



Contagion or interdependence? Comparing spillover indices

Raisul Islam¹ · Vladimir Volkov¹

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Abstract

We propose a novel risk measure that is built on comparing high-frequency time-varying volatility and low-frequency return spillover estimates. This measure permits to identify the markets that are epidemic in their complex interdependence. We conjecture that initially a highly volatile market experiences episodes of risk transmission, but only later absorbs risk and becomes an epidemic market. Moreover, we can detect newly emerging ‘contagion’ in the system. We examine the behaviour of 30 global equity markets and compare spillover measures, which encapsulate many large and small crises episodes. Instead of relying on ex post crisis information, our model identifies crises periods. An important implication of the proposed approach is that highly interrelated markets, such as China, are less likely to transmit a global economic crisis under the current interdependence setting.

Keywords Systemic risk · Signed spillover · Contagion · Interdependence

JEL Classification C3 · C32 · C45 · C53 · D85 · G10

1 Introduction

The multiple crises of the last two decades provide an ideal testing ground to identify systemic risks facing global equity markets. Understanding systemic risks using empirical tests on contagion, spillovers and financial networks has been a long standing research question. While the literature stretches back as early as King et al. (1994) on spillovers and Allen and Gale (1998) on contagion, the empirical literature on

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✉ Raisul Islam
raisul.islam@utas.edu.au

¹ Tasmanian School of Business and Economics, University of Tasmania, Hobart, Australia

networks and financial spillovers is more recent. Allen and Gale (2000) and Gai and Kapadia (2010) evaluated network effects within the financial sector, while Acemoglu et al. (2015) showed how real economy shocks can become the source of crises that spread dramatically via financial interconnectedness as ‘fragility’, affecting otherwise ‘robust’ networks. Empirical representations show how the networks themselves change over time, between calm and crisis periods, and with the development and growth of emerging financial markets (Billio et al. 2012; Khandani et al. 2013; Demirer et al. 2018a). The changing nature of the links between those institutions can be considered a measure of contagion (Dungey and Gajurel 2015), while the links between spillovers and networks are highlighted in Diebold and Yilmaz (2014) via forecast error variance decompositions providing a single index of system’s vulnerability. This paper overcomes the limitations of the DY vulnerability index by highlighting vulnerability via newly proposed identification approaches using the signed return spillover index (Dungey et al. 2017b) complemented with a novel signed volatility spillover index.

We investigate risk transmissions in the global equity market using the Diebold and Yilmaz (DY) connectedness index,¹ the multivariate historical decomposition (MHD) index (Dungey et al. 2017b) and we propose a novel signed volatility decomposition (SVD) that helps extracting ‘contagion’ by identifying ‘excess volatility’ spillover matrices.

This paper makes several contributions into the literature. First, we propose a risk matrix that identifies sources of ‘contagion’. Then, we provide a rationale regarding the recent surge in speculation around crisis sources, and explore whether there is enough evidence aligning with these postulations. We examine if China is a potential source of crisis as suggested in Engle (2018), Akhtaruzzaman et al. (2021).² We produce evidence that it is unlikely that China is a source of financial contagion. Finally, we address some key questions that have long puzzled researchers. Can we identify excessively contagious markets out of sample taking into consideration their degree and dynamics of systemic connections? How different are contagion patterns in more recent times compared to earlier periods? Can we disentangle large contagion waves driving global economies towards a potential crisis? Identifying potential sources of ‘contagion’ and patterns underpinning contagious markets will allow regulators to take timely action attenuating the exposure of domestic markets to a large-scale crisis.

We also investigate changing dynamics in the risk transmission and in the resilience matrices, especially during the global economic slowdown as a direct result of Covid-19 pandemic.

¹ Yilmaz et al. (2018), Demirer et al. (2018a, b), Yilmaz (2017), Diebold et al. (2017), Diebold and Yilmaz (2015) and Diebold and Yilmaz (2014).

² In Akhtaruzzaman et al. (2021), the authors produce evidence of China transmitting contagion to South Asia compared to the USA, considering trade intensity, economic downturns, and negative net equity capital outflows influencing dynamic conditional correlations (DCC) between US/Chinese and South Asian financial stock returns. However, Syriopoulos et al. (2015) disputes efficacy of DCC models quoting that, ‘despite the attractive properties of the DCC model, empirical estimation and interpretation can be seriously constrained by complexities due to excessive parameter requirements, biased estimates and convergence limitations over the estimation process, especially whenever additional exogenous variables are introduced into the conditional mean and variance specifications’.

A primary objective of this paper is to show that signed risk measures are better suited to model crises than popular DY risk measures. It examines market dynamics across all episodes of crisis and compares the derived signals with actual events juxtaposed against popular DY risk measures. Such comparison concentrates out the degree of misidentification if crisis modelling is reliant on a single framework, and more than one framework may not only complement each other's findings but also reduce the gaps in the outcome. Hence, this objective addresses that running multiple important risk analysis frameworks simultaneously may have important implications in understanding both the degree and direction of crisis and in better modelling of crisis episodes. This is even more interesting as the global economies have significantly slowed down facing the Covid-19 pandemic. It warrants investigation if a Covid-19 pandemic and the economic downturn emerging in response have significant impact on systemic connections and how the popular DY model responses differently to the signed risk model.

A secondary objective of this paper is to detect excessively contagious markets in the past and newly emerging contagious markets using a single framework. A major gap in the extant literature is the effects of 'interdependence' are often enveloped within the potential effects coming from 'contagion' and as such are not well studied. This gives rise to a bias resulting from heteroscedasticity and often leading to failure in adopting a proper policy response to an imminent crisis. Interdependence bears less negative connotation compared to contagion, and the voluminous literature simply fails to incorporate major perspectives in crisis studies. This has resulted in an abundance of incomplete crisis examinations. Among the 124 papers reviewed in the taxonomy of Seth and Panda (2018), only 4 mention contagion, interdependence and integration.

Simultaneous increase in volatility facing a crisis is often wrongly attributed as resulting from contagion. It is because such amplifications in risks pertain to interdependence and overcast the effect of contagion for a particular market. An important significance of the current paper is that we propose a tractable novel approach that separates contagion effects out of effects due to interdependence, yet offers better crisis demarcation without prior knowledge on crisis.

More recently, Dungey and Renault (2018) relying on Forbes and Rigobon's (2002) findings showed how to distinguish contagion from interdependence. Dungey and Renault (2018) suggested that swings in the volatility of common factors may transpire from reasons pertaining to 'source' or 'target' markets and may induce simultaneous volatility jumps. The evolution of innovations in one entity that is immediately reflected in another when a crisis does not precede and as such may not pertain to contagion. However, a crisis period co-movement in volatility requires careful exploration, as volatility in the common factor of a 'target' itself may overcast the effects coming from the 'source'. In our work, we adopt a combined yet simpler approach considering the nexus between two issues and distinguishing markets with different levels of contagion.

In the current paper, we define 'contagion' as the difference between return spillover and realised volatility spillover. This allows us to identify if risks emanating from a market are purely due to a swing in the local volatility factor or if it is a response to a shock in the network. Moreover, 'contagion' identified in this approach allows us to separate out a long term 'contagion', and the dynamics for the 'more contagious' markets do not shift with every past, current and future crisis episode. Hence, allowing

us a ‘contagion’ identification that does not require re-estimation with every crisis periods.

A novelty in our method is that crisis demarcation is not a necessary condition for contagion identification, unlike earlier methods. We do not need to concur with Forbes and Rigobon (2002) in knowing the crisis and calm periods to separate contagion from interdependence. We support the work of Dungey and Renault (2018) while progressing the current tenet by identifying the more contagious markets from the less contagious or not contagious markets with a single approach. This is a key contribution to the current literature investigating the real time evolution of contagion and, by extension, the early warning literature.

Our results also allow us to focus on the potential risks of crisis and the emergence of China as an important conduit market as outlined in a number of studies.³

We identify the most crisis-prone markets and explain how the effect of innovations in these markets is different from the less crisis-prone markets. We examine the shock transmission dynamics in the global markets facing the Covid-19 pandemic.

Finally, five key arguments concerning the time-varying nature of systemic risk estimates leading to the detection of crisis transmission patterns are addressed. First, we examine whether policy interventions that restrict significant transmission paths help interconnected financial markets to deal with shocks. Second, we find that the changing interactions between markets result in changing patterns of shock spillovers. Third, we examine whether it is possible to detect which markets are more shock resistant in the sample period from 1998 to 2020. Fourth, we determine if a parametric signed identification approach can be used as an extension to the DY identification approach of return spillovers. Fifth, we examine if signed realised volatility identification approach can better identify ‘excess volatility’ in an interconnected system and help separating out excessively contagious markets.

The remainder of the paper proceeds as follows. Section 2 discusses a history of crisis episodes across the global equity market. Section 3 presents the empirical framework concerning GVD, static and dynamic networks, MHD and SVD. Section 4 outlines the dataset, consisting of 30 equity markets. This section also presents the filtering method and descriptive statistics on filtered data. Section 5 discusses the empirical results based on ‘system-wide connectedness’, before following on to the dynamic analysis and MHD measures explaining the effect of positive and negative shocks in the sample markets. We compare the results of MHD with SVD in this section. We discuss identifying ‘contagion’ and a subsection dedicated to ‘risk dynamics during Covid-19 pandemic’. Section 6 presents the conclusion to this paper.

2 Literature review

A key statement in the voluminous literature, which has generated several avenues of discussion regarding crisis control, is the heightening of integration resulting from modern globalisation, which is what causes contagion and systemic failures; see, for

³ Elliott (2017), Doff and Mullen (2017), Quijones (2017), Mauldin (2017), Friedman (2016) and Jolly and Bradsher (2015).

example, Atsalakis and Valavanis (2009), Bisiyas et al. (2012), Chinazzi and Fagiolo (2015), Benoit et al. (2017), Silva et al. (2017), Seth and Panda (2018).

It is important to understand that connectedness measures at large do not indicate risk transmission, but identifies the degree of systemic connections, in our case, across borders. Systemic risk transfer within borders may not lead to a full scale crisis, but risk transfer across borders, as Brunnermeier et al. (2016) suggested, may indicate a diabolic loop, or as highlighted in Farhi and Tirole (2017) a deadly doom loop creating a large scale crisis. While contagion measures may capture only the volatility spillovers as suggested in Masson (1998), Khan and Park (2009), Bekaert et al. (2013) that may emerge with large shocks spilling over onto the neighbours corresponding to an event, that is not likely be a systemic event (Dungey and Renault 2018). Hence, it is crucial to discuss the connection between systemic risk and financial contagion networks.

A second issue that has emerged from the extant literature is the imprecise identification of the constituents of a crisis (Romer and Romer 2015). What constitutes a crisis may range from asset price decline, bank run-on or, even institutional bankruptcies. In Silva et al.'s (2017) analysis of the systemic financial risk literature, a major issue found was the tendency to identify this phenomenon with banking crises (Silva et al. 2017). Further, Field (2003) found that this tendency was an underlying cause of many previously ineffective macroprudential responses, suggesting that macroprudential monitoring based on SIFI-centred risk identification only aggravated a systemic crisis. This concern is further reflected in the limited definition of systemic risk that the ECB (2009) produced as 'one perspective is to describe it as the risk of experiencing a strong systemic event. Such an event adversely affects a number of systematically important intermediaries or markets' (p.134). It is important to detect the connections SIFIs and capital markets' role in crisis generation.

We believe the issue of financial crisis require a balanced combination of arguments across streams of studies concerning financial crisis, financial contagion, systemic risk, equity and banking risk argument.

2.1 Contagion and systemic risk

Common shocks spilling out of origin and spanning across multiple sectors may build into a crisis. Systemic risks endowed within multiple sectors do not lead to cascade if there is no contagion and liquidity is well diversified. A pronounced rise in systemic risk may lead to credit risk transfer between sectors forming contagion. Contagion further exacerbates risk transmission as a conduit and a large-scale crisis may unearth. Systemic risk and contagion may go hand in hand in forming a crisis. A key issue in the current context is concentrating out the tipping point in shocks manifesting into crisis.

To understand this better, let us consider Allen and Carletti (2006) explaining risk transfer between banking and insurance sector that may or may not lead to crisis generation. Credit risk transfer between these two sectors is beneficial to welfare if there is uniform demand for liquidity, but is detrimental facing idiosyncratic risk. For crisis to manifest in terms of interdependence, the precept for both banking and insurance

sector is to manage long- and short-term assets across different contingencies, despite operating differently. Also, let us consider two contingencies, when both sectors have common demand for liquidity against when the sectors do not have common demand for liquidity. In autarky, the sectors having no interplay subjects the insurance sector to systemic risk, but banking sector less so. For the case of banks having common demand for liquidity facing no idiosyncratic risk, credit risk transfer is beneficial for welfare. For the case of banks having common demand for liquidity, but apart from facing idiosyncratic liquidity risks, credit risk transfer may not remain beneficial. In both the cases, a crisis is not manifest despite the sectors reaching crisis points. Contagion acts as conduit for systemic crises across insurance and banking sector and back to insurance sector leading to Pareto reduction in welfare. In the context of incomplete markets and plunging asset prices, contagion across many illiquid markets leads to a worsening spiral, involving many financial institutions. However, market exposure to each other depends more on the strength of their own institutional and economic fundamentals. ‘Spillover’ and ‘contagion’ are coined to address excessive co-movements of asset returns preceding a crisis due to unidentifiable sources of shocks.

There is a significant increase in the number of studies centred around contagion.⁴ However, only a fraction defines contagion and interdependence separately, and less so attempts to distinguish the terms empirically. This is partly due to a lack of tractable framework that does not require nesting of multiple methods. The hypothesis underpinning ‘Interdependence’ having a lesser negative connotation than ‘contagion’ or ‘systemic risk’, and as such are less conspicuous in empirical techniques. To postulate that we can gauge one without considering the other simply draws us further away from the objective of finding ways to fend off a crisis. Seminal work from Forbes and Rigobon (2002) distinguishes ‘interdependence’ and ‘contagion’, and proposes a widely accepted definition. Forbes and Rigobon (2002) suggests that in the case of two markets, countries or entities explicitly showing co-movements during calm periods will not be considered contagious despite amplifying co-movements and crisis engulfing both indices. It is contagion, when such co-movements are triggered facing a widespread crisis only. Key to this insight is the simultaneous volatility increases underpinning the increases in cross-correlation between factors. The bias is a result of heteroscedasticity and if untreated gives spurious identification. Hence, in all turbulence the gyrations in cross correlation index are erroneously dubbed as contagion. In similar spirit, albeit in a different framework Duffie et al. (2009) and Darolles and Gouriéroux (2015) distinguishes frailty from contagion. This, in fact, explains why contagion identification is abound in the current tenet of studies. Earlier, the implications of such spurious identification of contagion are highlighted in Billio and Pelizzon (2003).

