Multilateral and Bilateral Multi-Country Models: Differences in Spillover Estimates?*

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Abstract

Yes. Spillover estimates obtained from easy-to-implement bilateral (such as two-country VAR) models are less accurate than those obtained from technically more demanding multilateral (such as global VAR) models. In particular, the accuracy of spillover estimates obtained from bilateral models depends on two aspects of economies' integration with the rest of the world. First, accuracy deteriorates as direct bilateral transmission channels become less important, for example when the spillover-sending economy accounts only for a small share of the spillover-receiving economy's overall integration with the rest of the world. Second, accuracy worsens as indirect higher-order spillovers and spillbacks become more important, for example when the spillover-receiving economy is strongly integrated with the rest of the world overall. Empirical evidence on the global output spillovers from US monetary policy is consistent with these general results: Estimates of the spillovers obtained from two-country VAR models are systematically smaller than those obtained from a global VAR model; and the differences in spillover estimates between the two-country VAR models and the global VAR model are more pronounced for economies for which the US accounts for a smaller share of their overall trade and financial integration with the rest of the world and which are more integrated with the rest of the world overall.

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1 Introduction

Over the last decades the global economy has witnessed a dramatic deepening of trade and financial integration. The resulting growing potential for cross-country spillovers has given impetus to academics and practitioners alike to estimate the magnitude of this cross-border transmission of domestic shocks (see IMF, 2014). A recent example for the prominence spillovers have gained is the extensive discussion about the global effects of the exit from unconventional monetary policy in the US and the associated calls for more international monetary policy coordination (see Ostry and Ghosh, 2013; Rajan, 2013).

Essentially, two modelling frameworks have been put forth for the analysis of cross-country spillovers. On the one hand, some have used bilateral models which only consider the spillover-sending and the spillover-receiving economy. For example, several papers study the global spillovers from US monetary policy in two-country VAR models that include the US and one non-US economy at a time (Kim, 2001; Canova, 2005; Nobili and Neri, 2006; Mackowiak, 2007; Bluedorn and Bowdler, 2011; Ilzetzki and Jin, 2013). Another set of papers has used two-country VAR models to study the impact of (in particular US) monetary policy on exchange rates (Eichenbaum and Evans, 1995; Cushman and Zha, 1997; Kim and Roubini, 2000; Faust and Rogers, 2003; Faust et al., 2003; Bjørnland, 2009; Voss and Willard, 2009). While a bilateral framework is technically straightforward to implement, it does not capture explicitly higher-order spillovers and spillbacks that reach the spillover-receiving economy through third and further economies. Despite not explicitly accounting for higher-order geographic channels, it is believed that bilateral models are still able to capture consistently the spillovers.

On the other hand, others have used multilateral, global modelling frameworks which consider a number of economies jointly. For example, the global VAR (GVAR) model developed by Pesaran et al. (2004) has also been used to study the global effects of US monetary policy considering a large number of non-US economies simultaneously (Chen et al., 2012; Feldkircher and Huber, 2015; Georgiadis, forthcoming). In a similar vein, Canova and Ciccarelli (2009) put forth high-dimensional multi-country VAR models which they suggest to estimate by Bayesian methods. Moreover, a number of global (semi-)structural models are being developed for the purpose of cross-country spillover analysis (Carabenciov et al., 2013; Vitek, 2014).[1] In contrast to bilateral models, multilateral models account for higher-order spillovers and spillbacks explicitly but are technically more difficult to implement, in particular as they are quickly subject to the curse of dimensionality.

This paper advances our understanding of the analysis of cross-country spillovers by investi-

[1]Factor augmented VAR models (Bernanke et al., 2005; Stock and Watson, 2005) and large Bayesian VAR models (Banbura et al., 2010) are additional approaches that could be used for spillover analysis under a multilateral framework but have so far been only applied for domestic settings.

gating whether it pays off to use a multilateral rather than bilateral models. In particular, I investigate whether spillovers are estimated more accurately in a multilateral model which captures explicitly higher-order spillovers and spillback than in bilateral models. The main result of the paper is that spillover estimates obtained from bilateral models are in general inconsistent asymptotically and less accurate than those obtained from a multilateral model in finite samples. Moreover, I find that the inferior accuracy in the spillover estimates obtained from bilateral models relative to those from a multilateral model is particularly pronounced when (i) the spillover-receiving economies are more susceptible to developments in the rest of the world overall, and when (ii) the spillover-sending economy accounts for a small share of the spillover-receiving economy's overall integration with the rest of the world. The accuracy of the spillover estimates obtained from bilateral models thus depends on the relative importance of direct bilateral spillovers and indirect higher-order spillovers and spillbacks.

I arrive at these conclusions in three steps. First, I explore asymptotically whether the parameter (and spillover) estimates obtained from a bilateral model that considers only the spillover sending and the spillover-receiving economy are consistent if the true data-generating process is given by a multilateral model involving N economies—arguably the most plausible data-generating process for macroeconomic variables in an era of unprecedented trade and financial globalisation. The results suggest that the spillover estimates from the bilateral model are in general inconsistent asymptotically due to omitted variable bias. Moreover, I find that the spillover-receiving economy's global integration properties determine the magnitude of the asymptotic bias of the spillover estimates obtained from the bilateral model. In particular, the asymptotic bias of the spillover estimates rises with the spillover-receiving economy's overall susceptibility to developments in the rest of the world, and it falls with the relative importance of the spillover-sending economy in the spillover-receiving economy's overall integration with the rest of the world.

Second, in order to evaluate the properties of spillover estimates from bilateral models in finite samples and to understand how a bilateral modelling framework may be expected to perform relative to the alternative of a multilateral framework I carry out a Monte Carlo experiment. Specifically, I simulate data based on a multilateral data-generating process and estimate spillovers using bilateral two-country VAR models and a multilateral GVAR model. Consistent with the asymptotic results, I find that the finite sample bias and the root mean square error (RMSE) of the spillover estimates obtained from the bilateral model relative to those from the multilateral model worsens with the spillover-receiving economy's overall degree of integration with the rest of the world, and that it improves with the relative importance of the spillover-sending economy in the spillover-receiving economy's overall integration with the rest of the world.

Finally, I illustrate the possible practical consequences of using bilateral models instead of a multilateral model by estimating the global output spillovers from US monetary policy using two-country VAR models and a GVAR model. Specifically, I find that the GVAR model produces spillover estimates which are economically and statistically larger than those from the two-country VAR models. Moreover, I find that in line with the asymptotic results and those from the Monte Carlo experiment the differences in the spillover estimates across the two-country VAR models and the GVAR model can be accounted for by spillover-receiving economies' overall integration with the rest of the world and the relative importance of the US therein.

