Measuring the Connectedness of the Global Economy
Technical Annex

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A.1 Introduction

This Annex provides supplementary information for *Measuring the Connectedness of the Global Economy* by Matthew Greenwood-Nimmo, Viet Hoang Nguyen and Yongcheol Shin. It proceeds in four sections. Section A.2 outlines the specification of the GNS25 model, which is an updated version of the GVAR model analysed by Greenwood-Nimmo et al. (2012). Detailed notes on the construction of the GVAR link matrices using bilateral trade data are also provided. Section A.3 provides further details on the aggregation schemes used in the paper to evaluate connectedness among countries and groups of common variables. Section A.4 provides a detailed description of the construction of the dataset including a comprehensive list of data sources and full details of the transformations that have been applied to the data.

A.2 The GNS Global Model

Greenwood-Nimmo, Nguyen and Shin (2012, GNS) develop a global VAR model consisting of 26 countries with a total of 176 variables. In the current paper, we employ an updated version of this model (henceforth the GNS25 model) which differs from the original in two respects:

(i) The GNS25 model excludes Argentina, as this proves necessary to ensure dynamically stable solutions once the sample period is extended to include the crisis period. The stability issues encountered in the original 26 country model seem to be rooted in the unstable time series behaviour of the Argentine inflation, interest rate and equity price data, which may experience multiple structural breaks during our sample period.

(ii) The global covariance matrix in the GNS25 model is estimated with greater precision by excluding any covariance terms which are found to be insignificant using the weak cross section dependence test of Pesaran (2004).

In all other respects, the GNS25 model is identical to that of Greenwood-Nimmo et al. (2012). As such, the GNS25 model contains 169 endogenous variables covering 25 countries/regions that collectively account for the large majority of global trade and output. The 25 countries are (1) USA; (2) Eurozone; (3) Japan; (4) UK; (5) Norway; (6) Sweden; (7) Switzerland; (8) Canada; (9) Australia; (10) New Zealand; (11) South Africa; (12) Brazil; (13) Chile; (14) Mexico; (15) India; (16) Korea; (17) Malaysia; (18) Philippines; (19) Singapore; (20) Thailand; (21) China; (22) Indonesia; (23) Peru; (24) Turkey; and (25) Saudi Arabia.

A.2.1 Country-Specific Models

The first step in constructing the GNS25 model is to estimate a country-specific VARX* model for each country in the system. Consider a global economy consisting of N economies, indexed by $i = 1, 2, .., N$. Denote the country-specific variables by an $m_i \times 1$ vector $\boldsymbol{y}_{it}$ and the country-specific foreign variables by an $m_i^* \times 1$ vector $\boldsymbol{y}_{it}^* = \sum_{j=1}^{N} w_{ij}\boldsymbol{y}_{jt}$, where $w_{ij} \geq 0$ is the set of granular weights with $\sum_{j=1}^{N} w_{ij} = 1$, and $w_{ii} = 0$ for all i. The country-specific VARX* $(2, 2)$ model can be written as:

$$\begin{aligned} \boldsymbol{y}_{it} &= \boldsymbol{h}_{i0} + \boldsymbol{h}_{i1}t + \boldsymbol{\delta}_{i0}d_{it} + \boldsymbol{\delta}_{i1}d_{i,t-1} + \boldsymbol{\delta}_{i2}d_{i,t-2} + \boldsymbol{\Phi}_{i1}\boldsymbol{y}_{i,t-1} \\ &+ \boldsymbol{\Phi}_{i2}\boldsymbol{y}_{i,t-2} + \boldsymbol{\Psi}_{i0}\boldsymbol{y}_{it}^* + \boldsymbol{\Psi}_{i1}\boldsymbol{y}_{i,t-1}^* + \boldsymbol{\Psi}_{i2}\boldsymbol{y}_{i,t-2}^* + \boldsymbol{u}_{it}, \end{aligned} \tag{A.1}$$

where d_{it} is a country-specific intercept-shift dummy variable which captures country-specific structural breaks (if any). The choice of whether or not to include an intercept shift dummy for a given country takes account of both statistical evidence derived from the CUSUM test statistics developed by Brown et al. (1975) as well as anecdotal evidence on macroeconomic events that are likely to have contributed to structural changes in specific countries/regions. Examples of such events include the 1997 Asian currency crisis and the South American hyperinflation of the 1980s. The dummy variable, d_{it}, follows the same lag structure as the continuous variables in the model. The dimension of $\boldsymbol{h}_{ij}$ and $\boldsymbol{\delta}_{ij}$, $j = 0, 1, 2$, is $m_i \times 1$ while the dimensions of $\boldsymbol{\Phi}_{ij}$ and $\boldsymbol{\Psi}_{ij}$, $j = 0, 1, 2$, are $m_i \times m_i$ and $m_i \times m_i^*$. As usual, we assume that $\boldsymbol{u}_{it} \sim iid\,(0, \boldsymbol{\Sigma}_{ii})$ where $\boldsymbol{\Sigma}_{ii}$ is an $m_i \times m_i$ positive definite matrix.