Piccotti (2017) argued that there exists a symbiotic relationship between contagion and systemic risk (financial contagion defines the spread of market disturbances and poses a potential threat for economies by attempting to integrate with international financial system. This also explains the extent to which a local crisis may propagate across neighbours and warrants investigation beyond real economic factors. Con-

⁴ Seth and Panda (2018) produces a taxonomy of contagion that spans the articles publishing from 1990 till 2015, encapsulating 151 papers among which only 4 concentrates on *contagion, spillover and integration* nested together.

versely, systemic risk suggests the risks that exist within a system of nodes comes from the strength of these nodes). Endogenous credit and capital constraints turn non-systemic risks into systemic risk as crisis propels through different markets followed by a reinforcing cycle. Additionally, crisis propagation brings about temporal changes to aggregate elasticity of temporal substitution affecting asset prices in different markets (Holmstrom and Tirole 1996, 1997; Kiyotaki and Moore 1997; Longstaff and Wang 2012; Elliott et al. 2014; Shenoy and Williams 2017). Hence, financial contagion increases all costs, as the marginal utility of consumption is negatively affected in the short term for long-term investors. Consequently, investors short-term holding time preference attributes a higher price to contagion (Van Binsbergen et al. 2012, 2013; Belo et al. 2015). Drawing a distinction, Piccotti (2017) suggested that financial contagion may positively affect the marginal utility of consumption corresponding to assets with a longer holding period, subsequently decreasing contagion costs while generating higher returns for risk-takers. Fernández-Rodríguez et al. (2016) define interconnectedness as a bridge between two crucial visions, 'pure contagion' and 'shock spillover'. We are provided with an ideal natural experiment to investigate the degree to which existing systemic risk makes a given market more contagious. In other words, we aim to identify if high-risk spillovers are positively associated with spikes in contagion.

2.2 Banks or equity markets?

Notably, since the 2008 credit crisis several restrictions were imposed on banking securitisation, especially in advanced economies. The Association of Financial Markets in Europe reported significant reduction in the securitisation activities, especially for the USA and European banks (AFMEA 2017). Evidently, this has impaired the capital and profitability of these banks as indicated by for International Settlements (2018). Mersch (2017) presented an account of attempts to revive risk transfer in capital markets, especially in USA and European economies, by providing a natural experiment to recover the changes in the risk transfer dynamics for these economies.

The 2008 crisis has also driven the central banks to enforce both measures to enhance liquidity provisions and interbank loan freezes for commercial banks against the fear of an untenable build up and unwinding of systemic risk within the interbank loan networks (Georg 2013). Banks face a stochastic supply of deposits and interbank loans that link the banks, ensuring there is a continuing buffer of credit among them: this is the key to banking operations. While such static interbank loan networks form the money market, Haldane (2013) defined these interbank networks as robust, yet fragile, suggesting that interbank networks work on a knife's edge. Moreover, static networks work well for maintaining liquidity provisions by enhancing liquidity allocation and risk share between depository institutions, and they are an intrinsic part in the globalisation of banks (Battiston et al. 2012; Ladley 2013; Gai and Kapadia 2010). Conversely, interbank networks amplify shocks for all participants and face the insolvency of a strongly connected participant. Acharya and Bisin (2014) defined such externality as a counterparty risk externality that fuels cascading defaults in banks, otherwise known as interbank contagion. Acharya and Bisin (2014) further suggests that

a similar effect arises from one bank's holding numerous other banks' assets. A correlation externality arises when common shocks rip through all parties in an interbank loan market due to the common holding of sub-prime assets sourced from defaulting banks. Therefore, the fundamental banking activities are the source of untenable cycles of shock transmission, coupled with securitisation or shadow banking which provides a potential means for a downward spiral. However, the contribution of each participant disproportionately contributes to each trigger event and crisis propagation, and trying to gauge a generalised index of risk from these banks often leads to aberrations in outcomes. For more recent and important studies in this domain, we refer to Fry-McKibbin et al. (2021) and Bratis et al. (2020).

Allen and Gale (1998) presented an interesting perspective to explain the crucial link between banks and equity markets, and policy direction geared towards impeding the growth of crisis in both sectors. A classical view sources crisis from 'mass hysteria', in which investors' panic due to an impending crisis is analogous to sunspots (Kindleberger 1978). These extraneous 'sunspot' panics emit from speculations and lead to self-fulfilling scenarios. Fearing a bank's failure to fulfil its commitment leads to a synchronised withdrawal that drains the bank of liquidity, leading to bank failure and crisis precipitation. Alternatively, policies blunting the initial panic ensures there are few full withdrawals, resumes confidence in the bank's commitment and dampens any further panic. Allen and Gale (1998) suggested that an 'optimal allocation' of risks is obtainable if bank runs are allowed within a controlled scenario. Banks shed risks into asset markets to stimulate cash flow. Facing a downturn, banks liquidate capital market assets that, in turn, forces asset prices down. Hence, if intervention strategies are simply geared towards preventing a capital market collapse, a Pareto improvement is observed in the banking sector, which satisfies the self-fulfilling prophecy. In this way, banking interventions can be a tool used to protect a few large banks from a cascade, and capital market interventions may protect the economy. In this regard, examining banking sectors for systemic risk-led crisis generation is investigating the wrong facet of the problematic.

This dichotomy is reflected in the tenet of studies identifying sources of crisis. The ubiquity of systemic stress across multiple sectors in the unfolding of a crisis makes it arduous to look for a unique sector reflecting the dynamics of crisis. Intuitively analysing the systemic banking connections identified by earlier studies has led to discourse in capturing the dynamics of boom-bust cycles. Evidently, there is strong interconnection between systemic risk propagation in banking and in stock markets. Myers (1977) asserted that fearing run-ons, banks naturally siphon off large, collateralised debts, which effectively devalues all common equities built into similarly constructed debt portfolios. A systemic decline in equity indices indicates widespread systemic banking declines. While investigating unprecedented losses in the long/short equity hedge funds during the USA quantitative meltdown of 2007 followed by coordinated deleveraging of equity market-neutral portfolios, Khandani and Andrew (2011) surprisingly found indications of macrostress building and shifting patterns in equity price expectations. Apparently, signs of distress across many sectors are more effectively gauged using equity market systemic risk analyses.

An increasing number of commentators give credence to this notion. Hanson et al. (2011) evinced that declines in equity indices are directly connected to forced liqui-

dation of similarly constructed debt portfolios in the banking sectors. A resulting fire sale triggers a twin crisis, which then merges micro-level downturns into a complete economic downturn. Diamond and Rajan (2011), Shleifer and Vishny (2010) and Stein (2010) found unerringly positive similarities between equity market fire sales and bank credit crunches. In effect, classic bank run-on is indistinguishable from a stock market crash (Gorton and Metrick 2012; Covitz et al. 2009). Further, the rapid accumulation of credit bubbles spurs macroeconomic vulnerabilities and systemic connections in equity markets, which provides a perfect platform for modelling crisis (Dungey et al. 2020; Krishnamurthy and Muir 2017; Alan and Alexi 2014; Adrian and Shin 2009; Reinhart and Rogoff 2009).

Most recently, Syllignakis and Kouretas (2011) asserted that institutional investors shifting investment preferences from stocks and bonds to treasury bills, with the preceding investment withdrawal from institutional to investor-managed, emerging market hedge funds and private equity by investors as the USA subprime crisis unfolded exacerbated crisis transmission and contagion in the emerging Eastern European markets. Evidently, connectivity between emerging and European export dominant countries had resurfaced, especially with Germany, Russia, the UK and the USA (Syriopoulos 2007; Lucey and Voronkova 2008; Syllignakis and Kouretas 2010). This warrants a complete investigation into the shift of contagion preferably in equity markets.

3 Empirical framework

We apply DY, MHD and signed volatility decomposition (SVD) approaches to a large panel of international equity markets. The DY provides a profile of increasing spillover effects between the markets across the sample period, highlighting periods of change in the intensity for these effects. However, the DY is limited in identifying the direction of contemporaneous risk measures. MHD analysis enhances the DY by identifying linkages between markets that amplify or dampen shocks and, further, how the system of markets fluctuates around the average relationship by accumulating shocks over time. MHD helps discerning negative in-shocks from positive out-shocks with signs. SVD analysis complements MHD by calibrating the model with innovations from realised variance estimates put into an impulse response framework. For the DY analysis, we use a rolling window of 100 days. The results are robust to different rolling sample sizes and data frequencies.

The DY provides information on the direction and size of spillovers, while the MHD provides the direction, size and sign, that is, whether the linkages dampen or amplify shock transmission. We calibrate the MHD further by the estimating signed index with realised variances, and separate out the self-exciting transitory signed volatility evolution from the signed return spillovers with our proposed signed volatility decomposition (SVD). This approach can be considered as an extension of vulnerability and transmission representations with MHD.

3.1 Diebold and Yilmaz spillover index (DY)

Diebold and Yilmaz (2012) proposed a VAR forecast error variance decompositions (FEVD) to compute DY spillover indices. The FEVD matrix is termed as the adjacency matrix (or ‘connectedness matrix’). Across the rows and down the columns all possible connections between the VAR variables are represented by in-shocks to the targets and effects of out-shocks to potential recipients.

Consider a VAR(p) of the form⁵

$$x_t = \sum_{i=1}^p \phi_i x_{t-i} + \varepsilon_t, \quad (1)$$

where x_t is the return vector $x_t = (x_{1,t}, \dots, x_{N,t})'$, ϕ is a $N \times N$ parameter matrix and ε_t represent residuals. The moving average representation of VAR(p) from (1) is

$$x_t = \sum_{i=0}^{\infty} A_i \varepsilon_{t-i}, \quad (2)$$

where,

$$A_i = \phi_1 A_{i-1} + \phi_2 A_{i-2} + \dots + \phi_p A_{i-p}.$$

Diebold and Yilmaz (2009) propose using the H-step-ahead forecast error variance decomposition (GVD) that is constructed from VAR (see Koop et al. 1996) to circumvent the order dependence issue. Following the work of Pesaran and Shin (1998), we denote this GVD by $\theta_{ij}^g(H)$ and that gives

$$\theta_{ij}^g(H) = \frac{a_{jj}^{-1} \sum_{h=0}^{H-1} (e_i' A_h \sum e_j)^2}{\sum_{h=0}^{H-1} (e_i' A_h \sum A_h' e_j)}, \quad (3)$$

where the co-variance matrix is \sum and a_{jj} is square root of error variance of j th equation and in the i th element, A_h is the moving average coefficient from VAR and e_j is a selection vector of ones.

Now $\sum_{j=1}^N \theta_{ij}^g(H) \neq 1$. However, after normalising, the rows in the FEVD matrix are defined as

$$\tilde{\theta}_{ij}^g(H) = \frac{\theta_{ij}^g(H)}{\sum_{j=1}^N \theta_{ij}^g(H)}, \quad (4)$$

in which we get $\sum_{j=1}^N \tilde{\theta}_{ij}^g(H) = 1$ and $\sum_{i,j=1}^N \tilde{\theta}_{ij}^g(H) = N$.

⁵ An intercept is suppressed for simplicity and without loss of generality.

The static spillover are computed by taking the sum of off-diagonal elements as proportion of sum of all elements, representing system wide connectedness. Notably, the directional spillover index identifies the return spillover of all other markets to market i

$$S_{i \leftarrow \text{all}}(H) = \frac{\sum_{j=1, j \neq i}^N \tilde{\theta}_{ij}^g(H)}{N} \times 100. \tag{5}$$

The return spillover from market i to the other markets is given by

$$S_{i \rightarrow \text{all}}(H) = \frac{\sum_{j=1, j \neq i}^N \tilde{\theta}_{ji}^g(H)}{N} \times 100. \tag{6}$$

Pairwise directional connectedness identifies gross shock transmission to and from the markets as

$$S_i^g(H) = S_{i \rightarrow}^g(H) - S_{i \leftarrow}^g(H). \tag{7}$$

3.2 Multivariate historical decomposition (MHD)

MHD, pioneered by Dungey et al. (2017a), provides a signed contribution of shocks from one to another market that captures the dampening effects. Here, the connectedness elements measured with B_{ij} explain the fraction of variation of i due to shocks in j at time t (excluding self-loops in a network).

Building on the VAR defined in equation (1) the generalised historical decomposition of j at time t can be used to estimate a signed spillover index. This is presented as follows:

$$\text{MHD}_{t+j} = \sum_{i=0}^{j-1} \text{IRF}_i \odot \mathcal{E}_{t+j-i} + \sum_{i=j}^{\infty} \text{IRF}_i \odot \mathcal{E}_{t+j-i}, \tag{8}$$

where $\mathcal{E}_{t+j-i} = [\varepsilon_{t+j-i}, \dots, \varepsilon_{t+j-i}]$ is an $N \times N$ residual matrix. IRFs' are one unit impulse responses (non-orthogonalised) and \odot is the Hadamard product. The estimated MHD provides an $N \times N$ matrix providing signed in-shocks across the rows and signed out-shocks down the columns of the matrix. This approach accommodates the nonlinear dynamics of the data.

MHD permits to estimate signed weights of shocks throughout the channels, as a function of impulse responses weighted by residuals ε_t . The system uses unconditional variance estimates as innovations for the impulse response estimates and, as such, is considered to represent signed spillovers in the returns.

3.3 Signed volatility decomposition (SVD)

Now the SVD is proposed by extracting spillover information drawn from realised variances associated with volatility transmissions within a network. We take the dif-

ference between return and volatility spillovers to identify whether a particular market is driven more by intrinsic volatility than by risks emerging from the network.

Moreover, we consider a nonparametric approach to estimate SVD, which follows the same algorithm as MHD. Unlike MHD computed from daily returns, we compute MHD from realised variance drawing from 5-min intervals in prices and, as such, the historic decomposition is depicted as SVD.

We begin by calculating intraday log returns with $r_{t,i} = \log(P_{t,i}) - \log(P_{t,i-1})$. Next, we compute squared returns for each 5-min interval and sum them up to find daily realised variances as

$$RV_t = \sum_{i=1}^N r_{t,i}^2$$

SVD is computed from using the estimates of RV_t in Eq. (8). To identify contagion in the associated network from volatility of common factors localised to a given market we simply take the spread between SVD and MHD:

$$\text{Spread}_t = \text{SVD}_t - \text{MHD}_t,$$

which is used in the empirical analysis section.

4 Data

The data are daily dollar denominated stock returns from 30 developed and developing countries' markets across Asia–Pacific, Europe, the Americas and the Middle East.⁶ The beginning of the sample corresponds to the Asian financial crisis period. Daily returns are generated from price indices for 1 January, 1998, to 15 June, 2020. Global economies endure 15 major crisis periods and several minor turmoils within the sample periods as outlined in Table 1.

Taking natural logarithms of the data, we transform price to returns data. We further use a two-day moving average filter, removing time zone effects as in Forbes and Rigobon (2002).