This paper is related to existing work. First, Chudik and Pesaran (2011) consider the estimation of VAR models in which both $N \longrightarrow \infty$ and $T \longrightarrow \infty$. Specifically, they assume that units $i = 2, 3, \ldots, N$ can be identified either as neighbours or non-neighbours of unit $i = 1$ based on the magnitude of their effect on unit 1 as $N \longrightarrow \infty$: While the impact of each individual neighbour does not vary as $N \longrightarrow \infty$, that of the non-neighbours vanishes. Chudik and Pesaran (2011) show that the neighbourhood effects can be estimated consistently in models which omit the non-neighbourhood units. While their work suggests that it is admissible to disregard some units from the analysis under specific conditions they do not recommend bilateral models, as the set of neighbours may well comprise more than a single unit giving rise to a multilateral model; moreover, in order for the estimates of the effects of neighbour units to be consistent it is critical to know a priori which units are non-neighbours, which suggests one should be cautious in omitting units. Relative to the work of Chudik and Pesaran (2011) this paper studies the bias that arises when bilateral models disregard economies without pondering whether the latter are non-neighbours or not, and do so even in the context of a fixed N.

Second, Chudik and Straub (2010) investigate the role of trade openness for an economy's sensitivity to foreign shocks and the relationship to the widely-used small open-economy concept in international macroeconomics. Chudik and Straub (2010) consider a structural multi-country model in which they let the number of economies $N \longrightarrow \infty$, finding that the diversification of economies' trade is critical for their international macroeconomic interdependence. In particular, if an economy diversifies its trade across partners and no economy in the world is locally or globally dominant, then asymptotically as $N \longrightarrow \infty$ the equilibrium solution for domestic endogenous variables does not depend on the idiosyncratic shocks in foreign economies; in contrast, if some economies are locally or globally dominant then it is not admissible to treat economies individually and as if they were closed, but rather sets of economies need to be modelled jointly based on the structure of direct bilateral and multilateral higher-order trade linkages. The major difference relative to Chudik and Straub (2010) is that in this paper I examine the role of integration with the rest of the world and the relative strength of country linkages for the bias in bilateral models in the context of fixed N and non-diversified trade linkages, which is more relevant for empirical applications in multi-country modelling.

It is also worthwhile distinguishing this paper from existing work that has emphasised the importance of high-dimensional models in order to correctly identify structural shocks (Bernanke et al., 2005; Christiano et al., 2005; Stock and Watson, 2005; Giannone and Reichlin, 2006; Canova and Ciccarelli, 2013). Specifically, in this paper I assume that the structural shock has been identified correctly—in empirical applications this could be achieved by a narrative approach (Romer and Romer, 2004), by exploiting high-frequency financial market information (Bernanke and Kuttner, 2005) or by extracting shocks from estimated dynamic stochastic general equilibrium models Georgiadis (2015)—and examine whether considering high-dimensional multilateral rather than bilateral models is critical for estimating consistently the propagation of that shock. Moreover, the empirical setting that motivates the analysis in this paper refers to the global economy, and the propagation of shocks to cross-country spillovers between the same variables–for example output growth—rather than transmission mechanisms across involving different variables as typically studied in closed or small-open economy structural models.

The rest of the paper is organised as follows. Section 2 derives the probability limit of the coefficient estimates from a bilateral model if the true data-generating process is given by a multilateral model. In Section 3 I carry out a Monte Carlo experiment to assess the performance of bilateral models relative to multilateral models in terms of bias and RMSE in finite samples. Section 4 illustrates the possible differences between spillover estimates from two-country VAR models and a GVAR model for the case of the global impact of US monetary policy shocks. Finally, Section 5 concludes.

2 Asymptotic Results

2.1 Conceptual Framework

Consider a data-generating process given by a stationary multilateral VAR model

$$\begin{bmatrix} x_{1t} \\ x_{2t} \\ \boldsymbol{x}_{3t} \end{bmatrix} \equiv \begin{bmatrix} \boldsymbol{x}_t \\ \boldsymbol{z}_t \end{bmatrix} \equiv \boldsymbol{y}_t = \boldsymbol{\Gamma}_0 \boldsymbol{y}_t + \boldsymbol{\Gamma}_1 \boldsymbol{y}_{t-1} + \boldsymbol{\Psi} s_t + \boldsymbol{\nu}_t, \quad \boldsymbol{\nu}_t \overset{i.i.d.}{\sim} (\boldsymbol{0}, \boldsymbol{I}), \text{ and } s_t \overset{i.i.d.}{\sim} (0, \sigma_s^2), \quad (1)$$

where $\boldsymbol{z}_t = \boldsymbol{x}_{3t}$, $\boldsymbol{x}_t = (x_{1t}, x_{2t})'$, x_{1t} and x_{2t} are scalar variables of economies 1 and 2, $\boldsymbol{x}_{3t}$ is an $(N-2)$-dimensional vector of variables pertaining to the remaining economies $i = 3, 4, \ldots, N$, $\boldsymbol{\Psi} = (1, 0, \ldots, 0)'$, and $Cov(s_t, \boldsymbol{\nu}_t) = \boldsymbol{0}$. I consider an exogenous variable s_t as a shock in economy 1 in order to abstract from issues of identification of structural shocks.[2] The reduced

[2]Practical analogues of this are applications in which structural shocks are identified and estimated outside of the model used to obtain impulse responses, such as the monetary policy shocks constructed by Romer and Romer (2004) through the narrative approach or those constructed by Bernanke and Kuttner (2005) using

form of the model is given by

$$\begin{aligned}(\boldsymbol{I}-\boldsymbol{\Gamma}_0)\boldsymbol{y}_t &= \boldsymbol{\Gamma}_1\boldsymbol{y}_{t-1}+\boldsymbol{\Psi}s_t+\boldsymbol{\nu}_t \\ \boldsymbol{y}_t &= (\boldsymbol{I}-\boldsymbol{\Gamma}_0)^{-1}\boldsymbol{\Gamma}_1\boldsymbol{y}_{t-1}+(\boldsymbol{I}-\boldsymbol{\Gamma}_0)^{-1}\boldsymbol{\Psi}s_t+(\boldsymbol{I}-\boldsymbol{\Gamma}_0)^{-1}\boldsymbol{\nu}_t \\ &= \boldsymbol{\Phi}\boldsymbol{y}_{t-1}+\boldsymbol{\Omega}s_t+\boldsymbol{u}_t, \end{aligned} \tag{2}$$

with $\boldsymbol{u}_t \overset{i.i.d.}{\sim} (\boldsymbol{0},\boldsymbol{\Sigma}^u)$, $\boldsymbol{\Sigma}^u=(\boldsymbol{I}-\boldsymbol{\Gamma}_0)^{-1}(\boldsymbol{I}-\boldsymbol{\Gamma}_0)^{-1\prime}$. For future reference define

$$\boldsymbol{\Sigma}^y = \begin{bmatrix}\boldsymbol{\Sigma}^y_{xx} & \boldsymbol{\Sigma}^y_{xz}\\ \boldsymbol{\Sigma}^y_{zx} & \boldsymbol{\Sigma}^y_{zz}\end{bmatrix} \equiv Var(\boldsymbol{y}_t) = \sum_{j=0}^{\infty}\boldsymbol{\Phi}^j\boldsymbol{\Omega}\boldsymbol{\Omega}'\boldsymbol{\Phi}^{j\prime}\cdot\sigma_s^2+\sum_{j=0}^{\infty}\boldsymbol{\Phi}^j\boldsymbol{\Sigma}^u\boldsymbol{\Phi}^{j\prime}, \tag{3}$$

and

$$\begin{bmatrix}\boldsymbol{\Sigma}_{xs}\\ \boldsymbol{\Sigma}_{zs}\end{bmatrix} \equiv \begin{bmatrix}Cov(\boldsymbol{x}_t,s_t)\\ Cov(\boldsymbol{z}_t,s_t)\end{bmatrix} = \boldsymbol{\Omega}\sigma_s^2. \tag{4}$$