Assuming that the country-specific foreign variables are weakly exogenous (an assumption which is borne out by formal tests as documented below), the VECM associated with (A.1) can be written as follows:

$$\begin{aligned} \Delta\boldsymbol{y}_{it} &= \boldsymbol{c}_{i0} + \boldsymbol{c}_{i0}^*\Delta d_{it} + \boldsymbol{c}_{i1}^*\Delta d_{i,t-1} + \boldsymbol{\Lambda}_i\Delta\boldsymbol{y}_{it}^* + \boldsymbol{\Gamma}_i\Delta\boldsymbol{z}_{i,t-1} \\ &+ \boldsymbol{\alpha}_i\boldsymbol{\beta}_i'\left(\boldsymbol{z}_{i,t-1} - \boldsymbol{\mu}_i d_{i,t-1} - \boldsymbol{\gamma}_i\,(t-1)\right) + \boldsymbol{u}_{it}, \end{aligned} \tag{A.2}$$

where $\boldsymbol{z}_{it} = (\boldsymbol{y}_{it}', \boldsymbol{y}_{it}^{*\prime})'$, $\boldsymbol{\alpha}_i$ is an $m_i \times r_i$ adjustment matrix of rank r_i and $\boldsymbol{\beta}_i$ is an $(m_i + m_i^*) \times r_i$ cointegrating matrix of rank r_i. Notice that (A.1) can be rewritten in terms of $\boldsymbol{z}_{it}$ as:

$$\boldsymbol{A}_{i0}\boldsymbol{z}_{it} = \boldsymbol{h}_{i0}^* + \boldsymbol{h}_{i1}t + \boldsymbol{A}_{i1}\boldsymbol{z}_{i,t-1} + \boldsymbol{A}_{i2}\boldsymbol{z}_{i,t-2} + \boldsymbol{u}_{it}, \tag{A.3}$$

where $\boldsymbol{h}_{i0}^* = \boldsymbol{h}_{i0} + \boldsymbol{\delta}_{i0}d_{it} + \boldsymbol{\delta}_{i1}d_{i,t-1} + \boldsymbol{\delta}_{i2}d_{i,t-2}$, $\boldsymbol{A}_{i0} = (\boldsymbol{I}_{m_i}, -\boldsymbol{\Psi}_{i0})$, $\boldsymbol{A}_{i1} = (\boldsymbol{\Phi}_{i1}, \boldsymbol{\Psi}_{i1})$, and $\boldsymbol{A}_{i2} = (\boldsymbol{\Phi}_{i2}, \boldsymbol{\Psi}_{i1})$. Note that the parameters of (A.3) can be obtained from those of (A.2) as $\boldsymbol{A}_{i0} =$

$(\boldsymbol{I}_{m_i}, -\boldsymbol{\Lambda}_{i0})$, $\boldsymbol{A}_{i1} = \boldsymbol{A}_{i0} + \boldsymbol{\Pi}_i + \boldsymbol{\Gamma}_i$, $\boldsymbol{A}_{i2} = -\boldsymbol{\Gamma}_i$, $\boldsymbol{h}_{i0}^* = \boldsymbol{c}_{i0} + \boldsymbol{c}_{i0}^* \Delta d_{it} + \boldsymbol{c}_{i1}^* \Delta d_{i,t-1} + (-\boldsymbol{\Pi}_i \boldsymbol{\mu}_i)\, d_{i,t-1}$, $\boldsymbol{h}_{i1} = -\boldsymbol{\Pi}_i \boldsymbol{\gamma}_i$ and $\boldsymbol{\Pi}_i = \boldsymbol{\alpha}_i \boldsymbol{\beta}_i'$.

The variables included in the GNS25 model are drawn from the following:

re_{it}	the real effective exchange rate
r_{it}	the short-term nominal interest rate
im_{it}	the log of real imports
ex_{it}	the log of real exports
q_{it}	the log of real equity prices
Δp_{it}	the rate of inflation
y_{it}	the log of real output
p_t^o	the log of the oil price

The weakly exogenous foreign variables are computed as weighted averages of the data for the remaining $(N-1)$ countries in the model. GNS adopt the convention of Dees, di Mauro, Pesaran and Smith (2007, DdPS) and define the weights using bilateral trade averages derived from the IMF's *Direction of Trade Statistics* over the period 1999-2001. As noted by GNS, the choice of weighting scheme does not exert a dominant influence over the model output. Following Dees, Holly, Pesaran and Smith (2007, DHPS), GNS define the log real effective exchange rate as $re_{it} = ee_{it} + p_{it}^* - p_{it}$, where $ee_{it} + p_{it}^* - p_{it} = (e_{it} - p_{it}) - (e_{it}^* - p_{it}^*) = \tilde{e}_{it} - \tilde{e}_{it}^*$ and where, in turn, e_{it} is the nominal exchange rate *vis-à-vis* the US\$, $e_{it}^* = \sum_{j=1}^N w_{ij} e_{jt}$, $ee_{it} = \sum_{j=1}^N w_{ij} e_{ijt}$ is the nominal effective exchange rate, p_{it} the national price level and p_{it}^* the foreign price level.

Where data availability is unconstrained (*i.e.* for countries $i = 2, 3, \ldots, 20$), the VARX* models include the following endogenous I(1) variables: $\boldsymbol{y}_{it} = (re_{it}, r_{it}, im_{it}, ex_{it}, q_{it}, \Delta p_{it}, y_{it})'$. For countries $i = 21, 22, \ldots, 24$, where the stock market data were unreliable or unavailable, we have $\boldsymbol{y}_{it} = (re_{it}, r_{it}, im_{it}, ex_{it}, \Delta p_{it}, y_{it})'$. Finally, for country $i = 25$ (Saudi Arabia) without an official interest rate, $\boldsymbol{y}_{it} = (re_{it}, im_{it}, ex_{it}, \Delta p_{it}, y_{it})'$. In all cases but the US, the vector of weakly exogenous foreign variables is given by $\boldsymbol{y}_{it}^* = (p_t^o, r_{it}^*, q_{it}^*, \Delta p_{it}^*, y_{it}^*)'$ where $y_{it}^* = \sum_{j=1}^N w_{ij} y_{jt}$, $p_{it}^* = \sum_{j=0}^N w_{ij} p_{jt}$, $\Delta p_{it}^* = \sum_{j=1}^N w_{ij} \Delta p_{jt}$, $r_{it}^* = \sum_{j=1}^N w_{ij} r_{jt}$, $e_{it}^* = \sum_{j=1}^N w_{ij} e_{jt}$, and $q_{it}^* = \sum_{j=1}^N w_{ij} q_{jt}$, w_{ij} is the share of country j in the trade of country i. The omission of ex_{it}^* and im_{it}^* from the model reflects the fact that our model covers more than 90% of the world trade in which case $im_{it} \simeq ex_{it}^*$ and $im_{it}^* \simeq ex_{it}$.