We use a balanced sample of 30 financial markets in this paper.⁷ We classify the markets into export crisis (EC) markets (i.e. leaders in commodity export), oil exporters into both emerging (OEE) and developed (OED) markets, European markets that have been directly affected by the Greek crisis (GIIPS) of 2010 onwards and high-yield Asia–Pacific markets directly affected by the Asian crisis (AC) of 1997–1998. We also include in the OED group the so-called conduit markets of the USA and Japan (BIS 1998; Baur and Schulze 2005). Table 1 provides the classification of the markets into five clusters, which is a common presentation in the literature.

⁶ The data are sourced from Thompson Reuters, and we follow the mnemonics indexed in Pukthuanthong and Roll (2009).

⁷ Australia, Austria, Belgium, Canada, Chile, China, France, Germany, Greece, Italy, India, Iraq, Ireland, Israel, Japan, Kuwait, Malaysia, New Zealand, Nigeria, Norway, Portugal, Russia, Saudi Arabia, Singapore, South Korea, Spain, Sri-Lanka, Thailand, the Philippines, the USA and the UK.

Table 1 Countries by analytical group

Exporters	Commodity exporters	Oil exporters	Greek crisis	Asian crisis	Conduit countries
EC	CE	OE	GIIPS	AC	CC
Australia	Australia	Canada	Italy	Australia	Japan
China	Canada	Ecuador	Spain	China	USA
Chile	France	Iraq ^a	Belgium	India	
Germany	Japan	Israel	Greece	Malaysia	
Nigeria	New Zealand	Kuwait	Ireland	Philippines	
Norway	UK	Nigeria	Portugal	Singapore	
Russia		Saudi Arabia		South Korea	
Saudi Arabia		Venezuela		Sri Lanka	
South Korea		USA		Thailand	

^aUsing Pakistan as a proxy market

Table 2 provides a brief description of each of these events along with the broad dating conventions.

Discussions concerning properties of asset returns dominate in both the current and early literature. Among early studies, Fama (1976) suggested that daily asset returns series are more non-Gaussian than are shorter frequency return series. Additionally, Cont (2001) emphasised persistence and nonlinearity, while Stărică and Granger (2005) focused more on non-stationarity inherent within stock returns data.

Recently, Joseph et al. (2017) classified stock returns as non-Gaussian and time varying, with smooth compact support over low-frequency spectral content. Others suggested that the daily stock returns data are negatively skewed, nonlinear, noisy and volatile (Joseph and Larrain 2008; Atsalakis and Valavanis 2009; Joseph et al. 2011; Kremer and Schäfer 2016; Zhong and Enke 2017). It is crucial to use appropriate filtering and transforming techniques for better detection and decoding of cycles in source data.

Of the relevant studies examining prediction, Zhou et al. (2012) supported on the dissent in theory and practice regarding asset returns. Only the pre-processing of returns circumvents such misalignment, as suggested by Joseph et al. (2016, 2017), Atsalakis and Valavanis (2009) and Zhong and Enke (2017). A central context of data pre-processing with filtering is there is no discord in its importance in the relevant studies investigating returns (Joseph et al. 2017).

Finally, Smith et al. (1997) suggested that despite its simplicity as a method, moving average filters do much better compared to other digital signal processing techniques, such as single pole. Precisely, moving average handles discrete time series in a subtle manner (Smith et al. 1997).

Within the context of considering raw returns as non-Gaussian, nonlinear, time-variant random data, the importance of spectrum density/frequency domain analysis for pre-processing is undeniable. Hence, moving average is the chosen signal processing technique here. On another note, 'spectral windowing' is important to extract detectable edges and avoid aberrations caused from discontinuity in the raw data. Nat-

Table 2 Financial crises in the sample period

Crisis events Period	Description
1997–1998	Asian financial crisis
1998–2000	Russian financial crisis
2000–2002	Dot-Com bubble
2003–2008	Global energy crisis
2003	The SARS outbreak
2006	Gaza conflict
2007–2009	Global financial crisis
2009–2012	Eurozone crisis
2014–2017	Russian crisis
2016	Export crisis
2015–2016	Chinese crisis
2013–present	Venezuelan crisis

Collapse of Thai baht, resulting in Thailand becoming effectively bankrupt
 Devaluation of the ruble followed by Russian Central Bank defaulting on its debt
 Stock market crash in 2002 followed by excessive speculations prevalent in 1997–2000 together with the September 2011 terrorist attack on US
 Increasing tensions in Middle East together with rising concerns over oil price speculations followed by a significant fall of US dollar; resulted in oil prices rise abruptly, exceeding three time the price at the beginning
 First identified in Guangdong province in China, rapidly took an epidemic form worldwide, slowing down economic interactions with China to many markets
 Israel-Lebanon war breaks out
 Subprime mortgage crisis followed by 2005 housing bubble burst
 In the wake of Great recession in the late 2009, several Eurozone members (Greece, Portugal, Ireland, Spain, Cyprus) failed to bailout over-indebted banks and repay foreign debt
 Collapse of Russian ruble, followed by economic sanctions imposed on Russia and the collapse of Russian stock markets
 Germany, Chile, France, China, UK, Australia among others experience historic decline in total exports to others, followed by the so-called 'oil-glut'
 A massive drop in Chinese stock markets results in markets terminating transactions in the wake of concerns over a Chinese Crisis
 Termed as the Great depression of Venezuela, the deterioration of major macroeconomic indicators in Venezuela since 2013, resulted in significant social and political degradation. The extent of this deterioration is such that Venezuela topped the misery index 2013 and ranked lowest by the IFC in investing country index

Table 2 continued

Crisis events Period	Description
Empirical analysis comparing DY, MHD, SVD 2018	Global financial shock Facing the emerging US-China trade tensions, followed by central banks turning off the money taps and cooling growth in former hot spots wipes 10 percent off world's stocks equivalent to \$7 trillion USD. MSCI's 47-country world stocks index is hit with its first double-digit loss since the 2008 global financial crisis. Among others, Germany's DAX index enters bear market territory, down 22% from its high in January and 18 percent from the start of the year; the CAC 40 of France finished the year down 11%; and Britain's FTSE 100 lost 12.5%. Most Asian markets including China sees significant drop in the value of their stocks in 2018; nearly \$5 trillion (€4.35 trillion) wipes off their value; annual losses in Shanghai and Shenzhen stocks pile up to 25 and 33 percent, respectively, due to a bitter trade conflict with the US. The Hong Kong Stock Exchange ends the year nearly 14 percent lower
2019	Emergence of Covid recession 1. The COVID-19 global economic recession which is the direct result of the COVID-19 pandemic. It is by far the worst global economic crisis since the Great Depression 2. Following a global stagnation of stock markets and global economic slowdown, the COVID-19 lockdowns and other precautions to control COVID-19 pandemic threw the global economy into crisis 3. Within seven months, every major developed and emerging economies had fallen to recession or depression. It is now estimated that in some regions a full recovery will not be achieved until 2025 or beyond. IMF reports that the world economy was going through a 'synchronised slowdown', entering into its slowest pace since the financial crisis of 2007–08. The IMF identifies 'heightened trade and geopolitical tensions', sourcing the slowdown, especially citing Brexit and the US-China trade war as to blame for slowdowns in 2019
2020	Global financial and Economic crisis The 2020 stock market crash was a major and sudden global stock market crash that began on 20 February 2020 and ended on 7 April. Though the crash began on 20 February, selling was intensified during the first half of March to mid-March. During this time major indices dropped 20 to 30% in late February and March. The ongoing recession and the 2020 Russia–Saudi Arabia oil price conflict led to a drop in the price of oil, while the Covid recession continues to cause a collapse of tourism, the hospitality industry, the energy industry; and a downturn in consumer activity unseen before

urally, the chosen window size is 2 in our paper, which is consistent with Oppenheim and Schafer (2014) and Forbes and Rigobon (2002).

The transform function

$$a(1)y(n) = b(1)x(n) + b(2)x(n-1) + \dots + b(n_b+1)x(n-\eta_b) - a(2)y(n-1) - \dots - a(\eta_a+1)y(n-\eta_a)$$

handles both infinite and finite impulse responses. The moving average filter derived from the rational transfer function allows input of different window size (ω_s)

$$y(n) = \frac{1}{\omega_s} (x(n) + x(n-1) + \dots + x(n-(\omega_s-1))).$$

Indeed, our pre-processed data characterised by the frequency contents of the signals better detect the periodicity than do the raw unprocessed returns data. Table 3 presents a selection of statistics for the 30 return indices; including average, minimum, maximum, standard deviation and Jarque–Bera test results for normality in distribution. The greatest spread between minimum and maximum is found for Venezuela, Kuwait and Iraq, all of which have high standard deviations. As is usual for returns normality is rejected at the 5% significance level. Rather, these indices have more leptokurtic and skewed distributions, consistent with the crisis effects throughout the sample period (Brown and Warner 1985; Fama and French 1988; Kim et al. 1991; Corhay and Rad 1994; Longin 1996). In addition to robustness tests with different rolling windows, we have examined the possibility of multicollinearity in residuals. We found correlation coefficients to be null and insignificant in the residuals, ruling out the possibility of loss of consistency in our estimation outputs.

In the following section, we present a comparison in the estimates gauged from DY, MHD and SVD. Note that, while DY and MHD estimates are computed drawing on data from the complete sample size from January 1998– June 2020, the MHD–SVD spread draws on from 5 min interval prices for September 2009 until September 2017.⁸

5 Empirical results

In this section, we discuss the empirical results obtained from the DY, MHD and SVD methods (see Figs. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 and 21). A detailed explanation of the amplifying and dampening transmissions and vulnerability is also presented in Tables 4 and 5. The empirics of the study covers multiple methodologies across multiple sample classifications. While a concise description of the observations from analysis is discussed, a more detailed comparative description

⁸ Due to the limited availability of 5-min interval prices for important South Asian countries, such as Singapore, we trim the data down to fit vector sub-spaces within the specified matrix space, for all other vectors retaining Singapore. For similar reasons, we also remove Middle Eastern markets. We include Mexico in the sample, as it represent an important, emerging oil exporting market. We do not extend the data to fit Covid-19 period in the identification of ‘contagion’. While the identification of ‘contagion’ during Covid-19 is not a major concern for this paper, as we have identified the dynamics in excessively contagious markets remaining consistent for decades, it might present a scope for a future study to investigate this issue.

Table 3 Descriptive statistics

Descriptive statistics	USA	AUS	IND	JAP	MYS	NZL	SGP
Min	-6.629	-8.364	-9.852	-8.239	-19.017	-5.406	-8.848
Max	6.202	8.107	10.783	6.618	17.587	5.138	8.071
Median	0.049	0.069	0.106	0.037	0.022	0.062	0.047
Mean	0.018	0.021	0.038	0.009	0.019	0.017	0.026
Standard Deviation	0.817	1.026	1.244	0.965	1.105	0.832	0.993
JB test <i>p</i> Value	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Critical Value	5.951	6.008	6.043	6.015	5.986	5.992	5.983
	PHL	KOR	SLK	THA	NIG	VEN	KWT
Min	-8.23	-12.50	-9.95	-10.25	-17.09	-145.75	-62.81
Max	13.890	12.320	11.797	15.888	6.777	20.320	62.554
Median	0.044	0.000	0.000	0.029	0.000	0.008	0.0043
Mean	0.024	0.044	0.025	0.034	0.007	-0.003	0.012
Standard Deviation	1.181	1.514	0.858	1.321	1.129	3.557	1.871
JB test <i>p</i> Value	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Critical Value	6.019	5.975	5.987	5.988	6.005	5.995	5.996
	IRQ	SAU	CHN	ISR	CAD	GRC	PRT
Min	-41.219	-10.573	-7.863	-6.253	-9.432	-10.350	-7.060
Max	40.780	7.914	6.493	6.506	7.828	8.331	7.494
Median	0.000	0.008	0.020	0.063	0.084	0.064	0.039
Mean	0.027	0.022	0.036	0.028	0.019	-0.012	-0.008
Standard Deviation	2.508	1.013	1.243	0.986	0.985	1.523	1.041
JB test <i>p</i> Value	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Critical Value	6.003	5.948	6.010	5.996	6.012	5.964	5.986
	IRL	AUT	RUS	NOR	GER	CHL	UK
Min	-11.500	-7.505	-16.801	-10.805	-6.706	-6.202	-9.703
Max	5.901	8.191	13.811	7.301	7.104	8.321	7.112
Median	0.0702	0.0701	0.0602	0.071	0.071	0.052	0.043
Mean	0.011	0.021	0.021	0.0161	0.021	0.032	0.015
Standard Deviation	1.061	1.011	1.809	1.258	1.141	0.821	0.941
JB test <i>p</i> Value	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Critical Value	5.981	5.971	5.971	6.031	6.031	5.941	5.951

for each methodologies across each sample classification is discussed in detail in Table 4 for risk transmissions and in Table 5 for risk receivings.

The analysis holds for two fundamental principles.

1. First, a common phenomenon that largely holds is that big transmitters are generally more susceptible to global contagion shocks and that propagation of crisis with contagion is one-directional.
2. Second, in identifying ‘contagion’ from an aggregate risk assessment, our economic prior is that for the markets in which locally induced volatility swings together with spillover, the increases coming from interconnection amplify the aggregate risk estimates, which reverts the market to a steady state by releasing excess risks onto others. Hence, in times of excess volatility, markets are more epidemic in nature.

Next, we discuss comparisons by market blocks (see Table 4): Asian crisis (AC), Export crisis (EC), Greek crisis (GIIPS), Oil exporting developed (OED) and Oil exporting emerging (OEE) countries’ markets.

India, Singapore and Thailand in the AC cluster are highly susceptible to their own market shocks, but this holds less so for Malaysia, South Korea and the Philippines. While many past studies have contended (including our DY estimates) that Malaysia and the Philippines are more resilient for not being deeply connected to global networks as others (Raghavan and Dungey 2015), our MHD estimates further suggest the latter set of markets receive strong shocks in major events. As given in Figs. 1, 6, 11, 16 and 21, we suggest that the Indian, Malaysian and South Korean markets are more vulnerable to globally induced contagion than are the rest. The transmission estimates uphold this phenomenon by depicting these markets as low transmitters that are highly vulnerable to an epidemic in the holistic network. As Thailand, Singapore and the Philippines remain more susceptible to local volatility, unsurprisingly they emerge as strong transmitters as they release ‘excess volatility’ to other peripheries (see Tables 4 and 5). This ‘excess volatility’ refers to the accumulation of instantaneous self-exciting stochastic volatility in excess of volatility spillovers coming from the network itself.