A typical object of interest in empirical applications is the impulse response function of the endogenous variables $\boldsymbol{y}_t$ to some exogenous shock. Specifically, for the multilateral VAR model in Equation (2) the impulse response functions to the exogenous variable s_t are given by

$$IRF(h) = \begin{bmatrix}IRF_x(h)\\ IRF_z(h)\end{bmatrix} \equiv \begin{bmatrix}\frac{\partial \boldsymbol{x}_{t+h}}{\partial s_t}\\ \frac{\partial \boldsymbol{z}_{t+h}}{\partial s_t}\end{bmatrix} = \boldsymbol{\Phi}^h\boldsymbol{\Omega}, \quad h=0,1,2,\dots\ . \tag{5}$$

Now suppose that rather than estimating the full multilateral VAR model in Equation (2), a smaller bilateral VAR model in which the variables of economies $i=3,4,\dots,N$ in $\boldsymbol{z}_t$ are omitted is considered. Specifically, assume the partitions

$$\boldsymbol{\Phi} = \begin{bmatrix}\boldsymbol{\Phi}_{xx} & \boldsymbol{\Phi}_{xz}\\ \boldsymbol{\Phi}_{zx} & \boldsymbol{\Phi}_{zz}\end{bmatrix} \quad \text{and} \quad \boldsymbol{\Omega} = \begin{bmatrix}\boldsymbol{\Omega}_x\\ \boldsymbol{\Omega}_z\end{bmatrix}, \tag{6}$$

and consider the bilateral VAR model

$$\boldsymbol{x}_t = \boldsymbol{\Phi}_{xx}\boldsymbol{x}_{t-1}+\boldsymbol{\Omega}_x s_t+\underbrace{(\boldsymbol{u}^x_t+\boldsymbol{\Phi}_{xz}\boldsymbol{z}_{t-1})}_{\equiv\boldsymbol{\epsilon}_t}, \tag{7}$$

with estimated impulse response functions

$$\widehat{IRF}^{bl}(h) = \widehat{\boldsymbol{\Phi}}^h_{xx}\widehat{\boldsymbol{\Omega}}_x. \tag{8}$$

In the following I assume that $\boldsymbol{\Phi}_{xz}\neq\boldsymbol{0}$ which precludes the trivial case in which there are no higher-order spillovers; obviously, in case $\boldsymbol{\Phi}_{xz}=\boldsymbol{0}$ the bilateral model in Equation (7) will deliver consistent estimates. The main question of this paper is whether the impulse response functions in Equation (5) can be estimated consistently for a shock in the spillover-sending

information on financial market expectations. See Section 4 for more details.

economy 1 to the spillover-receiving economy 2 in the bilateral VAR model in Equation (7) if there are higher-order spillovers, that is whether

$$\underset{T\to\infty}{plim}\, \widehat{IRF}^{bl}(h) = IRF_x(h). \tag{9}$$

2.2 Consistency of Spillover Estimates in the Bilateral Model

In order to facilitate the exposition notice that from Equation (5) it follows that the true spillovers are given by

$$\begin{aligned} IRF_x(0) &= \boldsymbol{\Omega}_x, & (10)\\ IRF_x(1) &= \boldsymbol{\Phi}_{xx}\boldsymbol{\Omega}_x + \boldsymbol{\Phi}_{xz}\boldsymbol{\Omega}_z, & (11)\\ IRF_x(2) &= (\boldsymbol{\Phi}_{xx}^2 + \boldsymbol{\Phi}_{xz}\boldsymbol{\Phi}_{zx})\boldsymbol{\Omega}_x + (\boldsymbol{\Phi}_{xx}\boldsymbol{\Phi}_{xz} + \boldsymbol{\Phi}_{xz}\boldsymbol{\Phi}_{zz})\boldsymbol{\Omega}_z. & (12)\\ &\vdots \end{aligned}$$

Obviously, Equations (10) to (12) suggest that consistency of the parameter estimates in the bilateral model implies inconsistent spillover estimates, that is

$$\underset{T\to\infty}{plim}\, \widehat{\boldsymbol{\Phi}}_{xx} = \boldsymbol{\Phi}_{xx} \wedge \underset{T\to\infty}{plim}\, \widehat{\boldsymbol{\Omega}}_x = \boldsymbol{\Omega}_x \implies \underset{T\to\infty}{plim}\, \widehat{IRF}^{bl}(h) \neq IRF_x(h). \tag{13}$$

This is because using the true values for $\boldsymbol{\Phi}_{xx}$ and $\boldsymbol{\Omega}_x$ for calculating the spillovers in the bilateral model according to Equation (8) cannot yield the true spillovers as the higher-order spillovers arising through the terms involving $\boldsymbol{\Phi}_{xz}$ in Equations (10) to (12) are omitted. However, if the parameter estimates obtained from the bilateral model are inconsistent, it may in principle be that the asymptotic bias is such that it offsets the bias arising due to the omission of the global dimension.

In order to determine whether the spillover estimates obtained from the bilateral model are consistent it is thus crucial to determine the probability limits of the parameter estimates in Equation (7). Denoting by

$$\boldsymbol{X} \equiv \begin{bmatrix} \boldsymbol{x}_0, \boldsymbol{x}_1, \ldots, \boldsymbol{x}_{T-1} \\ s_1, s_2, \ldots, s_T \end{bmatrix}, \quad \boldsymbol{Y} \equiv [\boldsymbol{x}_1, \boldsymbol{x}_2, \ldots, \boldsymbol{x}_T], \quad \boldsymbol{\epsilon} \equiv [\boldsymbol{\epsilon}_1, \boldsymbol{\epsilon}_2, \ldots, \boldsymbol{\epsilon}_T], \quad \boldsymbol{B} \equiv [\boldsymbol{\Phi}_{xx}, \boldsymbol{\Omega}_x],$$

the ordinary least squares estimator of the bilateral VAR model in Equation (7) delivers

$$\begin{aligned}
\widehat{\boldsymbol{B}} &= \boldsymbol{Y}\boldsymbol{X}'(\boldsymbol{X}\boldsymbol{X}')^{-1} \;=\; \boldsymbol{B}+\boldsymbol{\epsilon}\boldsymbol{X}'(\boldsymbol{X}\boldsymbol{X}')^{-1} \\
&= \boldsymbol{B}+\left[\sum \boldsymbol{\epsilon}_t\boldsymbol{x}_{t-1}', \sum \boldsymbol{\epsilon}_t s_t\right]\begin{bmatrix}\sum \boldsymbol{x}_{t-1}\boldsymbol{x}_{t-1}' & \sum \boldsymbol{x}_{t-1}s_t \\ \sum \boldsymbol{x}_{t-1}'s_t & \sum s_t^2\end{bmatrix}^{-1} \\
&= \boldsymbol{B}+\left[\sum (\boldsymbol{u}_t^x+\boldsymbol{\Phi}_{xz}\boldsymbol{z}_{t-1})\boldsymbol{x}_{t-1}', \sum (\boldsymbol{u}_t^x+\boldsymbol{\Phi}_{xz}\boldsymbol{z}_{t-1})s_t\right]\begin{bmatrix}\sum \boldsymbol{x}_{t-1}\boldsymbol{x}_{t-1}' & \sum \boldsymbol{x}_{t-1}s_t \\ \sum \boldsymbol{x}_{t-1}'s_t & \sum s_t^2\end{bmatrix}^{-1} \quad (14)
\end{aligned}$$