The US $(i = 1)$ is treated as the reference country such that its exchange rate is determined through the $N-1$ remaining country-specific models. Hence, re_{1t} is excluded from the endogenous variable set for the US model while $\tilde{e}_{1t}^*$ is included among its weakly exogenous foreign variables. Furthermore, following DdPS, we include the oil price as an endogenous variable in the US model, reflecting the dominant position of the US in the global economy. We also treat the vector of weakly exogenous foreign variables slightly differently, as the US economy is sufficiently large to drive events in global financial markets. In this regard we exclude both r^*_{1t} and q^*_{1t} from the US model as they are unlikely to be weakly exogenous. Therefore, we have $\boldsymbol{y}_{1t} = (p^o_t, r_{1t}, im_{1t}, ex_{1t}, q_{1t}, \Delta p_{1t}, y_{1t})'$ and $\boldsymbol{y}^*_{1t} = (\tilde{e}^*_{1t}, \Delta p^*_{1t}, y^*_{1t})$.

Table 1 in the main text presents a concise summary of the GNS25 model specification, while Table A.1 records the results of standard statistical tests for structural breaks, co-breaking and weak exogeneity for each of the country-specific models in turn. The tests provide strong foundations for the specification adopted in the paper.

A.2.2 Combining the National Models into the Global Model

GNS define the $(m+1)\times 1$ vector of intermediate global variables as $\tilde{\boldsymbol{y}}_t = (\tilde{\boldsymbol{y}}'_{1t}, \tilde{\boldsymbol{y}}'_{2t}, ..., \tilde{\boldsymbol{y}}'_{Nt})'$, where $\tilde{\boldsymbol{y}}_{1t} = (\tilde{e}_{1t}, p^o_t, r_{1t}, im_{1t}, ex_{1t}, q_{1t}, \Delta p_{1t}, y_{1t})'$, $\tilde{\boldsymbol{y}}_{it} = (\tilde{e}_{it}, r_{it}, im_{it}, ex_{it}, q_{it}, \Delta p_{it}, y_{it})'$ for $i = 2, ..., N$ and $m = \sum_{i=1}^N m_i$. Insodoing, all of the endogenous variables from each of the country-specific VARX* models are collected into the global vector $\tilde{\boldsymbol{y}}_t$.

Next, one must define the $(m_i + m^*_i)\times(m+1)$ link matrices, denoted $\boldsymbol{W}_i$. We follow the typical approach in the literature, which employs time-invariant bilateral trade weights based on IMF DOTS data in the construction of the link matrices.[1] Employing the country ordering given in Section A.2 and also shown in Table 1 of the main text, the $\boldsymbol{W}_i$'s are given by:

$$\underset{10\times 170}{\boldsymbol{W}_1} = \begin{pmatrix} \boldsymbol{R}_{11} & \mathbf{0}_{7\times 7} & \cdots & \mathbf{0}_{7\times 7} & \mathbf{0}_{7\times 6} & \cdots & \mathbf{0}_{7\times 6} & \mathbf{0}_{7\times 5} \\ \mathbf{0}_{3\times 8} & \boldsymbol{W}_{1,2} & \cdots & \boldsymbol{W}_{1,19} & \boldsymbol{W}_{1,20} & \cdots & \boldsymbol{W}_{1,24} & \boldsymbol{W}_{1,25} \end{pmatrix},$$

$$\underset{12\times 170}{\boldsymbol{W}_i} = \begin{pmatrix} \boldsymbol{R}_{i1} & \boldsymbol{R}_{i2} & \boldsymbol{R}_{i3} & \cdots & \boldsymbol{R}_{i,25} \\ \boldsymbol{W}_{i1} & \boldsymbol{W}_{i2} & \boldsymbol{W}_{i3} & \cdots & \boldsymbol{W}_{i,25} \end{pmatrix}, \ i = 2, ..., 25,$$

where

$$\boldsymbol{R}_{11} = \begin{bmatrix} \mathbf{0}_{7\times 1} & \boldsymbol{I}_7 \end{bmatrix}, \ \boldsymbol{R}_{i1} = \begin{bmatrix} -w_{i1} & \mathbf{0}_{1\times 7} \\ \mathbf{0}_{6\times 1} & \mathbf{0}_{6\times 7} \end{bmatrix}, \ i = 2, ..., 25,$$

$$\{\boldsymbol{R}_{ij}\}_{j=2}^{20} = \begin{Bmatrix} \begin{bmatrix} -w_{ij} & \mathbf{0}_{1\times 6} \\ \mathbf{0}_{6\times 1} & \mathbf{0}_{6\times 6} \end{bmatrix} & \text{if } j \neq i \\ \boldsymbol{I}_7 & \text{if } j = i \end{Bmatrix}, \ i = 2, ..., 25,$$

[1] It should be noted that a wide range of alternative weighting schemes could be adopted in practice. For example, Chen et al. (2009) employ time-invariant financial weights in their analysis of bank and financial sector risk transmission while Cesa-Bianchi et al. (2012) use a time-varying weighting scheme to evaluate the changing position of China and the Latin American economies in the global system. Alternatively, one could employ appropriately defined spatial matrices or even a combined weighting scheme.

