.2010–30.12.2016)					
In-degree	7.29	7.00	2.99	0.00	13.00
Out-degree	7.29	5.00	7.40	0.00	34.00
Betweenness centrality	28.14	14.52	43.21	0.00	211.56
Eigenvector centrality	0.02	0.02	0.01	0.01	0.05

Note: We use the network measures of in-degree, out-degree, betweenness centrality, and eigenvector centrality to capture the centrality of a country's position in the global financial network and its closeness to all other countries in these networks.

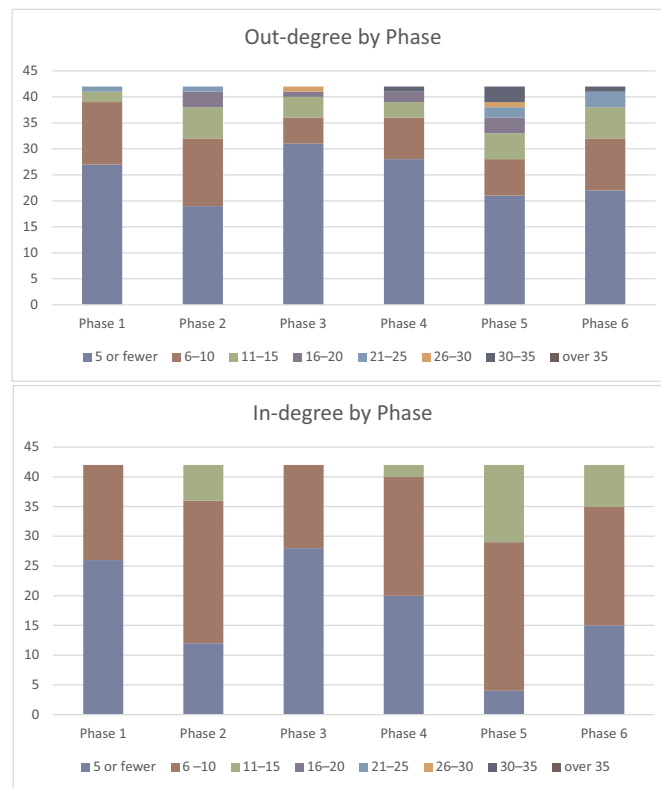


Fig. A1. Figures for in-degree and out-degree by phases.  
 Note: See Table 2 for the phases and their corresponding time periods.

Table A.2  
 Network statistics for the whole sample.

Vertex/country	In-degree	Out-degree	Betweenness centrality	Eigenvector centrality
Argentina	7	4	6.5658	0.0113
Australia	18	13	24.3210	0.0309
Austria	14	13	32.6658	0.0261
Belgium	11	7	9.6903	0.0189
Brazil	11	19	36.7235	0.0318
Canada	11	24	52.5183	0.0360
Chile	12	6	9.7601	0.0211
China	6	16	12.7719	0.0204
Czech Republic	15	10	20.6217	0.0252
Denmark	9	6	4.4163	0.0197
Egypt	9	7	6.6775	0.0174
Finland	12	7	8.1179	0.0217
France	10	19	53.7337	0.0275
Germany	11	9	8.4845	0.0213
Greece	7	18	21.7494	0.0239
Hong Kong	17	8	18.1500	0.0259
Hungary	12	9	15.3452	0.0235
India	11	6	9.2375	0.0195
Indonesia	15	28	56.8902	0.0381
Ireland	10	29	58.3729	0.0352
Italy	9	9	11.1405	0.0217
Japan	13	29	50.0405	0.0344
Malaysia	15	6	14.3542	0.0235
Mexico	5	37	76.6419	0.0406
Netherlands	10	7	1.3214	0.0158
New Zealand	9	6	9.0325	0.0185
Pakistan	6	5	4.4446	0.0108
Philippines	10	2	1.8190	0.0163
Poland	15	4	8.2548	0.0228
Portugal	13	1	2.4349	0.0176
Singapore	13	8	12.9077	0.0222
South Africa	14	7	17.6159	0.0235
Republic of Korea	18	9	15.7321	0.0271
Spain	13	7	11.3760	0.0221
Sri Lanka	6	0	1.8586	0.0068

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Table A.2 (continued)

Vertex/country	In-degree	Out-degree	Betweenness centrality	Eigenvector centrality
Sweden	9	4	2.8124	0.0177
Switzerland	14	5	10.1012	0.0210
Taiwan	13	13	19.8328	0.0260
Thailand	16	12	25.2410	0.0279
Turkey	11	7	10.1564	0.0208
United Kingdom	14	11	17.6546	0.0281
United States	10	37	90.4137	0.0398

Shocks may transmit between nodes through other nodes. A measure of the extent of this effect is the “betweenness” centrality, which effectively assesses the substitutability of a node. This measures the number of times a given node acts as part of the shortest path between two other nodes. It helps to determine how important a node may be in transmitting information through a network. A node with a normalized betweenness centrality measure of one is involved in the shortest path between all nodes in the network, and hence its removal could be of substantial importance for the network. (This node does not obviously need to be the biggest in the network or the source of a shock. Bear-Stearns forms a good example of this type of risk during the global financial crisis.) A market with a betweenness measure of zero is unimportant in retaining the network.

Table A.1 shows that the average betweenness centrality of the network rises dramatically in Phase 3 of the sample but, in Phase 5, it drops from the previous pre-crisis sample period. Betweenness clearly differs across the phases, pointing to the different structures of core nodes during the different periods, as will be discussed below.

Eigenvector centrality is also an indicator of proximity between nodes. The eigenvector centrality of each market is determined by the eigenvector centralities of the markets to which it is connected. That is, eigenvector centrality of country  $i$ ,  $ev_i$ , is given by,  $ev_i = \frac{1}{\lambda} \sum_j A_{ij} ev_j$ , where  $\lambda$  is a constant that provides a nontrivial solution and  $A_{ij}$  is an adjacency matrix; see Bonacich (1972) and Chuluun (2017). In this way eigenvalue centrality is a measure of connectedness in the entire market network. Although it has a similar form to the PageRank algorithm used in assessing systemic risk in Dungey, Luciani, and Veredas (2013) and van de Leur, Lucas, and Seeger (2017), because eigenvalue centrality is based on eigenvalues which do not vary much between phases, the eigenvalue centrality measure does not move between the phases. This points to the importance of understanding the measures which are being used; the relatively unchanging eigenvalues is consistent with Pesaran and Yang (2016) who find that the wholesale trade sector is the dominant economic sector over multiple samples in a real economy network. (Unlike in their form, there is no individual node with an eigenvalue of  $> 0.5$  in our sample that can be considered statistically dominant.) There is little information content in the eigenvalue centrality measure for assessing the changing nature of a network of nodes in financial markets over time. Table A.2 provides the betweenness centrality, closeness centrality and eigenvalue centrality figures for each individual node assessed over the entire sample. It is evident that there is no great variation in the closeness and eigenvalue centrality measures across different countries. In contrast Wang et al. (2018) derive a variety of centrality and closeness measures for 57 international equity markets and observe patterns consistent with crisis periods, although the range of their statistics does not vary greatly over time.

Thus far we have established that: (i) the number of connections between nodes changes between phases, (ii) that some edges are removed from the system while (iii) some edges are formed each time, (iv) that the connectedness of nodes as measured by in-degree and out-degree changes in what appears to be a discernible way, increasing during periods of stress, (v) the nodes which are more or less involved in the network during various phases may change, and that (vi) measures of centrality do not provide definitive information about changing financial networks during periods of stress. This information is gleaned from the summary measures of the network for each phase.

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