with summations running from $t = 2$ to T. Under standard assumptions (see Lütkepohl, 2007, chpt. 3) we have

$$\underset{T\to\infty}{plim}\ \widehat{\boldsymbol{B}} \;=\; \boldsymbol{B}+[\boldsymbol{\Phi}_{xz}\boldsymbol{\Sigma}_{zx}^{y}, \boldsymbol{0}]\begin{bmatrix}\boldsymbol{\Sigma}_{xx}^{y} & \boldsymbol{\Sigma}_{xs} \\ \boldsymbol{\Sigma}_{sx} & \sigma_s^2\end{bmatrix}^{-1}, \tag{15}$$

and applying the partitioned inverse we obtain

$$\underset{T\to\infty}{plim}\ \widehat{\boldsymbol{\Phi}}_{xx} \;=\; \boldsymbol{\Phi}_{xx}+\boldsymbol{\Phi}_{xz}\boldsymbol{\Sigma}_{zx}^{y}\left(\boldsymbol{\Sigma}_{xx}^{y}-\boldsymbol{\Sigma}_{xs}\boldsymbol{\Sigma}_{sx}\sigma_s^{-2}\right)^{-1}, \tag{16}$$

$$\underset{T\to\infty}{plim}\ \widehat{\boldsymbol{\Omega}}_{x} \;=\; \boldsymbol{\Omega}_{x}-\boldsymbol{\Phi}_{xz}\boldsymbol{\Sigma}_{zx}^{y}\left(\boldsymbol{\Sigma}_{xx}^{y}\right)^{-1}\boldsymbol{\Sigma}_{xs}\left[\sigma_s^2-\boldsymbol{\Sigma}_{sx}(\boldsymbol{\Sigma}_{xx}^{y})^{-1}\boldsymbol{\Sigma}_{xs}\right]^{-1}. \tag{17}$$

Equations (16) and (17) suggest that the parameter estimates and the impulse response functions obtained from the bilateral VAR model are in general inconsistent asymptotically due to the omission of the rest of the world $\boldsymbol{z}_t$. Therefore, when there exist higher-order spillovers and $\boldsymbol{\Phi}_{xz} \neq \boldsymbol{0}$ the parameter estimates obtained from the bilateral model are inconsistent. Moreover, and importantly, plugging in the probability limits in Equations (16) and (17) in Equations (10) to (12) it is *not* the case that the asymptotic bias is such that it compensates for the terms missing due to disregarding the global dimension of the true data-generating process. As a result, in the presence of higher-order spillovers the spillover estimates obtained from bilateral are inconsistent.

2.3 Determinants of the Asymptotic Bias

If we think of the multilateral model in Equation (1) as a macroeconomic model of the world economy, how is the inconsistency in the parameter estimates of the bilateral VAR model in Equations (16) and (17) related to economies' overall and bilateral integration patterns? In order to shed light on this question, assume without loss of generality that the matrices $\boldsymbol{\Gamma}_\ell$ in Equation (1) are given by

$$\boldsymbol{\Gamma}_0 \;=\; \boldsymbol{W}\odot\left(\boldsymbol{\iota}'\otimes\gamma_0\right), \tag{18}$$

$$\boldsymbol{\Gamma}_1 \;=\; \boldsymbol{\Gamma}_1^{(d)}+\boldsymbol{W}\odot\left(\boldsymbol{\iota}'\otimes\gamma_1\right), \tag{19}$$

where $\odot$ represents element-wise multiplication, $\boldsymbol{\iota}$ is an $N \times 1$ vector of ones, $\boldsymbol{\Gamma}_1^{(d)}$ is a diagonal matrix, and the matrix $\boldsymbol{W}$ has zeros on its diagonal and its row sum is unity. The matrix $\boldsymbol{W}$ thus reflects a bilateral weight matrix and $w_{ij} \equiv [\boldsymbol{W}]_{ij}$ the importance of economy j to economy i relative to the other economies $k \neq j$. In turn, $[\boldsymbol{\gamma}_\ell]_i$ reflects the overall susceptibility of economy i to developments in the rest of the world. For example, w_{ij} could be related to the share of economy j in economy i's overall trade and financial integration with the rest of the world, and $[\boldsymbol{\gamma}_\ell]_i$ to economy i's overall trade and financial integration with the rest of the world.

The assumptions in Equations (18) and (19) result in

$$\boldsymbol{\Phi}_{xz} = \boldsymbol{\Phi}_{xz}(\boldsymbol{W}, \boldsymbol{\gamma}_0, \boldsymbol{\gamma}_1), \tag{20}$$

$$\boldsymbol{\Sigma}_{zx}^{y} = \boldsymbol{\Sigma}_{zx}^{y}(\boldsymbol{W}, \boldsymbol{\gamma}_0, \boldsymbol{\gamma}_1, \boldsymbol{\Psi}, \boldsymbol{\Sigma}_u, \sigma_s^2), \tag{21}$$

$$\boldsymbol{\Sigma}_{xx}^{y} = \boldsymbol{\Sigma}_{xx}^{y}(\boldsymbol{W}, \boldsymbol{\gamma}_0, \boldsymbol{\gamma}_1, \boldsymbol{\Psi}, \boldsymbol{\Sigma}_u, \sigma_s^2), \tag{22}$$

$$\boldsymbol{\Sigma}_{sx} = \boldsymbol{\Sigma}_{sx}(\boldsymbol{W}, \boldsymbol{\gamma}_0, \boldsymbol{\gamma}_1, \boldsymbol{\Psi}, \sigma_s^2). \tag{23}$$

The inconsistency in the estimates $\widehat{\boldsymbol{\Phi}}_{xx}$ and $\widehat{\boldsymbol{\Omega}}_x$ obtained from the bilateral VAR model in Equations (16) and (17) thus depends on economies' bilateral integration patterns reflected by the weight matrix $\boldsymbol{W}$ and on their overall susceptibility to developments in the rest of the world reflected by $\boldsymbol{\gamma}_\ell$, $\ell = 0, 1$.