ISO Code	Structural Break Test[a]		Co-breaking test[b]	Weak exogeneity test[c]					
	Breaks identified by test	Chosen break		p_t^o	r_{it}^*	q_{it}^*	Δp_{it}^*	y_{it}^*	$\tilde{e}_{0t}^*$
US				–	–	–	1.53	0.12	1.26
EU				1.74	5.25 †	0.26	0.28	2.16	–
JP	r(1993Q2), q(1992Q1)	1992Q1	68.94 [0.00]	1.29	0.97	0.86	0.79	1.81	–
GB	y(1992Q2)	1992Q4	41.03 [0.00]	4.03	0.97	1.86	4.21	0.23	–
NO				2.37	0.29	0.83	0.27	6.04 †	–
SE				1.13	2.20	0.04	2.04	3.31	–
CH				1.03	1.60	3.41 †	4.67 †	0.96	–
CA				0.60	5.60 †	2.04	1.28	0.74	–
AU				0.71	1.77	0.74	1.08	1.12	–
NZ				1.29	2.09	0.43	1.03	0.92	–
ZA				0.50	0.08	0.38	4.03 †	1.51	–
BR	r(1996Q1), im(1993Q2)	1994Q3	60.93 [0.00]	0.55	2.22	1.05	5.71 †	2.56	–
CL				0.72	0.66	1.47	0.67	0.52	–
MX	None	1995Q1	70.98 [0.00]	0.81	1.49	1.55	3.91 †	2.00	–
IN				1.57	0.47	0.27	0.71	0.41	–
KR	y(1998Q1)	1997Q4	52.15 [0.00]	2.76	2.15	0.74	2.36	0.29	–
MY	r(1998Q3)	1997Q3	48.39 [0.00]	1.90	2.91	2.80	4.20 †	3.25 †	–
PH	None	1997Q4	89.66 [0.00]	0.74	2.63	0.60	2.37	1.43	–
SG				0.90	2.91	0.62	2.00	0.72	–
TH	None	1997Q3	72.56 [0.00]	3.96 †	1.33	0.07	1.71	0.85	–
CN				1.10	2.65	0.86	3.95	0.43	–
ID	None	1997Q3	110.32 [0.00]	1.29	0.32	0.99	0.44	3.51 †	–
PE	im(1995Q1), Δp(1997Q1)	1994Q3	34.21 [0.00]	1.02	2.21	0.39	0.54	2.43	–
TR				0.39	0.60	1.05	0.59	0.37	–
SA				0.33	0.39	3.27	0.56	0.45	–

[a] Breaks identified by the CUSUM test where (.) is the break point for the named series. Break points are identified using the 10% significance level. {.} the breakpoints included in the model are chosen as a compromise between the empirical test results and our knowledge of historical economic events.
[b] LR-Stat $\sim \chi_r^2$ for the null of co-breaking, where r is the number of cointegrating vectors and [.] is the p-value.
[c] F-Stat $\sim F(r, T-k)$ for the null of weak exogeneity, where k is the number of regressors in the unrestricted model, and '†' denotes rejection of the null at the 1% level.

Table A.1: Tests for Structural Breaks, Co-breaking and Weak Exogeneity

$$\{\boldsymbol{R}_{ij}\}_{j=21}^{24} = \left\{ \begin{array}{cc} \begin{bmatrix} -w_{ij} & \mathbf{0}_{1\times 5} \\ \mathbf{0}_{6\times 1} & \mathbf{0}_{6\times 5} \end{bmatrix} & \text{if } j \neq i \\ \boldsymbol{I}_6 & \text{if } j = i \end{array} \right\},\ i = 2, ..., 25,$$

$$\boldsymbol{R}_{i,25} = \left\{ \begin{array}{cc} \begin{bmatrix} -w_{i,25} & \mathbf{0}_{1\times 4} \\ \mathbf{0}_{6\times 1} & \mathbf{0}_{6\times 4} \end{bmatrix} & \text{if } i \neq 25 \\ \boldsymbol{I}_5 & \text{if } i = 25 \end{array} \right\},$$

$$\{\boldsymbol{W}_{1j}\}_{j=2}^{20} = \begin{bmatrix} w_{1j} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & w_{1j} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & w_{1j} \end{bmatrix},$$

$$\{\boldsymbol{W}_{1j}\}_{j=21}^{24} = \begin{bmatrix} w_{1j} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & w_{1j} & 0 \\ 0 & 0 & 0 & 0 & 0 & w_{1j} \end{bmatrix},\ \boldsymbol{W}_{1,25} = \begin{bmatrix} w_{1,25} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & w_{1,25} & 0 \\ 0 & 0 & 0 & 0 & w_{1,25} \end{bmatrix},$$

and for $i = 2, ..., 25$,

$$\boldsymbol{W}_{i1} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & w_{i0}^{*} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & w_{i0}^{**} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & w_{i0} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & w_{i0} \end{bmatrix},\ \{\boldsymbol{W}_{ij}\}_{j=2}^{20} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & w_{ij}^{*} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & w_{ij}^{**} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & w_{ij} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & w_{ij} \end{bmatrix},$$

$$\{\boldsymbol{W}_{ij}\}_{j=21}^{24} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & w_{ij}^{*} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & w_{ij} & 0 \\ 0 & 0 & 0 & 0 & 0 & w_{ij} \end{bmatrix},\ \boldsymbol{W}_{i,25} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & w_{i,25} & 0 \\ 0 & 0 & 0 & 0 & w_{i,25} \end{bmatrix}.$$

where w_{ij} is the weight of country i in the trade of country j, w_{ij}^{*} is the ith country's adjusted trade-weight with the jth country after allowing for the lack of Saudi interest rate data, and w_{ij}^{**} is the ith country's trade-weight with the jth country adjusted to accommodate the lack of reliable stock market data for China, Indonesia, Peru, Turkey and Saudi Arabia. Notice that $\sum_{j=1}^{N} w_{ij} = \sum_{j=1}^{N} w_{ij}^{*} = \sum_{j=1}^{N} w_{ij}^{**} = 1$, and $w_{ii} = w_{ii}^{*} = w_{ii}^{*} = 0$ for all i.