Simultaneous volatility changes in common factors with large-scale events often pollute the degree of actual spillovers as suggested in Dungey and Renault (2018). In Figs. 2, 7, 12, 17 and 21 we identify risks generated out of interconnections in the network from localised volatility changes for the EC (i.e. Germany, Chile, France, China, the UK and Australia) market cluster with MHD–SVD spread. We identify that Germany, Chile and the UK are predominantly more vulnerable to instantaneous transitory spikes in volatility, polluting the actual degree of shocks received from interconnections within the network. Consistent with the principle of high spreaders being less susceptible to vulnerability coming from a global contagion, the UK and France turn out to be high transmitters of crisis, especially during the GFC and eurozone crisis. For Australia, transmissions are triggered strongly with ‘excess volatility’ and, as such, it is highly vulnerable to epidemic shocks in the network. As opposed to Dungey and Renault (2018), who suggested Germany does not suffer from the same market reassessment risk as major markets and is distanced from other connections, we find Germany and China are highly susceptible to crisis received from other markets with ‘excess volatility’ most recently. Consequently, this indicates the degree of systemic risk found within these markets is due to contagion. At the onset of the Chinese and export crises, the heightened volatility in the German and Chinese market

starts spilling excessive risks onto others, resulting in amplified transmission in the network as laid out in the second principle.

In comparing DY and MHD, we find MHD rejects DY's depictions of Germany and France as the highest spreaders of crisis. Despite occasional spikes in resilience responding to major global events spanning our sampling periods, Germany remains more vulnerable to crisis coming from contagion than does France or the UK. While we may attribute the degree of transmissions coming from France as neutral to dampening, the UK is largely a spreader with strong resilience to contagion.

Figures 3, 8, 13, 18, and 21 depict that the GIIPS countries' (i.e. Greece, Italy, Ireland, Portugal, Spain) markets are very sensitive to events contributing to global contagion. These markets are less characterised by local shocks and the shocks generated in the neighbouring nodes, except for Greece and Belgium. However, the MHD measure selects Greece and Austria as becoming more resilient as the eurozone crisis subsides, while Portugal and Ireland become more vulnerable. This can be attributed to investments moving out of Greece and Belgium and into Portugal and Ireland, making the latter deeply connected. Moreover, MHD captures Croatia remaining strongly resilient to shocks across the periods spanning our sample, which DY fails to detect.

Our transmission estimates for GIIPS countries and the transmission vulnerability mechanism are in line with what we provided in the first principle. As Portugal becomes more vulnerable to global contagion more recently, it is of no surprise to find that Portugal and Ireland transmit stronger shocks in the past. This suggests Portugal and Ireland remain deeply connected with the other peripheries since before the GFC. Moreover, with dropping vulnerability coupled with 'excess volatility', Croatia emerges as a strong transmitter during the eurozone crisis.

Figure 21 shows the volatility jumps unique to Greece and Ireland, in which the excess vulnerability also sets off network transmissions to other markets. In contrast, transmissions emerging from Portugal and Austria that correspond to excess vulnerability are coming from volatility and, hence, are short-lived. Notably, there is little risk of spillover over-identification for Belgium and Croatia.

The figures concerning OED countries' (i.e. the USA, Canada, Russia, Norway, Japan and New Zealand) markets depict that stochastic local volatility predominantly affects the vulnerabilities of the USA, Norway and Mexico (Figs. 4, 9, 14, 19, and 21). In fact, the recent degree of risks stemming from the USA and Russia is emanating mostly from 'excess volatility'. In contrast, exceeding return spillovers following the onset of export crisis for Norway, Japan and New Zealand suggests these markets are especially contagious. The spread falls for Canada and, very recently, for Mexico, suggesting the spillovers in these markets are driven less by local volatility and more by their dominance in the holistic network.

Taking a more granular view with our MHD and DY comparison, the Japanese and New Zealand transmissions provide further reassurance as to the nature of these markets' vulnerabilities. Japanese volatility transmission is depicted as contagion transmission, which corresponds with Japan emerging as a highly connected market out of its long-lasting economic stagnation in early 2000. Neutral to dampening volatility transmissions stemming from the USA, but also a curving up of its transmission swings with a shifting regime, gives credence to BIS (1998) suggestion that both the USA and Japan are 'conduits' for contagion transmission. Conversely, the

Table 4 Empirical analysis comparing DY, MHD, SVD

Vulnerability Blocks	DY	MHD	MHD-SVD
AC	<p>1. India, Malaysia and Thailand show consistently slow increase in vulnerability across the years.</p>	<p>1. India, Malaysia and Thailand show lasting resilience across the years spanned by our sample, except for pronounced rises only for India and Thailand in the GFC. Moreover, sheer resilience for India is depicted in Fig. 6 in the period following the GFC. Among others, Thailand remains somewhat vulnerable, with little spikes in vulnerability corresponding to major events such as the GFC and eurozone crisis.</p>	<p>Coming to the identification of small contemporaneous shocks spawning from volatility characteristics of a market, out of mutually reinforcing long-lived correlations, we find India, Singapore and the Philippines are predominantly volatile. Strong inter-temporal volatility contributing mostly to vulnerability predominates for India, Singapore and the Philippines. While sheer resilience for the Philippines during the eurozone crisis is depicted in Fig. 11, this cannot be held true for the others. However, vulnerability for Malaysia, Thailand and, more recently, for South Korea is coming from far less volatility than are Singapore and the Philippines. This suggests that the former countries are more susceptible to international contagion than to local shocks</p>

Table 4 continued

Vulnerability Blocks	DY	MHD	MHD-SVD
	<p>2. We see dramatic resilience building for Singapore, South Korea and the Philippines, corresponding to that of the USA with the arrival of the Iraq invasion while the USA recovery from dotcom bubble also remains a more conspicuous factor. The general buoyance in the Asian markets resonates with the recoupling in the USA market coupled with expectations soaring with the invasion. Soon after, vulnerability starts rising for the aforementioned countries' markets.</p>	<p>2. In contrast to the findings with DY, we do not see resilience building up dramatically for South Korea, the Philippines and Singapore. Indeed, profound amplifications and dampening are depicted in the South Korean and Philippines markets, adding up to what seems like big jumps in the absolute representation of DY. Rather, we find vulnerability to be the more conspicuous factor attributable to South Korea and the Philippines markets. Attributed with a high degree of systemic risk, both these markets' vulnerabilities amplify in response to almost all the major events presented in our sample period. Despite remaining mostly vulnerable, the degree of vulnerability and resilience reverts to the mean degree for Singapore following the post-Asian financial crisis period.</p>	

Table 4 continued

Vulnerability Blocks	DY	MHD	MHD-SVD
EC	<p>1. A strong resilience building up for Germany in late 2002 is consistent with the USA, Singapore, South Korea and Japan. This period marks the recovery of the USA and Japanese markets from economic downturns. This period also marks the advent of the Iraq invasion, which rekindled confidence in the energy stocks. For Germany, the sheer resilience is followed by a pronounced drop following the Iraq invasion. Aggregate vulnerability increases with exogenous shocks coming from oil and commodity indices. This observation holds true for other EC markets such as the UK, France, Chile and China. Australian resilience starts to pick up in the Iraq invasion period. Predominantly a major exporter of energy resources, Australian resilience build-up can arguably be attributable to the tightening of oil supply from the OPEC countries following the Iraq invasion, boosting confidence in Australian commodities market.</p>	<p>1. Resilience amplifications are mounting for Germany with DY, but less so with MHD. However, unlike DY, MHD captures the German market remaining vulnerable across most of the sample period, with occasional resilience build-up phases around the GFC and eurozone crisis. Hence, more phases of resilience are identifiable with MHD for Germany. Similar observations accord well with the France vulnerability pattern. The UK market remains strongly resilient, spanning across the entire sample period. In accordance with DY findings, the MHD plot for the UK in depicts strong resilience in the post-GFC and during the eurozone crisis. While remaining a strong spreader and being susceptible to shocks during the GFC as held by the global literature, it is indeed promising that the degree of rebounding in the UK market complements recoupling.</p>	<p>Contemporaneous small shocks that builds up temporal interdependence corresponding to unprecedented local events rather than long-term interdependence is prevalent in Germany, Chile and France. In other words, the market vulnerabilities of Germany, Chile and the UK are less determined by contagion as outlined in the work of Dungey and Renault (2018). Moreover, we concur with Dungey and Renault (2018) in regards to Germany not suffering from the same market reassessment of default risk as the others. Such can be also be held true for France. Although we find strong volatility spikes contributing to aggregate vulnerability for Germany and China during the eurozone crisis and for the UK in the export crisis (see Table 2), return spillovers prevailing for France, Australia and China since the export crisis indicate that these markets' degree of susceptibility increases with 'contagion' within the network itself. Therefore, little decoupling can be expected for these markets and as an economic prior only strong shifts in the network structure may drift the markets away from their current degree of impulses into vulnerability</p>

Table 4 continued

Vulnerability Blocks	DY	MHD	MHD-SVD
	<p>2. Germany, the UK and France are conceivable as potent crisis spreaders as the eurozone crisis unfolds. Consequently, they show strong resilience build-up during the same period. Among others, with the announcement of Brexit, the UK sees resilience picking up again. Resilience also picks up strongly for China as the market recovers, followed by a strong recoupling phase.</p>	MHD	<p>2. Chinese market remains largely vulnerable as depicted in Fig. 7. A short-lived resilience during the recent Russian crisis is followed only by more periods of vulnerability for China, with the onset of the Chinese stock market crash. MHD finds Chinese vulnerability is repeated across major global events, providing a better rationalisation for the Chinese market mechanism than for DY. Mostly, DY could not detect the cycles of amplification and dampening corresponding to many past events.</p>
	<p>3. Chile remains vulnerable, with vulnerability accelerating more in recent periods corresponding to oil and commodity inclusion, than previously.</p>	MHD	<p>3. Similar to the DY vulnerability pattern for Australia, MHD also suggests Australia remains vulnerable in the years spanned by our sample. This holds true also for Chile.</p>

Table 4 continued

Vulnerability Blocks	DY	MHD	MHD-SVD
GIIPS	<p>1. Greece, Portugal and Spain remain highly vulnerable across the sample period. Market resilience starts to pick up slowly in the post-GFC period. Figure 8 depicts an increase in resilience for the Italy that coincides with commencement of Greek's new austerity measures. Resilience starts to build in the periods that follow for Greece and Portugal up until the new austerity measure is adopted as the eurozone crisis slows down. Vulnerability amplifies for Greece and Portugal with new Greek austerity measures in place. We conjecture from DY that Greece is more at the receiving end of shocks from its peripheries than transmitting the shocks to others.</p>	<p>1. Preceded by a strong amplification in vulnerability facing the eurozone crisis, the Italian market's vulnerability begins to drop with Greece adopting new austerity measures. The Italian pattern resonates well with DY and also holds for Portugal. Moreover, MHD captures that in the most recent periods, with the eurozone crisis subsiding, Greek resilience building accelerates, while vulnerability dominates the risk curve of Portugal.</p>	<p>1. Contemporaneous small surges in volatility due to shocks inherent to local factors have little effect on the GIIPS markets, except for very recently. This suggests 'contagion' influences the GIIPS markets since the onset of the eurozone crisis. During the eurozone crisis and with the phases of Greek austerity measures, Fig. 13 shows that positive in-shocks from return spillovers for Portugal, Ireland and, especially, Greece far exceed any localised volatility risk</p>

Table 4 continued

Vulnerability Blocks	DY	MHD	MHD-SVD
	<p>2. Gyration in the vulnerability of Spain is more pronounced than for Ireland and Italy. While the amplification in vulnerability levels off for Ireland and Belgium, as the eurozone crisis becomes full-fledged, the Spanish pattern remains volatile. Facing the dampening of exports, vulnerability for Spain and Greece amplifies.</p>	<p>2. MHD provides better information in the systemic risk swings compared to DY. In contrast with the information produced with DY, MHD supports that Greek systemic risk swings lie well within the boundary outside the vulnerability region. Greek market remains rather resilient to shocks across the sample periods. As opposed to the DY pattern, the Portugal systemic risk pattern depicts rapid deceleration in vulnerability, moving the curve towards neutrality in the post-GFC period, and also holds for Ireland. Albeit smaller spikes in vulnerability are discernible for Belgium and Ireland during the eurozone crisis compared to the spikes observable during the GFC, the markets are becoming more resilient.</p>	<p>2. In the period following the eurozone crisis, Portugal, Greece and Ireland become more susceptible to volatility interconnections than to financial contagion. This indicates that these markets have less risks due to contemporaneous associations with peripheries</p>

Table 4 continued

Vulnerability Blocks	DY	MHD	MHD-SVD
OED	<p>As the USA market recovers from debacles following the dotcom bubble and the Japanese market rebounds from the long-lasting debt crisis, resilience in both the markets peaks profoundly. These two major economies recover results with similar outcomes for other deeply connected markets such as Germany, South Korea and Singapore. Canada, New Zealand and Norway's vulnerabilities slowly grow since the GFC unfolds. The Canadian curve shows several episodes of short-term resilience building along the way. However, Canada and New Zealand's vulnerability curve shifts up with the inclusion of oil and commodity indices, but less so for Norway. The strongest resilience build-up for Russia is depicted during the USA embargo on Russia. It emerges that with the embargo, the limited node connections cast out risks for Russia.</p>	<p>Consistent with DY, the MHD plots for the USA and Japan show the strengthening of resilience in early 2000. While vulnerability for the USA and Canada remains positive all along, Japanese resilience peaks correspond to the phases of confidence building in the markets and preceded by recovery periods associated with all major global events. This holds to a much less extent for Norway, and to a moderate extent for New Zealand. From MHD, what re-emerges is that these three countries' markets suffer from the same market assessment of default risk. Unlike what DY depicts, the Russian market remains resilient for the sample period with MHD.</p>	<p>Strong local volatility factors casting off risks are attributable to the USA, Canada, Russia and Norway in the eurozone crisis. This is not so for Japan, which highlights Japanese vulnerability to conditional correlations with the other peripheral markets as depicted in Fig. 14. We find that in the post-eurozone crisis and with the onset of export drag, Russia, Norway and Japan become highly susceptible to 'contagion' followed by some degree of decoupling</p>

Table 4 continued

Vulnerability Blocks	DY	MHD	MHD-SVD
OEE	<p>In line with the global literature, Fig. 10 depicts the heightening of resilience for large exporters of oil such as Saudi Arabia, Iraq and Nigeria. This is explained global investors' move towards energy securities and away from MBS in the advent of GFC. The increasing resilience for Kuwait and Israel is better explained by boosted investors' confidence as the Iraq invasion is happening. This is due to the conflict between Iraq and Kuwait and Israel in the regime. However, Venezuelan resilience building in the most recent periods can only be attributed to its disentangling of connections, as the whole economy is at a worsening spiral. The vulnerabilities for Israel and Nigeria significantly increase when adding oil and commodity shocks to the system.</p>	<p>MHD perfectly captures the resilience building for Saudi Arabia in DY. However, what DY fails to capture is the strong jump in vulnerability that follows. MHD further captures the neutralising of systemic risks emitting from Iraq. This finding can be better conceived as providing a better rationalisation for the cessation of Iraqi market activities with the invasion. Hence, DY is more misleading for the Iraq case. Despite Kuwait and Israel's resilience building given by both DY and MHD, MHD identifies that this is not as strong for both the markets in comparison to what is drawn from DY. In contrast, DY does not emphasise the peaks in Israeli vulnerability with the GFC. With the fall of Iraq, weakening of OPEC and increasing USA support for Israel in the regime, it is conceivable that Western investors' interest in the Israeli market spikes as barriers drop. This explains the spike in vulnerability for Israel during the GFC with the deepening of interconnections with the USA. Conspicuously in the MHD of Venezuela, which is unlike the results of DY, the economic collapse of Venezuela only fuels its vulnerability in the most recent periods. Nigeria remains vulnerable across the sample period with DY and holds for MHD.</p>	<p>We replace the Middle Eastern markets with New Zealand and Mexico as major oil exporting countries. We find the vulnerabilities in both these markets are coming more from financial 'contagion' and less from local volatility factors</p>