While the relationships in Equations (20) to (23) are too complex in order to read off directly the impact of $\boldsymbol{W}$ and $\boldsymbol{\gamma}_\ell$ on the asymptotic bias in the spillover estimates in Equations (16) and (17), the latter can be illustrated graphically. Specifically, rewrite the stacked model in Equation (1) as

$$x_{1t} = \sum_{j=2}^{N} \gamma_{0,1j} x_{jt} + \gamma_{1,11} x_{1,t-1} + \sum_{j=2}^{N} \gamma_{1,1j} x_{j,t-1} + s_t + \nu_{1t}, \tag{24}$$

$$x_{it} = \sum_{j=1,\, j\neq i}^{N} \gamma_{0,ij} x_{jt} + \gamma_{1,ii} x_{i,t-1} + \sum_{j=1, j\neq i}^{N} \gamma_{1,ij} x_{j,t-1} + \nu_{it}, \quad i = 2, \ldots, N, \tag{25}$$

again assuming that $\gamma_{\ell,ij} = [\boldsymbol{\gamma}_\ell]_i \cdot w_{ij}$ with $\sum_j w_{ij} = 1$ as in Equations (18) and (19). Based on the parametrisation

$$\gamma_{1,ii} \sim N(0.6, 0.05^2), \tag{26}$$

$$[\boldsymbol{\gamma}_\ell]_2 = \bar{\gamma} \quad \text{for } \ell = 0, 1, \tag{27}$$

$$[\boldsymbol{\gamma}_0]_i \sim N\left(0.1, 0.025^2\right) \quad \text{for } i \neq 2, \tag{28}$$

$$[\boldsymbol{\gamma}_1]_i \sim N\left(0.2, 0.025^2\right) \quad \text{for } i \neq 2, \tag{29}$$

$$s_t \sim N(0, 1^2), \tag{30}$$

$$w_{21} = \bar{\omega}, \tag{31}$$

$$w_{ij} = \widetilde{w}_{ij} / \sum\nolimits_j \widetilde{w}_{ij}, \quad \widetilde{w}_{ij} \sim N(1/N, N^{-2}), \quad \widetilde{w}_{ij} \geq 0, \quad \text{for } \; i \neq 2 \wedge j \neq 1, \tag{32}$$

Figure 1 displays the true impulse response functions for both the spillover sending economy 1 and the spillover-receiving economy 2 for small and large values of $\bar{\gamma}$ and $\bar{\omega}$. The magnitudes of the spillovers range from being hardly discernible to being as large as the effects in the spillover-sending economy.

Based on the parametrisation in Equations (26) to (32), the probability limits of the parameter estimates in Equations (16) and (17) as well as the impulse response functions in Equation (8), the asymptotic bias in the spillover estimates obtained from the bilateral model can be calculated for different values of $\bar{\gamma}$ and $\bar{\omega}$. In particular, denote by $IRF^{bl}_{21}(h)$ the impulse response function of the spillover-receiving economy 2 to the shock s_t in the spillover-sending economy 1 at horizon h. I consider the asymptotic bias over all impulse response horizons, at a fixed horizon $\bar{h}$ and for the peak spillover

$$bias^{asympt}_{average} = H^{-1} \sum_{h=1}^{H} \left[\underset{T \to \infty}{plim} \; \widehat{IRF}^{bl}_{21}(h) - IRF_{21}(h) \right] / \sum_{h=1}^{H} IRF_{21}(h), \tag{33}$$

$$bias^{asympt}_{fixhor} = \left[\underset{T \to \infty}{plim} \; \widehat{IRF}^{bl}_{21}(\bar{h}) - IRF_{21}(\bar{h}) \right] / IRF_{21}(\bar{h}), \tag{34}$$

$$bias^{asympt}_{peak} = \left\{ \underset{T \to \infty}{plim} \; \left[\underset{h}{max} \; \widehat{IRF}^{bl}_{21}(h) \right] - \underset{h}{max} \; \left[IRF_{21}(h) \right] \right\} / \underset{h}{max} \; \left(IRF_{21}(h) \right), \tag{35}$$

Figure 2 suggests that the different versions of the asymptotic bias in the spillover estimates rise monotonously with rising $\bar{\gamma}$, i.e. when the spillover-receiving economy 2's overall susceptibility to developments in the rest of the world rises. Moreover, the different versions of the asymptotic bias fall with rising $\bar{\omega}$, i.e. when the spillover-sending economy 1 accounts for an increasing share of the spillover-receiving economy 2's overall integration with the rest of the world. These results are consistent with the hypothesis that as a spillover-receiving economy's overall susceptibility to developments in the rest of the world rises, the spillovers it receives increasingly occur through higher-order spillovers and spillbacks which a bilateral model fails to capture adequately. Moreover, the results are consistent with the hypothesis that as the spillover-sending economy's importance in the spillover-receiving economy's overall integration with the rest of the world rises, spillovers occur less through such indirect and more through direct bilateral channels.

These asymptotic results provide some insight in the pitfalls of using bilateral models for spillover analysis. However, for empirical applications it is important to understand whether finite sample issues exacerbate the asymptotic bias, how that depends on the sample size N and T, and how bilateral models can be expected to perform relative to multilateral models. In the next section I consider a Monte Carlo experiment to shed light on these issues.

3 Monte Carlo Experiment

I carry out a Monte Carlo experiment in which I generate data from a multilateral VAR model and estimate the spillovers to economy 2 from shocks that occur in economy 1 using a bilateral VAR model and a multilateral GVAR model. The data-generating process is given by Equations (24) and (25) and the parametrisation in Equations (26) to (32). As in the analysis of the determinants of the asymptotic bias in Section 2.3, I consider variations in the data-generating process regarding (i) the overall susceptibility of the spillover-receiving economy 2 to developments in the other economies reflected by $\bar{\gamma}$, and (ii) the relative importance of the spillover-sending economy 1 in spillover-receiving economy 2's overall integration with the rest of the world reflected by $\bar{\omega}$.

3.1 The Bilateral Model

The bilateral model I estimate on the simulated data is given by

$$\begin{bmatrix} x_{1t} \\ x_{2t} \end{bmatrix} = \boldsymbol{A} \begin{bmatrix} x_{1,t-1} \\ x_{2,t-1} \end{bmatrix} + \boldsymbol{B} s_t + \boldsymbol{e}_t. \tag{36}$$

The impulse response functions for the bilateral model are given by

$$IRF^{bl}(h) \quad = \quad \boldsymbol{A}^h \boldsymbol{B}. \tag{37}$$

3.2 The Multilateral Model

For the multilateral model I consider a GVAR model and estimate for each economy

$$x_{it} = a_{ii} x_{i,t-1} + a^*_{0,i} x^*_{it} + a^*_{1,i} x^*_{i,t-1} + b_i s_t + e_{it}, \tag{38}$$

with $x^*_{it} \equiv \sum_j w_{ij} x_{jt}$. Each economy's model in Equation (38) can be re-written as

$$\begin{aligned} [1, -a^*_{0,i}] \begin{bmatrix} x_{it} \\ x^*_{it} \end{bmatrix} &= [a_{ii}, a^*_{1,i}] \begin{bmatrix} x_{i,t-1} \\ x^*_{i,t-1} \end{bmatrix} + b_i s_t + e_{it}, \\ \left[1, -a^*_{0,i}\right] \boldsymbol{L}_i \boldsymbol{y}_t &= [a_{ii}, a^*_{1,i}] \boldsymbol{L}_i \boldsymbol{y}_{t-1} + b_i s_t + e_{it}, \end{aligned} \tag{39}$$