Using these link matrices, the $\boldsymbol{z}_{it}$'s for each country-specific model may be re-written in terms of the vector of global variables, $\tilde{\boldsymbol{y}}_t$, as follows:

$$\boldsymbol{z}_{it} = \boldsymbol{W}_i \tilde{\boldsymbol{y}}_t, \;\; i = 0, 1, ..., N. \tag{A.4}$$

Using (A.4) in (A.3) and stacking the results, we obtain the following global model:

$$\boldsymbol{H}_0 \tilde{\boldsymbol{y}}_t = \boldsymbol{h}_0^* + \boldsymbol{h}_1 t + \boldsymbol{H}_1 \tilde{\boldsymbol{y}}_{t-1} + \boldsymbol{H}_2 \tilde{\boldsymbol{y}}_{t-2} + \boldsymbol{u}_t, \tag{A.5}$$

where $\boldsymbol{H}_i = (\boldsymbol{W}_1' \boldsymbol{A}_{1i}', ..., \boldsymbol{W}_N' \boldsymbol{A}_{Ni}')'$, $\boldsymbol{h}_0^* = \left(\boldsymbol{h}_{10}^{*\prime}, ..., \boldsymbol{h}_{N0}^{*\prime}\right)'$, $\boldsymbol{h}_1 = \left(\boldsymbol{h}_{11}', ..., \boldsymbol{h}_{N1}',\right)'$ and $\boldsymbol{u}_t = \left(\boldsymbol{u}_{1t}', ..., \boldsymbol{u}_{Nt}'\right)'$ for $i = 0, 1, 2$.

Since $\tilde{e}_{1t}$ is not included in the set of US variables for VARX* model but it is implicitly included in the global system, we must impose one additional restriction. Given that we define nominal exchange rates *vis-à-vis* the US Dollar, it follows that $e_{1t} = 0$ and thus, $\tilde{e}_{1t} = -p_{1t}$. By imposing this restriction we are able to solve the system, although we are now solving for the price level in the US as opposed to inflation in the remainder of the countries (see DdPS for further details).

Finally, we define the $m \times 1$ vector of global variables: $\boldsymbol{y}_t = \left(\mathring{\boldsymbol{y}}_{1t}', \tilde{\boldsymbol{y}}_{2t}', ..., \tilde{\boldsymbol{y}}_{Nt}'\right)'$, where $\mathring{\boldsymbol{y}}_{1t} = (p_t^o, r_{1t}, m_{1t}, x_{1t}, q_{1t}, p_{1t}, y_{1t})'$, and the $\tilde{\boldsymbol{y}}_{it}$'s are defined as above. To solve for the price level in the special case of the US, we set:

$$\tilde{\boldsymbol{y}}_t = \boldsymbol{S}_0 \boldsymbol{y}_t - \boldsymbol{S}_1 \boldsymbol{y}_{t-1}, \tag{A.6}$$

where $\boldsymbol{S}_0$ and $\boldsymbol{S}_1$ are $(m+1) \times m$ selection matrices given by:

$$\boldsymbol{S}_0 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & -1 & 0 & \boldsymbol{0} \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & \boldsymbol{0} \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & \boldsymbol{0} \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & \boldsymbol{0} \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & \boldsymbol{0} \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & \boldsymbol{0} \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & \boldsymbol{0} \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{I}_{m-m_1} \end{pmatrix}, \; \boldsymbol{S}_1 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & \boldsymbol{0} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \boldsymbol{0} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \boldsymbol{0} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \boldsymbol{0} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \boldsymbol{0} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \boldsymbol{0} \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & \boldsymbol{0} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0}_{m-m_1} \end{pmatrix}$$

Using $(A.6)$, $(A.5)$ can be rewritten in terms of $\boldsymbol{y}_t$ as follows:

$$\boldsymbol{F}_0\boldsymbol{y}_t = \boldsymbol{h}_0^* + \boldsymbol{h}_1 t + \boldsymbol{F}_1\boldsymbol{y}_{t-1} + \boldsymbol{F}_2\boldsymbol{y}_{t-2} + \boldsymbol{F}_3\boldsymbol{y}_{t-3} + \boldsymbol{u}_t, \tag{A.7}$$

where $\boldsymbol{F}_0 = \boldsymbol{H}_0\boldsymbol{S}_0$, $\boldsymbol{F}_1 = \boldsymbol{H}_1\boldsymbol{S}_0 + \boldsymbol{H}_0\boldsymbol{S}_1$, $\boldsymbol{F}_2 = \boldsymbol{H}_2\boldsymbol{S}_0 - \boldsymbol{H}_1\boldsymbol{S}_1$, and $\boldsymbol{F}_3 = -\boldsymbol{H}_2\boldsymbol{S}_1$. The final GVAR model is obtained as:

$$\boldsymbol{y}_t = \boldsymbol{g}_0^* + \boldsymbol{g}_1 t + \boldsymbol{G}_1\boldsymbol{y}_{t-1} + \boldsymbol{G}_2\boldsymbol{y}_{t-2} + \boldsymbol{G}_3\boldsymbol{y}_{t-3} + \boldsymbol{\varepsilon}_t, \tag{A.8}$$

where $\boldsymbol{G}_j = \boldsymbol{F}_0^{-1}\boldsymbol{F}_j$, $j = 1, 2, 3$, $\boldsymbol{g}_0^* = \boldsymbol{F}_0^{-1}\boldsymbol{h}_0^*$, $\boldsymbol{g}_1 = \boldsymbol{F}_0^{-1}\boldsymbol{h}_1$, and $\boldsymbol{\varepsilon}_t = \boldsymbol{F}_0^{-1}\boldsymbol{u}_t$, and $E\left(\boldsymbol{u}_{it}\boldsymbol{u}_{jt}'\right) = \boldsymbol{\Sigma}_{u,ij}$ for $t = t'$ and 0 otherwise.

Recall from the main text that we construct the covariance matrix from equation (A.7) taking into account the results of the cross section dependence test proposed by Pesaran (2004). Table A.2 records the results of the cross section dependence test. In those off-diagonal blocks where the null of cross section independence is rejected, we estimate the block as $\hat{\boldsymbol{\Sigma}}_{u,ij} = (\hat{\mathbf{u}}_{it}\hat{\mathbf{u}}_{jt}')/(T - \sqrt{n_i n_j})$ where n_i and n_j are the number of regressors in the country-specific models for countries i and j, respectively. Where the null of cross section independence is not rejected, we impose a null block.