Table 5 Empirical analysis comparing DY, MHD, SVD

Transmission Blocks	DY	MHD	MHD–SVD
AC	<p>1. Transmission mounts for India, Singapore and Thailand during the GFC.</p> <p>2. South Korean transmissions amplify during 2002–2004 when the global economy was riddled with many crises.</p> <p>3. The Malaysian and Philippines markets demonstrate neutral to dampening transmissions overall.</p> <p>4. Inclusion of oil and commodity indices amplifies transmission during crisis, but only for India and South Korea.</p> <p>5. Little amplification in transmission is observed for all participants facing the GFC.</p>	<p>1. Patterns accord well with DY results for India, Singapore and Thailand during the 2006–2008 GFC period.</p> <p>2. As opposed to DY depiction, the South Korean transmission bears a negative sign, suggesting the dampening of transmission is dominant during 2002–2004.</p> <p>3. The Philippines and South Korea portray negative transmissions, the only exception of which was during the GFC event. This supports the DY argument.</p> <p>4. Positive transmissions are plotted for all markets during the GFC, similar to the DY observations.</p>	<p>Transmissions in the AC cluster shows India, Malaysia and the Philippines are becoming more epidemic in nature. Strong volatility amplifications in Thailand and Singapore suggest transmissions of crisis from these markets are more endemic in nature</p>

Table 5 continued

Transmission Blocks	DY	MHD	MHD-SVD
EC	<p>1. We find a resurgence in transmission for Germany during 2002–2004 similar to that of South Korea mentioned earlier.</p> <p>2. France and UK transmissions amplify in the advent of the eurozone crisis, while remaining neutral in earlier crises.</p> <p>3. Australian transmissions slightly amplify during the GFC and export crisis. Dampening prevails in the transitions between crises.</p> <p>4. Chinese transmissions amplify mostly with the recent Chinese crisis. Earlier, Chinese transmissions amplify only during the GFC.</p>	<p>1. With Germany we again find negative transmissions across 2002–2004, rejecting DY depiction. This is similar to South Korean transmissions mentioned in the earlier cluster.</p> <p>2. Consistent with DY, MHD shows positive transmission across the eurozone crisis preceded by a negative dampening during the GFC for both France and the UK.</p> <p>3. MHD is consistent with DY for Australia.</p> <p>4. The findings are similar to DY.</p>	<p>1. Most in this cluster turn more epidemic, especially following the onset of Eurozone crisis. In contrast, short-lived volatility rises profoundly for China and Australia, corresponding to the Chinese crash</p> <p>2. Importantly, the patterns in Fig. 17 outline that the transmissions from this cluster are, on average, epidemic in the cooling-off period from the eurozone crisis. Soon after, markets revert to being endemic to varying degrees</p>

Table 5 continued

Transmission Blocks	DY	MHD	MHD-SVD
GIIPS	<p>1. Transmissions amplify for Greece, Portugal and Spain with the eurozone and Greek crises. Recently, Ireland transmissions ascend following a descend.</p> <p>2. Italy shows escalating transmissions facing the recent export shrinkage.</p>	<p>1. Greek transmission shows small surges in the positive direction, followed by strong negative dampening, mostly during the eurozone. In contradiction to DY, the strongest surges for Portugal and Ireland are found during the GFC.</p> <p>2. Portugal transmissions remain neutral to dampening. Unlike DY, the positive and negative estimates offset strong amplifications for Portugal.</p>	<p>1. Risk transmissions from this cluster appear not highly epidemic. Strong volatility sways simultaneously over Ireland and Greece following on from when the first Greek austerity measures are adopted</p> <p>2. Figure 18 highlights that in the most recent periods, Belgium and Austria cast off some risks at an epidemic level. These markets are not included in the sample markets of DY-GHD. However, this demonstrates peripheral markets not studied highly as GIIPS may cast off significant contagion, as captured well in the current model</p>
		<p>3. As the Greek crisis unfolds, positive transmissions resurge for Spain, Portugal, Ireland. This is not well identified with DY.</p>	

Table 5 continued

Transmission Blocks	DY	MHD	MHD-SVD
OED	<p>1. We find the strongest transmissions for the USA and Japan during the dotcom bubble. Transmissions resurge during the GFC and Greek crisis for the USA. Japanese transmissions decelerate during this period only to amplify in the post-GFC period, possibly corresponding to global export shrinkage coupled with oil flat. Crucially, transmissions are reduced with the inclusion of oil and commodity indices.</p> <p>2. Russian transmissions amplify in all major events across the sampling periods, leading to a phenomenal jump facing the recent Russian financial crisis of 2014–2015. Inclusion of oil and commodity indices slightly dampen the transmissions.</p> <p>3. The transmissions for both Canada and Norway sharply descend, corresponding to a dramatic decline in global oil prices immediately after climbing to an apex in the post-GFC period. For both these markets, oil and commodity inclusion reduces transmission levels.</p> <p>4. Gyration in the transmissions of New Zealand do not show sharp oscillations.</p>	<p>1. The anticipated ‘conduit effect’ of the USA and Japan (BIS 1998), which drives transmissions up from the USA, Japan to other countries and is supported in earlier studies, is dismissed with MHD. We identify dampening for the USA market during the dotcom bubble. Conversely, dampening in transmissions from the Japanese markets is preceded by a strong amplification during the dotcom bubble, suggesting the ‘conduit effect’ may still hold for Japan. The dampening for Japan is attributable to the debt crisis predominating during that period.</p> <p>2. Risk transmission from Russia remains strongly positive for the most part, with exceptions only during the advent of the GFC and Russian crisis of 2014–2015.</p> <p>3. The patterns accord well with the DY findings for both Canada and Norway. Additionally, the Norwegian market shows neither a dramatic dampening nor sharp amplification in its transmissions across the sample period, and the DY estimates may have misrepresented the degree of transmissions for Norway.</p> <p>4. The transmissions that New Zealand emit are predominantly near its mean. Except for a few spikes following the GFC and GC, New Zealand transmissions remain neutral to other major crises or volatility shocks.</p>	<p>1. Risk transmission stemming from locally induced volatility can be attributable to the USA, Russia, Mexico and Norway, especially following the recent Russian economic crisis and oil supply shock. In contrast, Japan, New Zealand and Canada are passing risks on to others in the network, without inflicting locally induced volatility in the process. Hence, we can refer more to these markets as ‘conduits’ than to others in recent years</p> <p>2. In the post-Chinese crisis, Japanese and New Zealand transmissions might become more pandemic than endemic</p>

Table 5 continued

Transmission Blocks	DY	MHD	MHD-SVD
OEE	<p>1. Transmissions peak during the GFC and export shrinkage for the Saudi Arabian market. Oil inclusion causes an overall drop in the transmission curve for this market.</p> <p>2. We identify transmissions amplifying with the onset of Iraq invasion for Israel. Transmissions from this market resurge again as the Greek debt crisis rolls into a full-fledged eurozone crisis.</p> <p>3. While Iraq's invasion of Kuwait does not decelerate the transmissions emitting from Iraq, this leads to the complete nullification of transmissions from Kuwait. A substantial amplification of transmission from Iraq in the ensuing GFC is identified with DY.</p> <p>4. Among the non-Middle Eastern OEE countries' markets, the Nigerian market shows sufficiently proximate contemporaneous small surges in transmission across the years spanned by our samples, and Venezuelan transmissions soar facing the export shrinkage.</p>	<p>1. Despite positive transmissions during the GFC complementing the findings of DY for Saudi Arabia, the transmissions are predominantly negative except for the GFC.</p> <p>2. Neutral to positive Israeli transmissions span the entire sample period, with small surges in the ensuing export shrinkage and stronger surges during Iraq invasion.</p> <p>3. DY fails to capture the strong amplifications in the Kuwait market with the Iraq invasion and export shrinkage. This suggests the Kuwait market is on the rebound as the Iraqi dominance subsides, becoming a central oil exporting partner in the periods that follow.</p> <p>4. DY patterns do not accord well with MHD for Nigeria and is not conducive to explaining fundamentals driving Nigerian market risk. DY fails to capture the dampening of Nigerian markets during the oil crisis following the Iraq invasion and also transmissions surging with the USA bubble. However, DY and MHD both identify the build-up of Venezuelan hyperinflation in the most recent period, as both show the unprecedented rise in transmissions from Venezuela.</p>	

upheavals in the global oil market influence the nature of New Zealand's contagion, more so than for other global events.

Comparing DY and MHD estimates, we further find that the USA and Japan are more susceptible to contagion risk transmissions than to the degree of risks they transmit themselves. The exaggeration of risk susceptibility is overlain with risks transpiring within, especially for the USA and Japan. Moreover, dismissing what is gauged from DY estimates regarding Russia, MHD substantiates Russian resilience spanning across the entire sample period. Additionally, Russian transmissions pick up in all major events. To a much lesser extent, this holds true for Norway as well.

Finally, turning to OEE countries' (i.e. Saudi Arabia, Israel, Iraq, Kuwait, Nigeria and Venezuela) markets, we conjecture these markets are not at all contagious by examining Figs. 5, 10, 15, 20 and 21. Although the countries in this cluster dominate the global oil market, an upheaval in the oil market increases market strength in these markets. Consequently, they demonstrate strong resilience in phases of price or supply shocks in the oil market.

In several occasions for the OEE cluster, DY estimates fail to produce convincing evidence that aligns with MHD. DY fails to capture the amplifications in vulnerability for Saudi Arabia corresponding to the advent of the GFC and the diminishing systemic risks emitting from Iraq. MHD captures this successfully. Further, more recently, DY fails to capture the increases in vulnerability for Venezuela, which is more sensible given the heightening of the Venezuelan economic crisis, but is depicted in the MHD curves. With MHD, we disentangle the spikes in volatility transmissions for Kuwait, which naturally responds to the Iraq invasion and oil supply shock. In both cases, confidence build-up occurs dramatically in the Kuwait market. Again, DY fails to capture the dampening of Nigerian systemic risk transmission with the oil price crash following the Iraq invasion. On balance, we provide evidence of MHD better capturing larger effects on the economy than DY.

In Sects. 5.1 and 5.2, we discuss the insights into a global economic crisis facing the Covid-19 pandemic. The insights are generated using proposed methods in the current paper, and we provide a rationale regarding the recent surge in speculation around china as a potential crisis source and explore whether there is enough evidence aligning with these postulations. Due to the strong connection between speculations around these areas of discussion, it is reasonable to argue that our models simultaneously focus on the following two related areas of study.

5.1 Covid-19 and crisis transmission

The Covid-19 trends are nested with parent risk dynamics presented in Figs. 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10. From the DY dynamics, spikes emerge during June 2019 financial year for India, Malaysia and Thailand that dampens in June 2020. The Philippines transmission is consistently high since 2018, which has also slowed down recently. The South Asian crisis markets show extreme vulnerability since 2018 that has spiked again recently. South Korean transmission was relatively controlled, while it remained highly vulnerable. However, MHD demonstrates a consistently high trans-

mission from South Korea, as opposed to DY. This unveils an increasingly risky South Asian market dynamics since 2018.

In contrast, as we shift our attention to global exporters, DY shows China remaining both high transmitter of shocks and yet the most vulnerable, similar to France. While Australia and the other major global exporters demonstrate a dampening shock transmission, vulnerability spikes since the beginning of the 2020 financial year. With MHD analysis, we uncover that China and Germany show negative vulnerability in the 2020 financial year. On the other hand, UK and Australia both exhibit a spike in both transmission and vulnerability to shocks from other stock markets.

Turning to GIIPS, interestingly, with DY we identify vulnerability drops for all except for Italy, while Greece and Ireland remain the highest transmitter of shocks in the most recent years. MHD detects a recent positive spike in vulnerability for Greece and Ireland, while significant positive spikes in vulnerability for Portugal and Spain are detected with MHD.

With DY, the developed markets demonstrate increasing vulnerability, that is especially true for the USA, Norway and Japan in 2020. In contrast, Russian resilience increases significantly during the same time. However, the results do not change with MHD for Japan. However, The USA and Canada depict a dampening in vulnerability in 2020 fiscal year and a decreasing Russian resilience.

The Middle eastern markets, especially the Saudi Arabia, Venezuela and Kuwait, show similar trend to the South Asian markets with DY, which demonstrates increasing vulnerability. Interestingly, with MHD, we detect negative vulnerability for the markets in Saudi Arabia, Kuwait and Iraq, with strong transmissions from these markets.

Overall, the markets mentioned above do not show aberrations to their risk transmission patterns identified prior to the grisly economic reality emerging with the Covid-19 scenario. Therefore, a drastic change in 'contagion' transmission dynamics is not expected. A detailed transmission and vulnerability pattern for the above markets can be found in Tables 1 and 2.

5.2 Identifying 'contagion'

A key contribution of the current paper is 'contagion' identification in the pool of markets from interconnection, for which crisis demarcation is not a necessary condition. While all interconnections and amplifications in the systemic risk that is found within this sample markets do not lead to contagion, contagion poses the unique threat of a financial pandemic. Hence, contagion is a necessary condition for a widespread crisis to ensue. We propose a tractable and simple technique to identify excessively contagious markets while the condition remains dynamic. Thus, a key question at this stage is, 'How diabolic is a contagious market today compared to the past?' In other words, are we going to experience a global meltdown similar to that of the GFC if a crisis is triggered from a contagious market?

From Fig. 21, we separate out Singapore, China, Australia and Japan as more contagious markets than the rest, especially in more recent times. Despite observing that the 2016 Chinese stock market crash sends shocks tumbling globally, the carnage is not as pronounced as in the GFC.

The models presented here shows that the Chinese stock market crash unfolding in January 2016 sets off a global rout, dragging down the stocks across the USA, Germany and rest of Europe and Brazil to 2 to 3%. Chinese economic growth plunges to 25-year low. Leading up to this, speculations and warnings reflected engendered fears of a global meltdown, including warnings issued by the International Monetary Fund (Mauldin 2017; Liang 2016; Mao 2009; Elliott 2017; Cheng 2017). The Chinese authority responded by imposing new trading curbs and devaluing currency. While commentators, including the China Securities Regulatory Commission, blamed surging speculation and irrational investment behaviour for sourcing the crisis, Mao (2009) suggested that the colossal shadow banking industry was responsible for heightening the risks in the Chinese markets much earlier. Presumably, potential risks are predominant in the shadow banks in China, which have quadrupled at an annual rate of 34% since 2008, and at that time the size of the Chinese shadow banks (US \$8 trillion) is equal to 4.3% of Chinese GDP (Mao 2009). Liang (2016) asserted that the burgeoning shadow economy, amidst the goal of boosting productivity against an overall drop in the labour market, posed a high risk to the financial stability of China given its current regulatory framework.