where $\boldsymbol{L}_i$ are link matrices containing the relevant weights w_{ij} for the construction of the "foreign" variables so that $(x_{it}, x^*_{it})' = \boldsymbol{L}_i \boldsymbol{y}_t$. In stacked form the GVAR model is given by

$$\begin{bmatrix} (1, -a^*_{0,1})\boldsymbol{L}_1 \\ (1, -a^*_{0,2})\boldsymbol{L}_2 \\ \vdots \\ (1, -a^*_{0,N})\boldsymbol{L}_N \end{bmatrix} \boldsymbol{y}_t = \begin{bmatrix} (a_{11}, a^*_{1,2})\boldsymbol{L}_1 \\ (a_{12}, a^*_{1,3})\boldsymbol{L}_2 \\ \vdots \\ (a_{1N}, a^*_{1,N})\boldsymbol{L}_N \end{bmatrix} \boldsymbol{y}_{t-1} + \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_N \end{bmatrix} s_t + \begin{bmatrix} e_{1t} \\ e_{2t} \\ \vdots \\ e_{Nt} \end{bmatrix}, \tag{40}$$

or more compactly

$$\begin{aligned} \boldsymbol{\mathcal{A}}_0 \boldsymbol{y}_t &= \boldsymbol{\mathcal{A}}_1 \boldsymbol{y}_{t-1} + \boldsymbol{\mathcal{B}} s_t + \boldsymbol{\epsilon}_t, \\ \boldsymbol{y}_t &= \boldsymbol{\mathcal{A}}_0^{-1} \boldsymbol{\mathcal{A}}_1 \boldsymbol{y}_{t-1} + \boldsymbol{\mathcal{A}}_0^{-1} \boldsymbol{\mathcal{B}} s_t + \boldsymbol{\mathcal{A}}_0^{-1} \boldsymbol{\epsilon}_t \\ &= \boldsymbol{A} \boldsymbol{y}_{t-1} + \boldsymbol{B} s_t + \boldsymbol{e}_t. \end{aligned} \tag{41}$$

The impulse response functions from the multilateral GVAR model are given by

$$IRF^{ml}(h) = \boldsymbol{A}^h \boldsymbol{B}. \tag{42}$$

3.3 Simulation Results

3.3.1 Finite Sample Bias and Root Mean Square Error

Denote the finite sample bias of the spillover estimates obtained from the bilateral and the multilateral models $j \in \{ml, bl\}$ by

$$bias^j_{average} = R^{-1} \sum_{r=1}^{R} H^{-1} \left[\sum_{h=1}^{H} \left(\widehat{IRF}^j_r(h) - IRF_r(h) \right) \right] / \sum_{h=1}^{H} IRF_r(h), \tag{43}$$

$$bias^j_{fixhor} = R^{-1} \sum_{r=1}^{R} \left(\widehat{IRF}^j_r(\bar{h}) - IRF_r(\bar{h}) \right) / IRF_r(\bar{h}), \tag{44}$$

$$bias^j_{peak} = R^{-1} \sum_{r=1}^{R} \left\{ \max_h \left[\widehat{IRF}^j_r(\bar{h}) \right] - \max_h \left[IRF_r(\bar{h}) \right] \right\} / \max_h \left[IRF_r(\bar{h}) \right], \tag{45}$$

and the corresponding RMSEs by

$$rmse^j_{average} = \sqrt{R^{-1}\sum_{r=1}^{R} H^{-1}\left[\sum_{h=1}^{H}\left(\widehat{IRF}^j_r(h) - IRF_r(h)\right)^2\right] / \sum_{h=1}^{H} IRF_r(h)}, \quad (46)$$

$$rmse^j_{fixhor} = \sqrt{R^{-1}\sum_{r=1}^{R}\left(\widehat{IRF}^j_r(\bar{h}) - IRF_r(\bar{h})\right)^2 / IRF_r(\bar{h})}, \quad (47)$$

$$rmse^j_{peak} = \sqrt{R^{-1}\sum_{r=1}^{R}\left\{\left[\max_h\left(\widehat{IRF}^j_r(h)\right) - \max_h\left(IRF_r(h)\right)\right]^2 / \max_h\left(IRF_r(h)\right)\right\}}, \quad (48)$$

where R represents the total number of replications in the Monte Carlo experiment.

In order to compare the properties of the spillover estimates obtained from the bilateral and the multilateral models I consider the difference in their absolute bias and the RMSE as defined in Equations (43) to (48), that is

$$\Delta bias_m = |bias^{ml}_m| - |bias^{bl}_m|, \quad m \in \{average, fixhor, peak\}, \quad (49)$$

$$\Delta rmse_m = rmse^{ml}_m - rmse^{bl}_m, \quad m \in \{average, fixhor, peak\}, \quad (50)$$

across different values of $\bar{\gamma}$ and $\bar{\omega}$. A negative value for $\Delta bias_m$ indicates that the finite sample bias of the spillover estimates obtained from the bilateral model is larger in absolute terms than that of the spillover estimates obtained from the multilateral model; similarly, a negative value for $\Delta rmse_m$ indicates that the RMSE of the spillover estimates obtained from the bilateral model is larger in absolute terms than that of the spillover estimates obtained from the multilateral model.

The results for the differences in the finite sample bias and the RMSE are displayed in Figure 3 and are consistent with those for the asymptotic bias of the bilateral model in Section 2.[3] In particular, the Monte Carlo results suggest that the finite sample bias and the RMSE of the spillover estimates obtained from the bilateral model rise relative to those of the spillover estimates obtained from the multilateral model with increasing $\bar{\gamma}$ and fall with increasing $\bar{\omega}$. Thus, the finite sample bias of the spillover estimates obtained from the bilateral model relative to that of the spillover estimates obtained from the multilateral model rises as the spillover-receiving economy becomes more susceptible to developments in the rest of the world overall, and it falls as the spillover-sending economy becomes more important in the spillover-receiving economy's overall integration with the rest of the world.

[3]These results are based on $N = 50$ and $T = 150$. See Section 3.3.4 below for results based on alternative choices of N and T.

3.3.2 Calibrated Weight Matrix

One could argue that the multilateral GVAR model considered in the Monte Carlo experiment is favoured relative to the bilateral model as it is estimated using the true weights in the matrix $\boldsymbol{W}$ for the link matrices $\boldsymbol{L}_i$ in Equation (39), which is typically not possible in practice. In order to render the Monte Carlo experiment more realistic in this regard, for the estimation of the multilateral model I consider a calibrated weight matrix $\boldsymbol{C}$ whose elements $c_{ij} \equiv [\boldsymbol{C}]_{ij}$ are given by

$$\widetilde{c}_{ij} = w_{ij} + \varsigma_{ij}, \qquad \varsigma_{ij} \sim N\left[0, (w_{ij}/\tau)^2\right], \tag{51}$$

$$c_{ij} = \widetilde{c}_{ij} / \sum\nolimits_j \widetilde{c}_{ij}. \tag{52}$$

The parameter τ can be interpreted as the accuracy of the calibrated weights. For τ=5, Figure 5 shows the difference in the finite sample bias and the RMSE of the spillover estimates obtained from the bilateral and the multilateral models if estimation of the latter is carried out using the calibrated weight matrix $\boldsymbol{C}$. The results are very similar to those from the baseline in Figure 3.