A.3 Details of the Aggregation Schemes used in the Paper

In this Section, we provide further details of the block aggregation routines used in the paper to evaluate connectedness among countries and among groups of common variables. Using the block representations of the renormalised connectedness matrix shown below, it is straightforward to compute the associated generalised connectedness measures following the derivations in Section 2.1 of the main text.

A.3.1 Connectedness Among Countries

The updated version of the GNS model used in the paper contains 169 globally endogenous variables covering 25 countries including one common global variable (the oil price, p_t^o). The endogenous variable set for country k, $\boldsymbol{y}_{k,t}$, is detailed in Table 1 in the main text. Maintaining the country order in Table 1, note that we may write the vector of global variables as:

$$\boldsymbol{y}_t = \left(p_t^o, \widetilde{\boldsymbol{y}}_{US,t}', \ldots, \boldsymbol{y}_{SA,t}'\right)' \tag{A.9}$$

	US	EU	JP	GB	NO	SE	CH	CA	AU	NZ	ZA	BR	CL	MX	IN	KR	MY	PH	SG	TH	CN	ID	PE	TR	SA
US	*NA*	-0.50	1.06	1.39	0.38	-1.44	**2.36**	**2.13**	0.57	0.70	**-2.62**	**-2.77**	-0.15	**3.16**	-0.33	0.77	-1.93	-1.09	**2.10**	0.02	-1.94	-0.51	0.83	0.98	1.22
EU	-0.50	*NA*	**2.82**	**3.94**	0.40	**2.32**	**4.95**	**2.55**	1.37	0.61	0.87	**-2.44**	**-4.44**	-0.16	-1.65	**-3.32**	**2.24**	**2.46**	1.72	**3.33**	**4.80**	**7.11**	1.32	-1.71	**-3.08**
JP	1.06	**2.82**	*NA*	0.42	1.01	-1.58	**4.53**	-0.77	**2.48**	-0.34	1.68	**-2.21**	0.94	1.05	-1.73	-1.26	-1.10	**-2.18**	-1.43	**-3.00**	-1.54	0.82	1.74	-1.92	**-2.81**
GB	1.39	**3.94**	0.42	*NA*	1.85	**2.58**	**4.26**	1.64	**2.17**	0.09	**-2.75**	**-2.05**	-1.46	**3.95**	1.20	-0.90	-1.82	-1.10	-0.83	**2.52**	0.62	**-2.18**	0.84	-0.27	**-2.27**
NO	0.38	0.40	1.01	1.85	*NA*	**3.02**	**3.36**	**2.42**	**2.35**	0.76	**3.07**	**-2.28**	0.47	**2.29**	0.47	-0.19	-0.90	-0.12	**2.32**	1.74	**2.16**	-0.38	0.83	0.87	0.28
SE	-1.44	**2.32**	-1.58	**2.58**	**3.02**	*NA*	**2.40**	**5.21**	**2.51**	-0.15	**2.80**	-0.84	**2.75**	**-3.60**	-0.93	**2.80**	0.77	-0.35	**2.34**	**2.37**	-0.68	-0.02	0.41	1.84	-0.70
CH	**2.36**	**4.95**	**4.53**	**4.26**	**3.36**	**2.40**	*NA*	1.81	1.57	-0.16	**2.72**	-1.46	-0.76	0.18	1.67	-1.31	1.13	-0.54	1.15	0.01	1.90	**3.96**	-1.08	0.74	**-3.30**
CA	**2.13**	**2.55**	-0.77	1.64	**2.42**	**5.21**	1.81	*NA*	**3.40**	1.37	0.30	1.83	1.09	1.89	-0.19	1.21	-0.54	-1.55	0.83	0.21	1.93	-0.41	0.35	0.66	0.43
AU	0.57	1.37	**2.48**	**2.17**	**2.35**	**2.51**	1.57	**3.40**	*NA*	**4.72**	**4.33**	1.74	1.69	0.62	1.00	-1.49	-0.59	-0.24	-1.76	0.56	1.73	0.95	0.89	0.25	-1.48
NZ	0.70	0.61	-0.34	0.09	0.76	-0.15	-0.16	1.37	**4.72**	*NA*	0.21	-0.91	-0.02	-0.77	-0.83	**-3.15**	-1.28	-1.85	**-2.57**	0.23	-0.93	**-2.03**	0.31	-0.94	-1.17
ZA	**-2.62**	0.87	1.68	**-2.75**	**3.07**	**2.80**	**2.72**	0.30	**4.33**	0.21	*NA*	1.46	0.50	-0.42	0.40	-0.39	**2.50**	0.51	-0.41	-0.13	**2.06**	**3.37**	-0.23	-0.64	-0.72
BR	**-2.77**	**-2.44**	**-2.21**	**-2.05**	**-2.28**	-0.84	-1.46	1.83	1.74	-0.91	1.46	*NA*	0.59	-0.44	0.25	1.28	1.64	**2.87**	**-2.87**	0.32	1.43	-0.09	**2.57**	**3.48**	**2.16**
CL	-0.15	**-4.44**	0.94	-1.46	0.47	**2.75**	-0.76	1.09	1.69	-0.02	0.50	0.59	*NA*	-0.17	**-2.21**	0.02	0.34	-0.25	**-2.67**	1.26	-1.31	**-3.26**	**2.25**	-0.45	-0.34
MX	**3.16**	-0.16	1.05	**3.95**	**2.29**	**-3.60**	0.18	1.89	0.62	-0.77	-0.42	-0.44	-0.17	*NA*	1.10	1.03	0.46	-1.40	1.40	-0.33	1.02	**-4.62**	**3.11**	**3.84**	-0.65
IN	-0.33	-1.65	-1.73	1.20	0.47	-0.93	1.67	-0.19	1.00	-0.83	0.40	0.25	**-2.21**	1.10	*NA*	**2.47**	1.80	1.67	**1.99**	1.74	**2.86**	1.04	**-3.14**	1.28	**2.81**
KR	0.77	**-3.32**	-1.26	-0.90	-0.19	**2.80**	-1.31	1.21	-1.49	**-3.15**	-0.39	1.28	0.02	1.03	**2.47**	*NA*	0.62	0.22	-0.59	**2.17**	-1.87	**-3.08**	-0.77	0.86	**3.40**
MY	-1.93	**2.24**	-1.10	-1.82	-0.90	0.77	1.13	-0.54	-0.59	-1.28	**2.50**	1.64	0.34	0.46	1.80	0.62	*NA*	-1.29	0.88	1.44	**3.80**	0.88	-1.35	0.76	-0.34
PH	-1.09	**2.46**	**-2.18**	-1.10	-0.12	-0.35	-0.54	-1.55	-0.24	-1.85	0.51	**2.87**	-0.25	-1.40	1.67	0.22	-1.29	*NA*	1.05	**2.91**	0.91	**2.48**	-0.16	**2.07**	**2.12**
SG	**2.10**	1.72	-1.43	-0.83	**2.32**	**2.34**	1.15	0.83	-1.76	**-2.57**	-0.41	**-2.87**	**-2.67**	1.40	**1.99**	-0.59	0.88	1.05	*NA*	0.07	-1.36	0.43	-0.61	1.06	1.38
TH	0.02	**3.33**	**-3.00**	**2.52**	1.74	**2.37**	0.01	0.21	0.56	0.23	-0.13	0.32	1.26	-0.33	1.74	**2.17**	1.44	**2.91**	0.07	*NA*	-1.34	1.26	-0.41	-0.85	1.27
CN	-1.94	**4.80**	-1.54	0.62	**2.16**	-0.68	1.90	1.93	1.73	-0.93	**2.06**	1.43	-1.31	1.02	**2.86**	-1.87	**3.80**	0.91	-1.36	-1.34	*NA*	-0.07	-0.43	-0.19	-0.72
ID	-0.51	**7.11**	0.82	**-2.18**	-0.38	-0.02	**3.96**	-0.41	0.95	**-2.03**	**3.37**	-0.09	**-3.26**	**-4.62**	1.04	**-3.08**	0.88	**2.48**	0.43	1.26	-0.07	*NA*	-0.15	-0.48	**-2.13**
PE	0.83	1.32	1.74	0.84	0.83	0.41	-1.08	0.35	0.89	0.31	-0.23	**2.57**	**2.25**	**3.11**	**-3.14**	-0.77	-1.35	-0.16	-0.61	-0.41	-0.43	-0.15	*NA*	**-1.97**	-1.19
TR	0.98	-1.71	-1.92	-0.27	0.87	1.84	0.74	0.66	0.25	-0.94	-0.64	**3.48**	-0.45	**3.84**	1.28	0.86	0.76	**2.07**	1.06	-0.85	-0.19	-0.48	**-1.97**	*NA*	0.75
SA	1.22	**-3.08**	**-2.81**	**-2.27**	0.28	-0.70	**-3.30**	0.43	-1.48	-1.17	-0.72	**2.16**	-0.34	-0.65	**2.81**	**3.40**	-0.34	**2.12**	1.38	1.27	-0.72	**-2.13**	-1.19	0.75	*NA*