We do not experience a replay of the 2008 GFC. Recently, Dungey et al. (2020) provided evidence of no new systemic crises emerging from China to other global markets given the resurgence in systemic risk. While our study purports to identify sources of crisis, the case for China is particularly interesting. Generally, the results capture a unique case of shadow banking and securitisation. There is a plethora of studies showing bank securitisation leads to higher systemic risks, while increasing bank profitability and ensuring a buffer of liquidity for the bank (Adrian and Shin 2009; Uhde and Michalak 2010; Nijskens and Wagner 2011; Nadauld and Weisbach 2012; Georg 2013; Battaglia et al. 2014; Bakoush et al. 2019). Although securitisation allows banks to shed their own idiosyncratic risks into financial markets and confirms a buffer of liquid assets coupled with higher profitability, a vicious cycle forms as banks' exposure to credit risk intensifies. The shadow banking industry is evolving to retain risks while pursuing regulatory arbitrage by means of retaining rollover risks pertaining to maturity mismatch. These pose a significant threat for the sponsors assuming these risks. In effect, conduits are attributed with systemic risk involving commercial banks, insurance institutions and equity market components. This also explains the USA or other advanced markets posing no significantly new threat in recent times, partly because the post-2008 credit crisis saw several restrictions imposed on banking securitisation, particularly in advanced economies. The Association for Financial Markets in Europe (2017) reported a significant reduction in securitisation activities within 10 years, especially for the USA and European banks. Evidently, this has impaired the capital and profitability of these banks, as suggested by the Bank for International Settlement (2018).

Moreover, we do not observe a re-emergence of global meltdown from China or other contagious markets because of the structural differences between cross-border capital diffusion to what was occurring with the USA during the GFC. Shirai and Sugandi (2018) reported that Hong Kong, Japan and Singapore are the major financiers of cross-border capital in the Asia–Pacific economies. While Singapore has the largest financial centres and is also the largest equity investor to the People's Republic of China

(PRC), Japan, Republic of Korea (ROK), and others in the Association of Southeast Asian Nations, Japan invests largely in Australian debt securities. Conversely, Hong Kong invests mostly in the equities issued by the PRC.

Issuing US\$3.5 trillion cross-border portfolio assets, Japan's exposure to the Asia-Pacific region is mostly through Australia (US\$572 billion) and vice versa. Despite this, the Asian Bond Funds administered and managed by banks for international settlement exclude Australia, Japan and New Zealand. The Asian Bond Funds ABF1 and ABF2 were introduced to develop the sovereign and quasi-sovereign bond markets dominated by the USA dollar and local markets, respectively. However, these countries are the main pathway for the USA and EU to invest in the region. Hence, 60% of the total shares issued in the USA and EU forms the cross-border portfolio for Japan, Australia and the ROK in the region establishing a strong bridge between the continents. Singapore is the largest investor in shares issued by the USA and EU. While the cross-border portfolio assets of Hong Kong, China, sum up to US\$1.1 trillion, its portfolio shares mostly concentrate on the PRC (50%) followed by the Association of Southeast Asian Nations-5 (37%). The USA and EU shares constitute only 24% of the cross-border portfolio trading in Hong Kong, China. Hong Kong invests US\$404 billion in the PRC-issued shares, compared with US\$235 billion by Japan and US\$218 billion by Singapore. Hong Kong has only US\$99 billion invested in USA assets and US\$165 billion invested in EU assets. In contrast, Australian foreign assets include 42% USA-issued securities, with only 26% from the EU (Shirai and Sugandi 2018).

In terms of cross-border portfolio liabilities, 73% of Japan's total cross-border portfolio liabilities (US\$1.7 trillion) are financed by the USA and EU, while the USA and EU finances 33% and 29%, respectively, of total liabilities of Australia (US\$966 billion). Interestingly, while the USA and EU finances 66% of the total cross-border portfolio liabilities of Hong Kong (US\$390 billion), Hong Kong finances 42% of the total liabilities of the PRC (US\$710 billion). As a net debtor of cross-border portfolio investments to the world, Australia remains highly exposed to the USA and EU, which account for over 70%. Since 2001, for Japan, Australia also remains its biggest investment destination, increasing investing into Australia by four times (US\$118 billion) in the post-GFC. The foreign portfolio asset and liabilities of Hong Kong and Singapore exceed that of Japan in the post-GFC, and for Hong Kong these grow by 157% and 142%, respectively (Shirai and Sugandi 2018).

In summary, as highly contagious markets, Japan and Singapore are not causing widespread crisis, as no crisis is revealed in these markets, or in the USA or EU in more recent times. In fact, the restrictions applied in the USA securitisation induce calmness in these markets. Hence, we are also observing calmness in the Australian markets. However, given the degree of exposure to each other and connectivity between these markets, a large enough shock in any of these markets may destabilise the other. In contrast, Hong Kong, China, concentrates investments mostly in the PRC. As both the economies are part of the PRC, this creates a closed-circuit transmitting wealth within. This is also a reason why the 2016 crash was absorbed mostly within the circuit and did not turn diabolical, despite having all the potential. In fact, this allows the central Chinese authorities to apply new restrictions, such as short selling bans or bans on stock investments as appeared in 2015, without inciting a global response.

6 Conclusion

In this paper, we have identified excessively contagious and more volatile markets relying on time-varying systemic risk in an associated network of markets. We began by exploring the transmission of risks and vulnerability to risks spanning across the sample period of nearly 20 years with DY return measures (DY), a well-known method proposed by Diebold and Yilmaz (2012). Next, we estimated return spillovers with signed spillover measures computed with MHD proposed recently by Dungey et al. (2019) and concluded that signed spillover measures capture all or more information than DY spillover measures. Third, we estimated signed volatility transmissions and vulnerabilities computing from MHD and drew on realised variances from 5-min intraday returns. Finally, we plotted the differences between time-varying volatility and return spillover estimates, which showed the markets that are epidemic in the complex network structure and the markets that are endemic in nature but predominantly volatile with a higher core volatility. Hence, we have addressed the issue of over-identification in the degree of systemic risk, which the markets emit in calm and crisis periods

We found that misidentification of contagion issues is prevalent when explaining risk transmissions and the build-up of market resilience across time with the DY spillover method only. We addressed these issues by re-estimating systemic risks with MHD. In the absolute representation of time-varying DY spillover measure, we found that DY spillover overestimates the level of actual resilience building for South Korea, the Philippines, Singapore, Germany, China and Israel. This measure also overestimates the degree of risk transmissions coming from Iraq, Venezuela, the USA (prior to the GFC) and, more recently, Nigeria and Greece. While the DY underestimates Greek, Croatian and Russian resilience building in recent years, it also underestimates the risks emanating from Kuwait, South Korea and Germany. Severe changes in market micro-structure corresponding to profound economic degradation is rather misrepresented as resilience building with DY for its absolute representation of spillovers. We found this holds for both Iraq and Venezuela. The signed spillover estimates captures the convergence in the swings of systemic risks as the economies in both the countries collapse.

We showed the separated influence of stochastic local volatility as opposed to the actual degree of systemic risks within a market. First, a market is not likely to be transmitting shocks and remain vulnerable at the same time. Moreover, during high-risk transmissions, markets turn more resilient or vice versa. However, it is more likely that high transmissions lead to a phenomenal increase in vulnerability for the market to negative in-shocks transpiring within the network. Second, in the amplification of total risk generation with the accumulation of self-exciting intraday local volatility added to systemic risks coming from the network, markets respond by casting off 'excess volatility' onto others. In other words, it is likely that a highly volatile market gives strong episodes of risk transmission at the start of an event without becoming an epidemic market. Nevertheless, such spikes may accompany a fall in the local market, as outlined in Bates (2019).

Complementing the work of Dungey and Renault (2018), our technique identified the degree of systemic risks free of simultaneous volatility increases accompanying a rise in volatility in common factors and may have various contributions to the field of

economics and machine learning. First, it may enable managers of risk to better rebalance portfolios, parsing information concerning epidemic and non-epidemic elements in the portfolio. Supervisors may find it useful to understand risks coming with big links, and to target issues amplifying risks. Machine-learning enthusiasts may find it interesting to feed forward networks of markets scaled with proper degrees of systemic risk indices. Further, Bayesian priors can be generated weighted with amplifications and dampening in signed risk estimates, and predictability of market risks can be improved. In all, the methods combined not only serve a purpose by producing comparisons, but produce better information regarding a market’s susceptibility to realised crashes and volatility evolution.

We attempted to explore complex market associations spanning across the last two decades, encapsulating major global events across many markets including the ongoing global economic crisis as a direct result of Covid-19 pandemic. The markets were selected to represent dynamic shifts that each subsequent event provides and were then grouped into a closed system. As with the precursors of systemic risk studies, limitations arose from the limited intraday data availability for the Middle Eastern markets. However, we substituted with additional markets that depicted a similar pattern. Alternatively, a target should be an investor sentiment analysis corresponding to risk patterns, leading to a better understanding of strong amplifications in risk propagation.

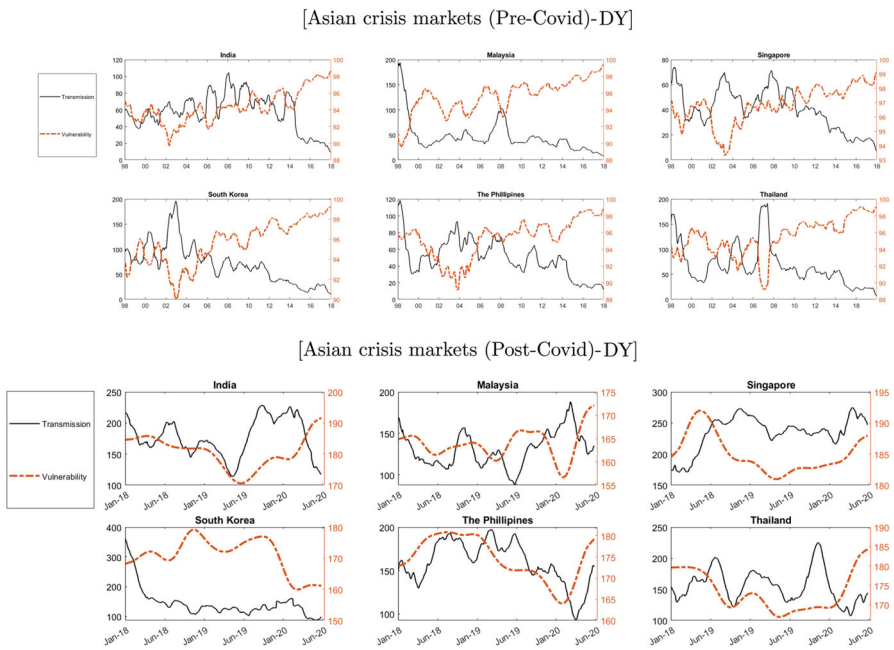


Fig. 1 Asian crisis markets—DY analysis

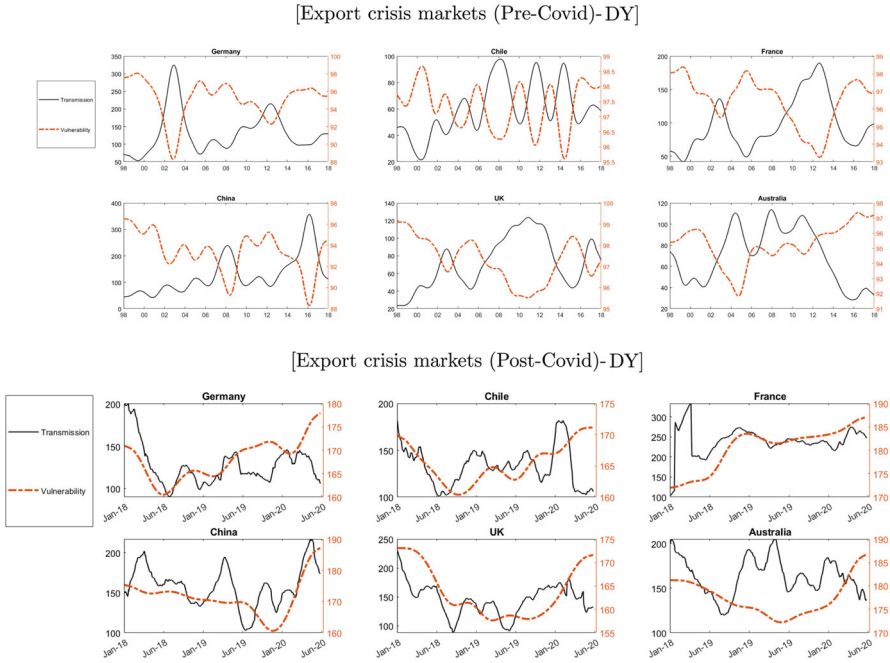
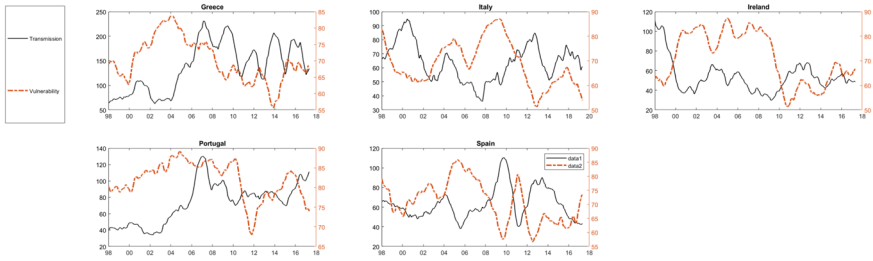


Fig. 2 Export crisis markets—DY analysis

Appendix

[GIIPS markets (Pre-Covid)-DY]



[GIIPS markets (Post-Covid)-DY]

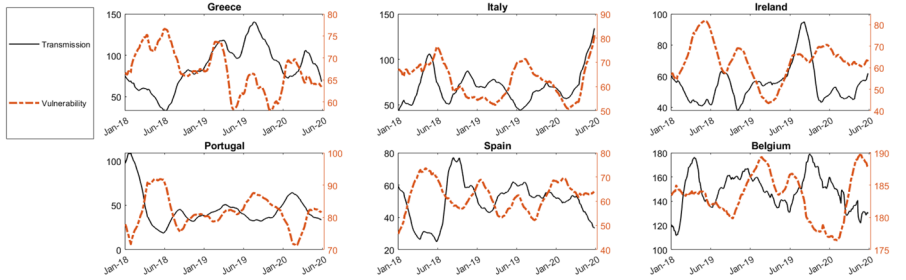
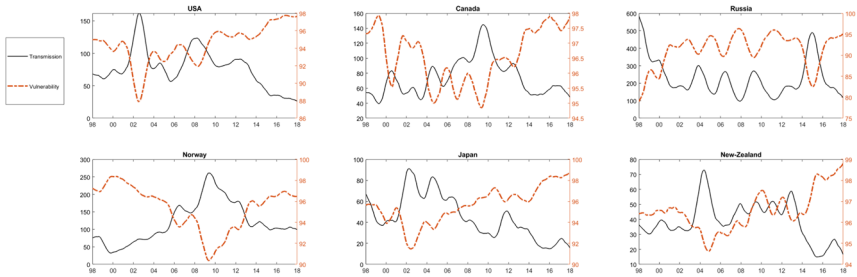