3.3.3 Factor-augmented VAR

As an alternative to the GVAR one could consider a factor-augmented VAR (FAVAR) model as a multilateral framework.[4] Specifically, denote by f_t the first principal component of economies' $i = 3, 4, \ldots, N$ variables $x_{3t}, x_{4t}, \ldots, x_{Nt}$ in $\boldsymbol{z}_t$. Then, consider the FAVAR

$$\begin{bmatrix} x_{1t} \\ x_{2t} \\ f_t \end{bmatrix} = \boldsymbol{A} \begin{bmatrix} x_{1,t-1} \\ x_{2,t-1} \\ f_{t-1} \end{bmatrix} + \boldsymbol{B} s_t + \boldsymbol{\zeta}_t, \tag{53}$$

and the impulse response functions

$$IRF^{favar}(h) = \boldsymbol{A}^h \boldsymbol{B}. \tag{54}$$

Figure 6 displays the differences between the finite sample bias and the RMSE of the spillover estimates to a shock s_t across the bilateral and the FAVAR model. The results suggest that the finding of the bilateral model delivering inferior spillover estimates relative to a multilateral

[4] Yet another alternative to the GVAR model is the multi-country VAR model of Canova and Ciccarelli (2009). Specifically, Canova and Ciccarelli (2009) propose to decompose the autoregressive coefficients in a multi-country VAR model such as the one in Equation (2) into a variable-specific, lag-specific, equation-specific and country-specific component. However, notice that for the case of the simple multilateral VAR model considered in this paper—a VAR of order one with only one variable per country—the approach of Canova and Ciccarelli (2009) implies only a single parameter to be estimated for each country. As a result, the unaccounted idiosyncratic variation in the dynamics are rather large and the estimation results rather inaccurate by construction.

model is not specific to selecting the GVAR model as benchmark. In particular, the finite sample bias and the RMSE of the bilateral model also rise relative to that of the FAVAR model for increasing $\bar{\gamma}$ and decreasing $\bar{\omega}$.

3.3.4 Response Surface Regressions

Tables 1 and 2 report the results from response surface regressions (see MacKinnon, 1994)

$$\Delta bias_j = \alpha_0 + \alpha_1 log(T_j) + \alpha_2 log(N_j) + \alpha_3 \bar{\gamma}_j + \alpha_4 \bar{\omega}_j + \epsilon_j, \quad (55)$$

$$\Delta rmse_j = \rho_0 + \rho_1 log(T_j) + \rho_2 log(N_j) + \rho_3 \bar{\gamma}_j + \rho_4 \bar{\omega}_j + \varsigma_j, \quad (56)$$

where j refers to runs of Monte Carlo experiments with different choices of $T \in \{100, 150, 500\}$, $N \in \{25, 50, 100\}$, $\bar{\omega}$ and $\bar{\gamma}$. Consistent with the graphical representation of the results from the Monte Carlo experiment in Figure 3, the response surface regressions suggest that both the difference in the finite sample bias and RMSE of the spillover estimates across the bilateral and the multilateral models rise with $\bar{\gamma}$ and fall with $\bar{\omega}$. This continues to hold when $\bar{\gamma}$ and $\bar{\omega}$ are entered in the regression in non-linear terms. Interestingly, the difference in the finite sample bias rises with increasing T, as the estimates obtained from the multilateral model converge to the true quantities while those from the bilateral model to the inconsistent probability limit. In contrast, the difference in the bias decreases with increasing N, as the magnitude of higher-order spillovers falls as the importance of units other than $i = 2$ for the spillover-receiving economy 1 vanishes; this result is consistent with the findings in Chudik and Straub (2010) according to which a bilateral model obtains as $N \longrightarrow \infty$ if the spillover sending economy is (the only) locally dominant unit for the spillover-receiving economy. The results for the effects of $\bar{\omega}$ and $\bar{\gamma}$ on the differences in the RMSE across the multilateral and the bilateral model are similar to those for the finite sample bias. However, in contrast to the results for the bias the differences in the RMSE also fall with increasing T, consistent with the convergence to the respective probability limits.

4 Estimating Spillovers Empirically

As an empirical illustration of the possible differences in spillover estimates obtained from bilateral and multilateral models and their determinants I consider the global output spillovers from US monetary policy. In particular, I estimate the spillovers from US monetary policy shocks using two-country VAR models and a GVAR model. In line with the previous analysis, I circumvent the problem of identifying US monetary policy shocks by using the time series of shocks s_t^j constructed by Romer and Romer (2004), Bernanke and Kuttner (2005), Sims and Zha (2006) as well as Barakchian and Crowe (2013).[5] Consistent with the exposition in the previous sections, the US economy is represented by the unit with index 1.

4.1 The Bilateral Model

The two-country VAR models are given by

$$\begin{bmatrix} \boldsymbol{x}_{1t} \\ \boldsymbol{x}_{it} \end{bmatrix} = \sum_{m=1}^{p} \boldsymbol{A}_{im} \begin{bmatrix} \boldsymbol{x}_{1,t-m} \\ \boldsymbol{x}_{i,t-m} \end{bmatrix} + \sum_{m=0}^{q} \boldsymbol{B}_{im} s_{t-m}^{j} + \sum_{m=0}^{q} \boldsymbol{C}_{im} g_{t-m} + \boldsymbol{e}_{it}, \quad i = 2, 3, \ldots, N, \tag{57}$$

where the vector of endogenous variables for the domestic economy in $\boldsymbol{x}_{it}$ includes output growth, inflation, short-term interest rates and the nominal bilateral exchange rate vis-à-vis the US dollar; the US variables in $\boldsymbol{x}_{1t}$ include US output growth, inflation and short-term interest rates; g_t is a global variable and includes oil price inflation. I allow for lags of the exogenous shock s_t^j in order for the bilateral VAR model to be able to display richer dynamics in the impulse response functions; moreover, introducing lags of the exogenous shock time series is also routinely done in the empirical literature (see, for example, Romer and Romer, 2004).

4.2 The Multilateral Model

The GVAR model is adopted from Georgiadis (forthcoming) and consists of unit-specific VAR models given by

$$\boldsymbol{x}_{it} = \sum_{m=1}^{p} \boldsymbol{A}_{im} \boldsymbol{x}_{i,t-m} + \sum_{m=0}^{p^*} \boldsymbol{A}_{im}^{*} \boldsymbol{x}_{i,t-m}^{*} + \sum_{m=0}^{q} \boldsymbol{B}_{im} s_{t-m}^{j} + \boldsymbol{e}_{it}, \quad i = 1, 2, 3, \ldots, N, \tag{58}$$

where the vector of domestic endogenous variables $\boldsymbol{x}_{it}$ includes output growth and inflation for all economies; for non-euro area economies, it also includes short-term interest rates and the nominal bilateral exchange rate vis-à-vis the euro. In the GVAR model of Georgiadis (forthcoming) one unit represents the ECB's monetary policy by a VAR model in which euro area short-term interest rates are determined as a function of GDP-weighted aggregate euro area output growth and inflation. Moreover, another unit refers to an oil block in which oil price inflation is determined endogenously as a function of GDP-weighted world output growth, inflation and interest rates. For all the economies in the GVAR model, the vector of foreign variables $\boldsymbol{x}_{it}^{*}$ includes oil price inflation as well as trade-weighted averages of global

[5] Georgiadis (forthcoming) shows that the spillover estimates obtained on the basis of these shocks are very similar to those obtained from applying sign restrictions on short-term interest rates, inflation and the nominal effective exchange rate (as well as output growth, oil prices and money growth) in order to identify US monetary policy shocks.

output growth, inflation and interest rates. For the euro area economies, the vector of "foreign" variables in addition includes euro area short-term interest rates which are determined in the ECB's model. The VAR models are estimated unit-by-unit, followed by the derivation of the global solution (see Equation (41)) which is used for the construction of impulse response functions.