∗ Note: Numbers in bold face are statistically significant at the 5% level.

Table A.2: Testing for Cross Section Dependence where $\widetilde{\boldsymbol{y}}_{US,t}$ denotes the vector of endogenous variables for the US excluding the oil price. The renormalised connectedness matrix corresponding to these groups is given by:

$$\underset{(m\times m)}{\mathbb{C}_R^{(h)}} = \begin{bmatrix} C^{(h)}_{p^o\leftarrow p^o} & \mathbf{C}^{(h)}_{p^o\leftarrow US} & \cdots & \mathbf{C}^{(h)}_{p^o\leftarrow SA} \\ \mathbf{C}^{(h)}_{US\leftarrow p^o} & \mathbf{C}^{(h)}_{US\leftarrow US} & \cdots & \mathbf{C}^{(h)}_{US\leftarrow SA} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{C}^{(h)}_{SA\leftarrow p^o} & \mathbf{C}^{(h)}_{SA\leftarrow US} & \cdots & \mathbf{C}^{(h)}_{SA\leftarrow SA} \end{bmatrix} \tag{A.10}$$

where $C^{(h)}_{p^o\leftarrow p^o}$ is a scalar measuring the own-variable FEV share of the oil price, $\mathbf{C}^{(h)}_{p^o\leftarrow \ell}$ is a $1\times m_\ell$ row vector collecting spillovers from country ℓ to the oil price, $\mathbf{C}^{(h)}_{k\leftarrow p^o}$ is a $m_k\times 1$ column vector collecting spillovers from the oil price to country k and $\mathbf{C}^{(h)}_{k\leftarrow \ell}$ is an $m_k \times m_\ell$ matrix containing spillovers from country ℓ to country k with $k,\ell = US, EU, \ldots, SA$.