Fig. 3 GIIPS markets—DY analysis

[OED markets (Pre-Covid)-DY]



[OED markets (Post-Covid)-DY]

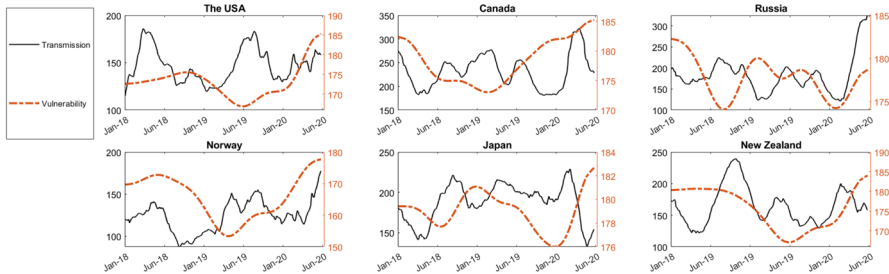


Fig. 4 Oil exporting developed markets—DY analysis

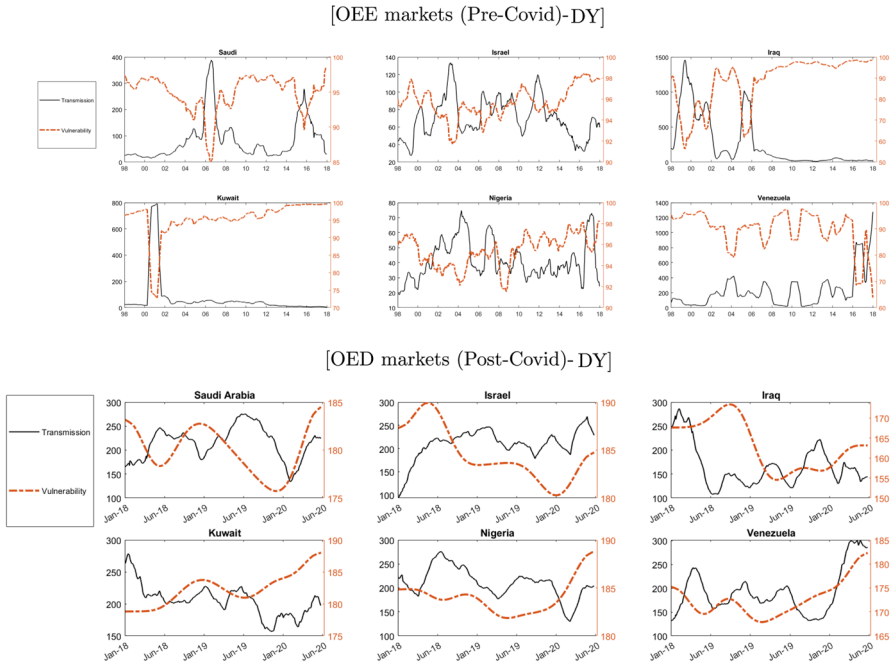


Fig. 5 Oil exporting emerging markets—DY analysis

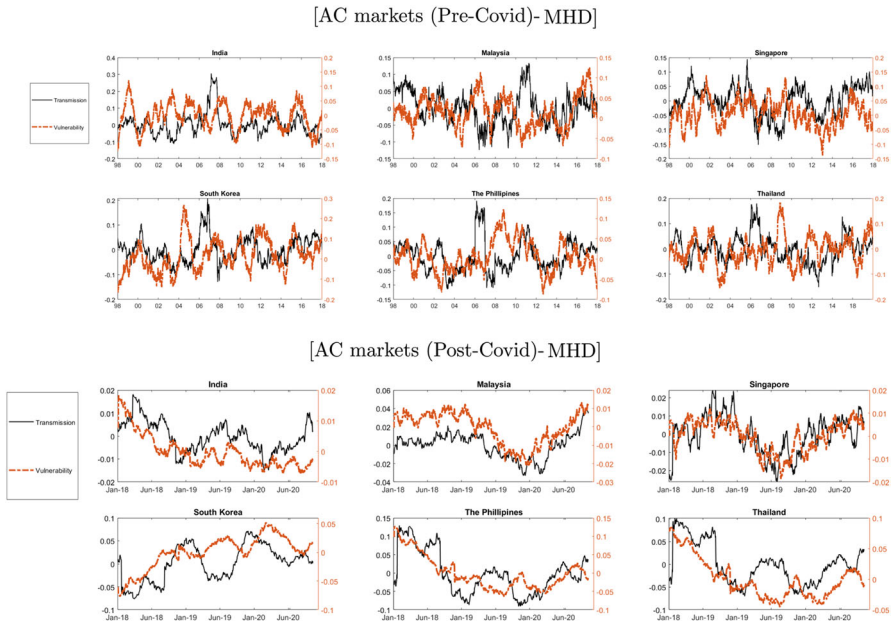


Fig. 6 Asian crisis markets—MHD analysis

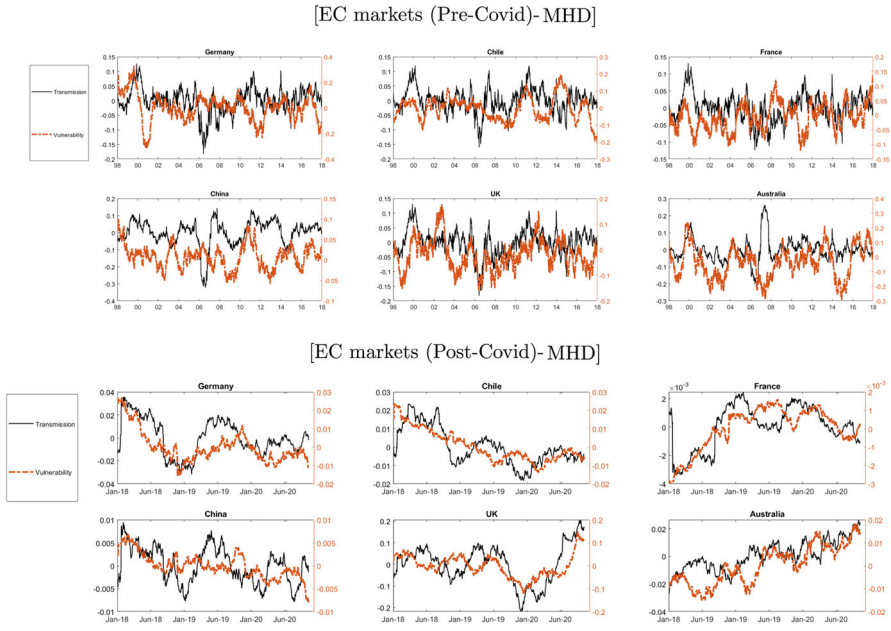


Fig. 7 Export crisis markets—MHD analysis

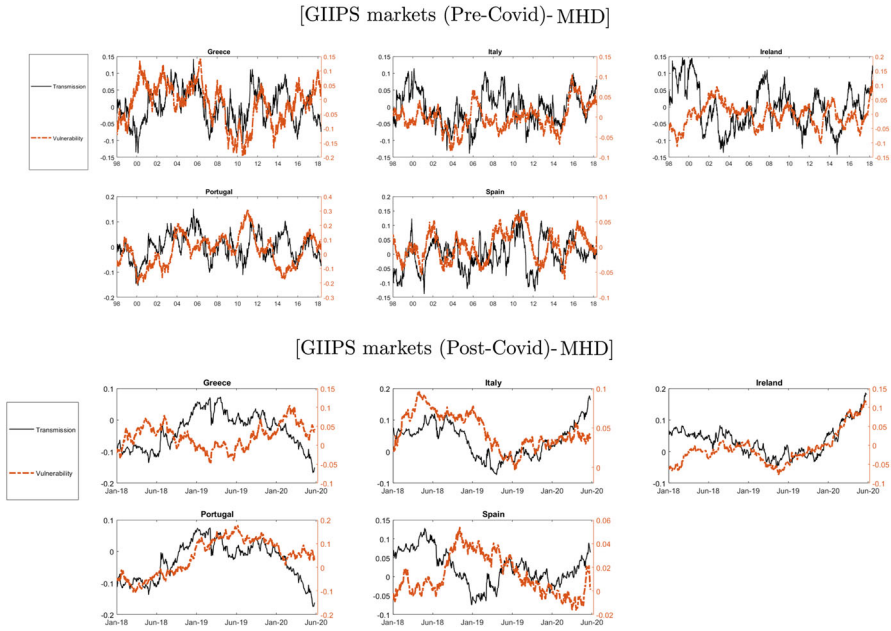


Fig. 8 GIIPS markets—MHD analysis

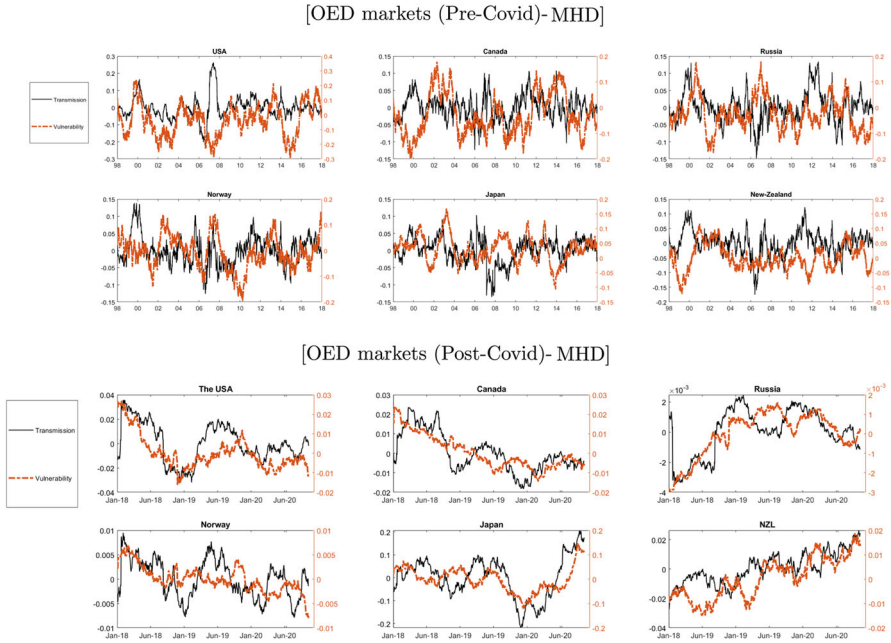


Fig. 9 Oil exporting developed markets—MHD analysis

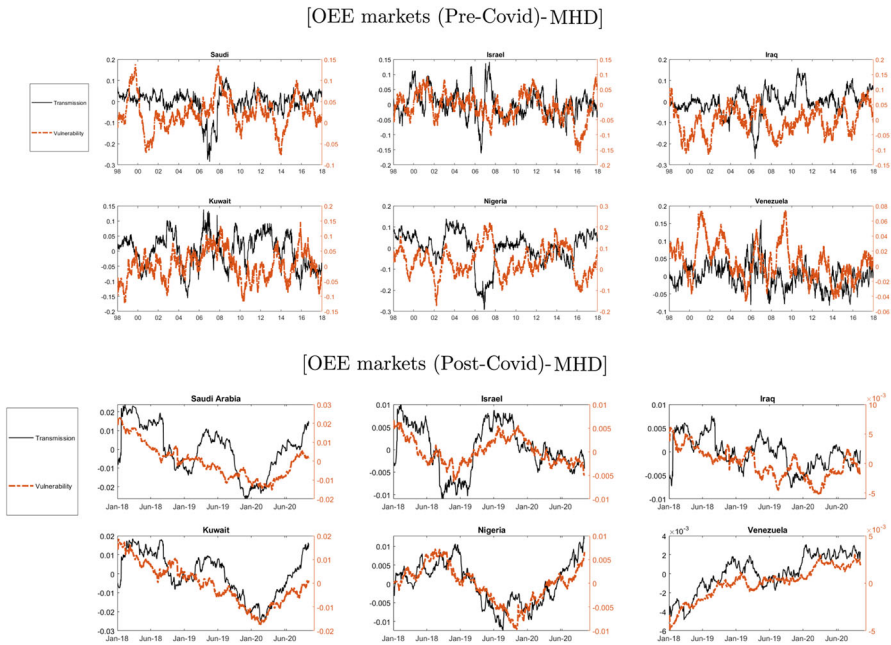


Fig. 10 Oil exporting emerging markets—MHD analysis

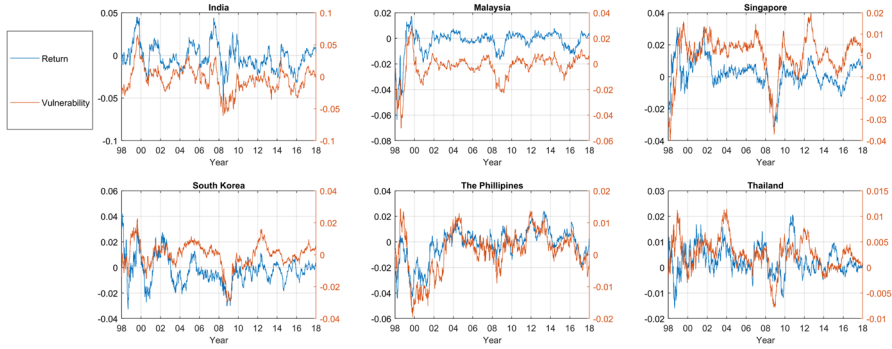


Fig. 11 MHD and SVD vulnerabilities: Asian crisis market. *Note:* This figure shows the signs of in-shocks sourced from the Asian crisis countries’ markets to targets listed in the AC cluster gauged in signed spillover index and the signed volatility index