Remark 1 *In many applications of high dimensional models in economics and finance, the researcher is principally interested in a subset of focus countries. In such cases, one could reduce the output dimensionality of the model by considering one or more focus countries separately while aggregating the remaining countries into appropriately defined blocs. This is a straightforward extension of the country-level case described above.*

A.3.2 Connectedness Among Groups of Common Variables

In Figures 4, 6 and 7 of the main text we evaluate connectedness among the following $G = 8$ variable groups: (1) the oil price, (2) the exchange rates for all countries, (3) the interest rates for all countries, (4) the stock indices for all countries, (5) real exports for all countries, (6) real imports for all countries, (7) inflation for all countries and (8) output for all countries. This is achieved by block aggregation of the renormalised connectedness matrix as follows:

$$\underset{(m\times m)}{\mathbb{C}_R^{(h)}} = \begin{bmatrix} G^{(h)}_{p^o\leftarrow p^o} & \mathbf{G}^{(h)}_{p^o\leftarrow re} & \cdots & \mathbf{G}^{(h)}_{p^o\leftarrow y} \\ \mathbf{G}^{(h)}_{re\leftarrow p^o} & \mathbf{G}^{(h)}_{re\leftarrow re} & \cdots & \mathbf{G}^{(h)}_{re\leftarrow y} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{G}^{(h)}_{y\leftarrow p^o} & \mathbf{G}^{(h)}_{y\leftarrow re} & \cdots & \mathbf{G}^{(h)}_{y\leftarrow y} \end{bmatrix} \tag{A.11}$$

where $G^{(h)}_{p^o\leftarrow p^o}$ is a scalar measuring the own-variable FEV share of the oil price, $\mathbf{G}^{(h)}_{p^o\leftarrow \ell}$ is a $1\times m_\ell$ row vector collecting spillovers from the ℓth variable group to the oil price, $\mathbf{G}^{(h)}_{k\leftarrow p^o}$ is a $m_k\times 1$ column vector collecting spillovers from the oil price to the kth variable group and $\mathbf{G}^{(h)}_{k\leftarrow \ell}$ is an $m_k\times m_\ell$ matrix containing spillovers from variable group ℓ to variable group k with $k,\ell = p^o, re, \ldots, y$. m_k and m_ℓ respectively denote the number of countries for which we have data for variable groups k and ℓ.

A.4 Data Construction

Real GDP — $y_{it} = \ln(Y_{it})$

Real GDP series for 32 countries were taken from the IMF's International Financial Statistics (IFS) database (Index, 2005 = 100). When unavailable, the IFS series were completed from other sources. Data from the OECD's Main Economic Indicators were used for Brazil from 1996Q1 onwards. When data was unavailable at the quarterly frequency, the annual series were interpolated following the method in DdPS (Supplement A). This technique was employed for Brazil from 1980-1995, China from 1980-1999, India from 1980-1996, for Indonesia from 1980-1982, for Malaysia from 1980-1987, for the Philippines for 1980, for Thailand from 1980-1992, for Turkey from 1980-1986, and for Saudi Arabia from 1980-2009. The data for Saudi Arabia from 2010 onwards were extrapolated using GDP growth rate from Saudi Arabian Central Department of Statistics and Information. Where necessary, the data were seasonally adjusted using the US Census Bureau's X12 routine.

Consumer Price Index — $p_{it} = \ln(CPI_{it})$

CPI data were collected from the IMF's IFS database (Index, 2005 = 100). CPI data for China from 1980-1986 and for Germany from 1980-1990 was provided by the Bank of Korea. The Chinese series was completed using IFS data from 1987 onwards.

Nominal Exchange Rate — $e_{it} = \ln(E_{it})$

Nominal exchange rates (E_{it}) measured in units of national currency per US Dollar were collected from the IMF's IFS database. The exchange rate series for the Eurozone are the ECU-EURO/USD rate from the OECD's Main Economic Indicators.

Short-Term Nominal Interest Rate — $r_{it} = 0.25 \times \ln(1 + R_{it}/100)$

Short-term interest rate series (R_{it}) measured in percent per annum were taken from the IFS Money Market Rate series. Where the IFS data was incomplete or unavailable, other IFS series were used. Particularly, the IFS Deposit Rate series was used for Chile, China and Turkey, the IFS Treasury Bill Rate series was used for Mexico and the IFS Discount Rate series was used for New Zealand and Peru. For India, the IFS Money Market Rate series over 1998Q2-2006Q2 were retrieved from the Reserve Bank of India. For Norway, the NIBOR 3-month rates from the OECD were used. Among Eurozone countries, Finland, Germany, Italy, and Spain have their own interest rate series over the full sample period whilst for Austria, Belgium, France, and Netherlands, the IFS Money Market Rate series ended at 1998qQ4 and were then augmented with overnight Euro interbank rates.

Real Exports and Imports — $ex_{it} = \ln\left(\frac{EXPORT_{it} \times E_{it}}{CPI_{it}}\right)$ & $im_{it} = \ln\left(\frac{IMPORT_{it} \times E_{it}}{CPI_{it}}\right)$

IFS Goods, Value of Exports series ($EXPORT_{it}$) and IFS Goods, Value of Imports series ($IMPORT_{it}$), measured in millions of US$, were available for 31 countries. Where necessary, the data were extrapolated backward using export and import growth rates obtained from the World Bank. This technique was applied for Belgium over the period 1980-1992 and for China in 1980. The quarterly series for Saudi Arabia were collected from the IMF's Direction of Trade Statistics (DOTS). All the series were then seasonally adjusted using the US Census Bureau's X12 routine.

Real Equity Price Index — $q_{it} = \ln\left(\frac{Q_{it}}{CPI_{it}}\right)$

Equity price indices (Q_{it}) were collected from the OECD's Main Economic Indicators (all shares/broad, 2005 = 100) for 31 countries. Where the OECD equity price series was incomplete or unavailable, IFS data were used. Specifically, the IFS industrial share price index series were used for Belgium from 1980-1985Q1, for Brazil from 1980-1992, for Chile from 1980-1989, for Korea for 1980, for Norway from 1980-1985, and for Spain from 1980-1984. Datastream series were used for Malaysia from 1980Q2 onwards, for Philippines from 1986Q2 onwards, for Singapore from 1981Q2 onwards, and for Thailand from 1995Q4 onwards.

Spot Price of Crude Oil — $p_t^o = \ln(POIL_t)$

The UK Dated Brent series ($POIL_t$), measured in US$ per barrel, was retrieved from the IMF's IFS Commodity Price database.

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