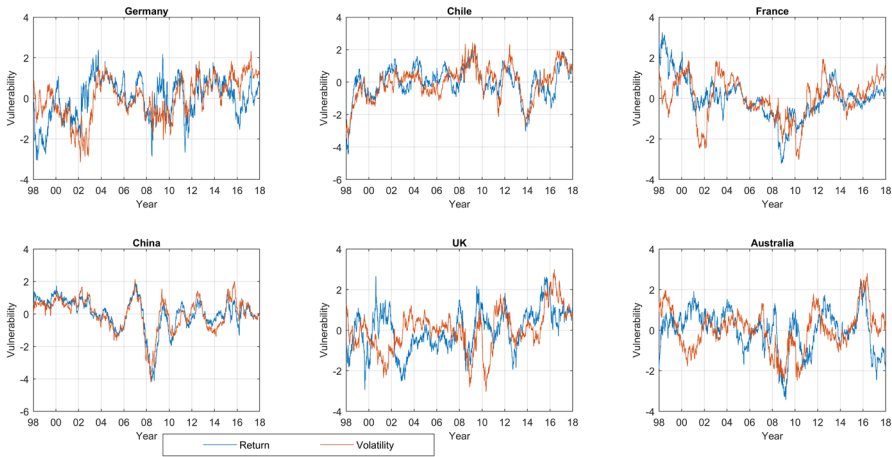


Fig. 12 MHD and SVD vulnerabilities: export crisis market. *Note:* This figure shows the signs of in-shocks sourced from export crisis countries’ markets targets listed in the EC cluster gauged in signed spillover index and the signed volatility index

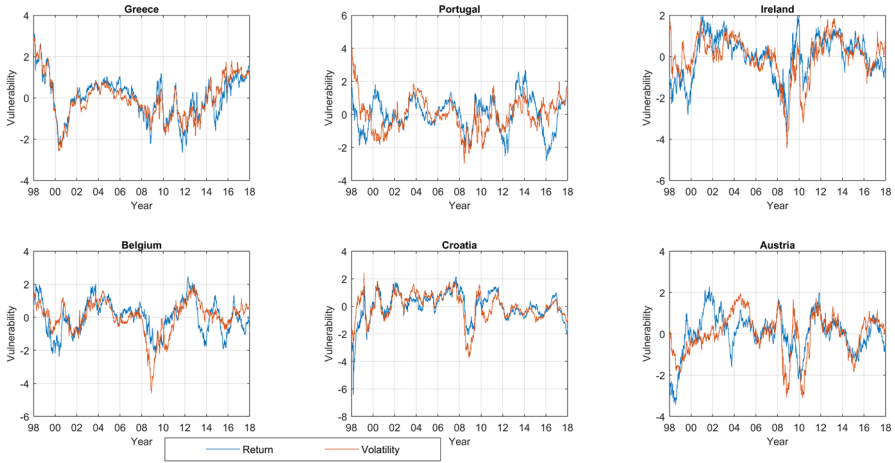


Fig. 13 MHD and SVD vulnerabilities: Greek crisis market. *Note:* This figure shows the signs of in-shocks sourced from Greek crisis countries' markets targets listed in the GIIPS cluster gauged in signed spillover index and the signed volatility index

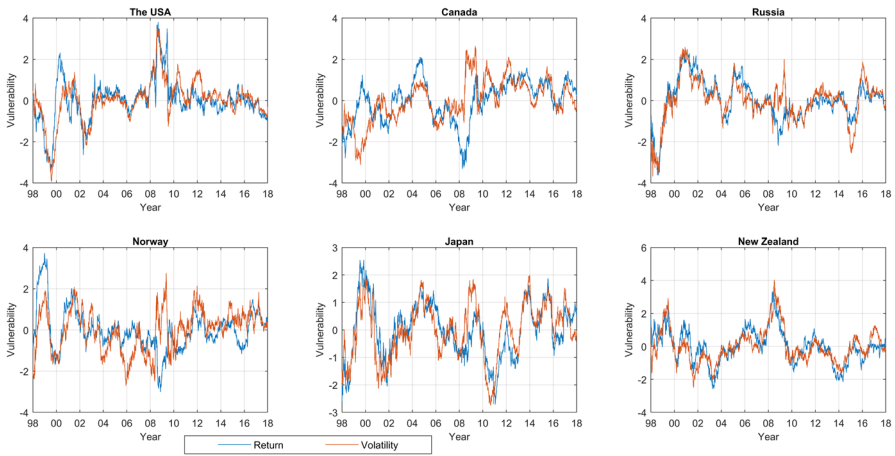


Fig. 14 MHD and SVD vulnerabilities: oil exporting developed countries' markets. *Note:* This figure shows the signs of in-shocks sourced from oil exporting developed countries' markets targets listed in the OED cluster gauged in signed spillover index and the signed volatility index .

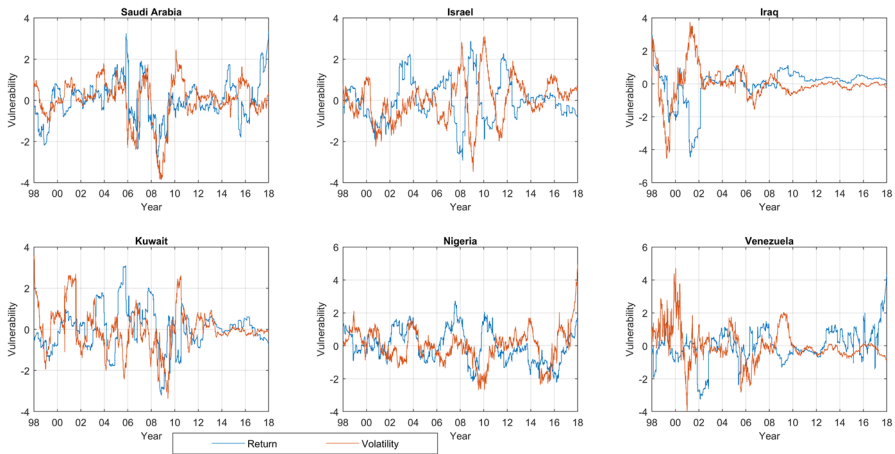


Fig. 15 MHD and SVD vulnerabilities: oil exporting emerging countries’ markets. *Note:* This figure shows the signs of in-shocks sourced from oil exporting emerging countries’ markets targets listed in the OEE cluster gauged in signed spillover index and the signed volatility index

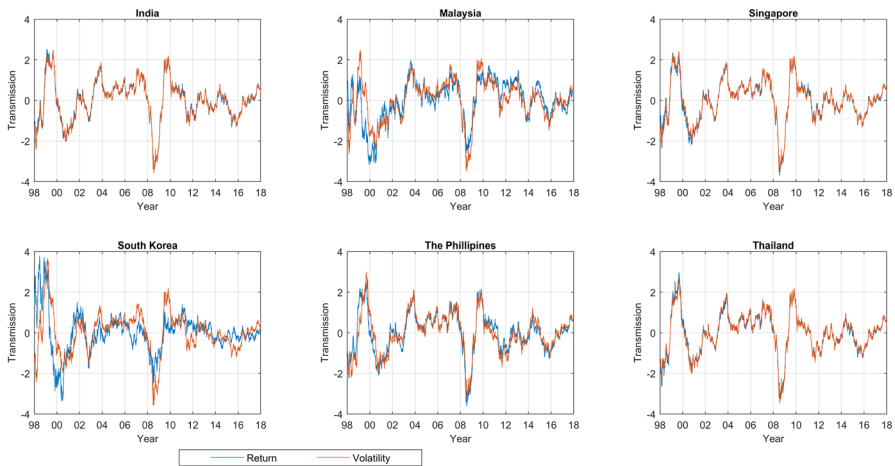


Fig. 16 MHD and SVD transmission: Asian crisis countries’ markets. *Note:* This figure shows the effects of out-shocks sourced from Asian crisis countries’ markets to recipients listed in the AC cluster gauged in signed spillover index and the signed volatility index

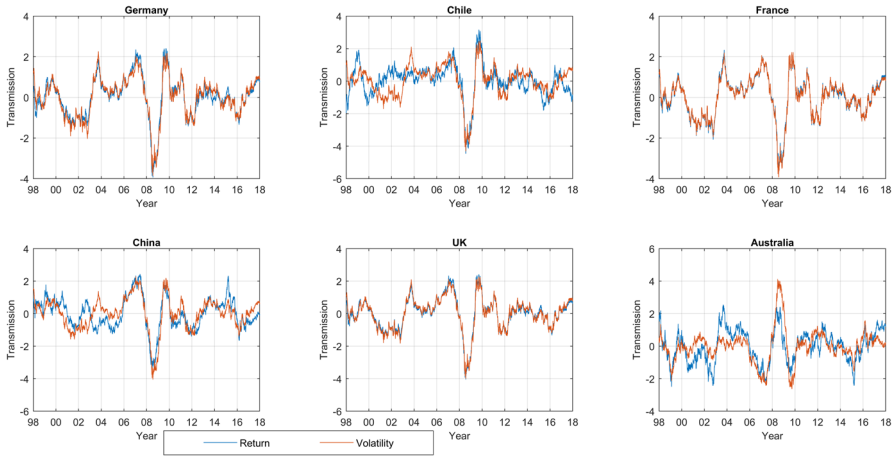


Fig. 17 MHD and SVD transmission: export crisis countries' markets. *Note:* This figure shows the effects of out-shocks sourced from Export crisis countries' markets to recipients listed in the EC cluster gauged in signed spillover index and the signed volatility index

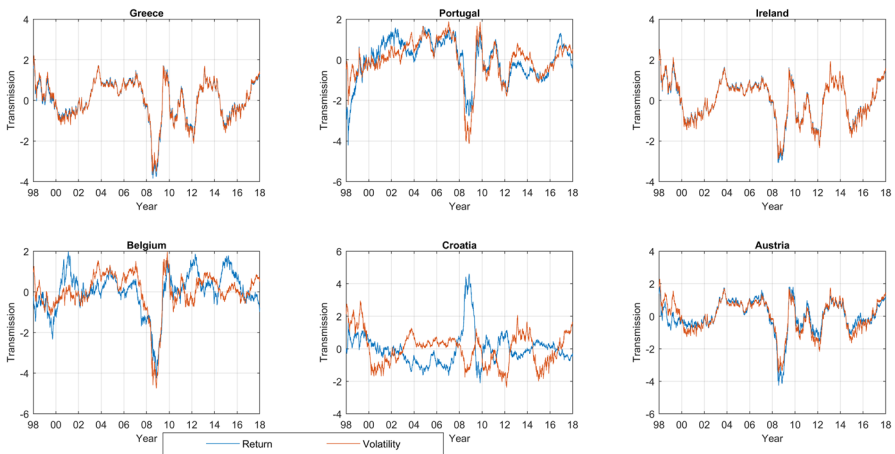


Fig. 18 MHD and SVD transmission: Greek crisis countries' markets. *Note:* This figure shows the effects of out-shocks sourced from Greek crisis countries' markets to recipients listed in the Greek crisis cluster gauged in signed spillover index and the signed volatility index

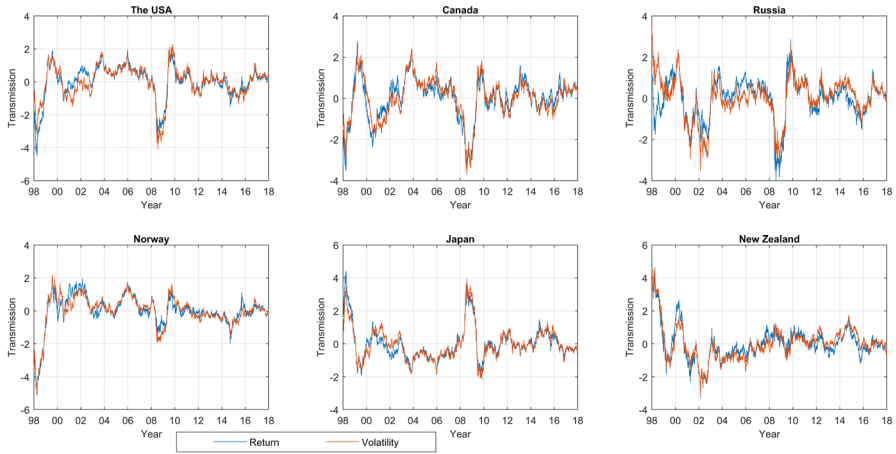


Fig. 19 MHD and SVD transmission: oil exporting developed countries' markets. *Note:* This figure shows the effects of out-shocks sourced from oil exporting developed countries' markets to the recipients listed in OED cluster gauged in signed spillover index and the signed volatility index

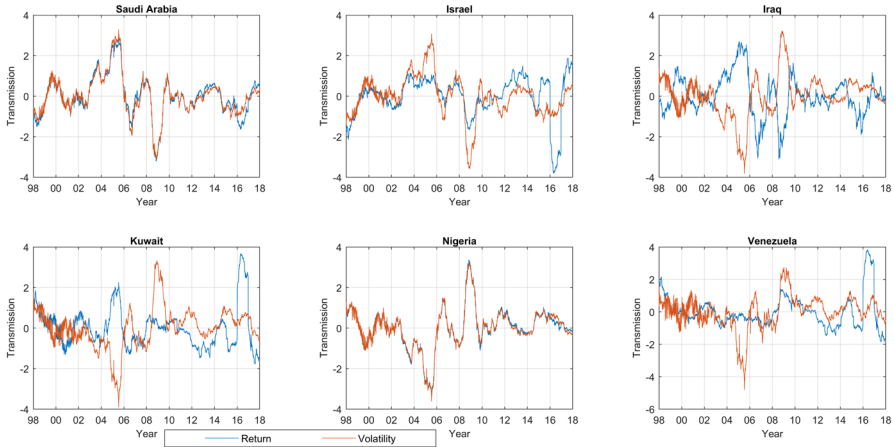


Fig. 20 MHD and SVD transmission: oil exporting emerging countries’ markets. *Note:* This figure shows the effects of out-shocks sourced from oil Exporting emerging countries’ markets to recipients listed in the OEE cluster gauged in signed spillover index and the signed volatility index

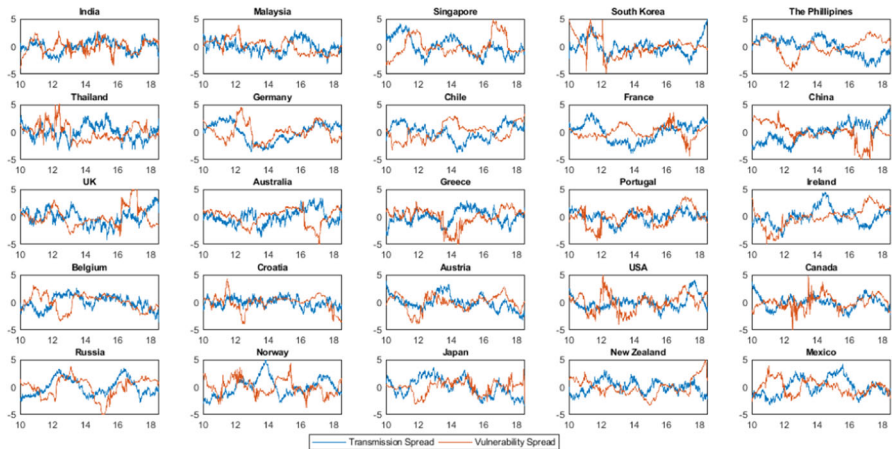


Fig. 21 The SVD-MHD spread: this SVD-MHD spread figure focuses out contagious markets from non-contagious markets by drawing on estimated differences between the MHD and SVD gauges

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