4.3 Baseline Results

Upon estimation of the models on quarterly data over the time period from 1999 to 2009 I calculate the impulse response functions of output to the exogenous US monetary policy shock s_t^j and determine the trough response (the maximum drop in output; see, for example, Georgiadis, forthcoming).[6,7]

Figure 7 presents a scatter plot of the output spillover estimates obtained from the two-country VAR models against those from the GVAR model using the monetary policy shocks constructed by Bernanke and Kuttner (2005).[8] Two observations stand out: First, as reflected by the statistically significant intercept estimate the global output spillovers from US monetary policy obtained from the two-country VAR models are systematically smaller (in absolute terms) than those obtained from the GVAR model: The estimates for the drop in economies' output in response to a 100 basis points tightening in US monetary policy from the GVAR model are on average larger by 50 basis points compared to those from the two-country VAR models. Second, as reflected by the statistically significant slope estimate being smaller than unity, while there is a positive correlation between the spillover estimates across the two-country model and the GVAR model the correspondence is not perfect.[9] And the regression results in Table 3 show that these findings are not specific to the use of the monetary policy shock time series constructed by Bernanke and Kuttner (2005).[10] Together with the results from the asymptotic analysis in Section 2 and those from the Monte Carlo

[6] The lag orders for both the two-country VAR and the country-specific VAR models in the GVAR model are determined using the Akaike information criterion.

[7] The results for the responses at fixed horizons are similar and omitted to conserve space.

[8] I identify and drop economies as outliers if their spillover estimate is more than four standard deviations away from the cross-country mean.

[9] Another observation that stands out is that the (trough) spillover estimates obtained from the two-country VAR models are positive for many economies. Positive spillover estimates from a US monetary policy tightening are theoretically possible for two reasons. First, the spillovers may be estimated imprecisely, not allowing one to reject the hypothesis that the true spillover is negative. Second, the true spillover can be positive or negative depending on whether expenditure-reducing or expenditure-switching effects dominate: On the one hand, the drop in US output leads to a fall in the spillover-receiving economy's foreign demand; on the other hand, the appreciation of the US dollar stimulates US demand for the spillover-receiving economy's goods. While theoretically possible, however, positive spillovers to a US monetary policy tightening are rather inconsistent with conventional wisdom according to which the US is an important driver of the global business cycle.

[10] In order to preclude that the spillover estimates based on a particular monetary policy shock time series have a disproportionate influence on the coefficient estimates in Equation (59), I standardise the variance of the spillover estimates for a given j whenever I run pooled regressions.

analysis in Section 3 this evidence points to a statistically and economically significant mismeasurement of the global spillovers from US monetary policy on the basis of two-country VAR models.

The evidence in Sections 2 and 3 suggests that the difference in the spillover estimates between the two-country VAR models and the GVAR model should be related to (i) spillover-receiving economies' overall integration with the rest of the world that renders them susceptible to developments abroad, and (ii) the importance of the US (the spillover-sending economy) in spillover-receiving economies' overall integration with the rest of the world. In particular, we would expect the two-country VAR models to produce spillover estimates that are close to those obtained from the GVAR model if an economy is less integrated in global trade and finance overall, and if the US accounts for a large share in spillover-receiving economies' overall trade and financial integration with the rest of the world.

In order to shed light on whether these hypotheses are borne out by the data, I exploit information on (i) economies' overall trade and financial integration, as well as on (ii) the relative importance of the US in economies' overall trade and financial integration. In particular, I consider the sum of imports and exports to GDP ($tradeopenn_i$) as a measure of an economy's overall trade integration; the ratio of gross foreign assets and liabilities to GDP ($finopenn_i$) as a measure of an economy's overall financial integration; the share of imports from and exports to the US in an economy's total trade ($tradeshareUS_i$) as a measure of the importance of the US in an economy's overall trade integration; and the sum of US financial assets held by an economy's domestic residents and an economy's foreign liabilities held by US residents relative to the economy's total foreign assets and liabilities ($finshareUS_i$) as a measure of the relative importance of the US in an economy's overall financial integration with the rest of the world.[11] Figure 8 displays the data and shows that there are pronounced cross-country differences in economies' overall integration with the rest of the world and the relative importance of the US therein. The top and middle panels of Figure 9 present scatterplots of the differences between the spillovers estimates obtained from the GVAR and the two-country VAR models on the one hand, and economies' overall integration with the rest of the world as well as the relative importance of the US therein on the other hand.[12] In line with the results from Sections 2 and 3, the scatterplots suggest that spillover estimates obtained from the GVAR model are systematically larger (in absolute terms) than those obtained from the two-country VAR models for economies which exhibit a stronger overall trade and financial

[11]The data on trade are taken from the World Development Indicators, those on gross foreign assets and liabilities from Lane and Milesi-Ferretti (2007), and those on bilateral holdings from the IMF Coordinated Portfolio Investment Survey. I take the logarithm of one plus the time averages over 1999 to 2009 of the raw data in order to alleviate the impact of possible outliers.

[12]To improve power and to account for possible measurement error in the construction of the monetary policy shock time series, I consider simultaneously the spillover estimates from the models using the monetary policy shock times series constructed by Romer and Romer (2004), Bernanke and Kuttner (2005), Sims and Zha (2006) as well as Barakchian and Crowe (2013). However, below it is shown that the results for individual monetary policy shocks are similar to those from the pooled samples considered here.

integration with the rest of the world; also in line with the results from Sections 2 and 3, the differences between the spillover estimates obtained from the GVAR and the two-country VAR models are smaller if the US accounts for a large share of an economy's overall trade and financial integration.

To move beyond unconditional correlations I run the following regression

$$\begin{aligned}\widehat{IRF}_i^{gvar,j} - \widehat{IRF}_i^{tcvar,j} &= \beta_0 + \beta_1 \cdot tradeopenn_i + \beta_2 \cdot tradeshareUS_i \\ &+\beta_3 \cdot finopenn_i + \beta_4 \cdot finshareUS_i \\ &+\beta_5 \cdot contiguityUS_i + e_i, \end{aligned} \quad (59)$$

where $\widehat{IRF}_i^j$ represents the estimated trough response of output to the US monetary policy shock obtained from the two-country VAR models and the GVAR model using the monetary policy shock time series constructed by Romer and Romer (2004), Bernanke and Kuttner (2005), Sims and Zha (2006) as well as Barakchian and Crowe (2013) ($j \in \{RR, BK, SZ, BC\}$). Recall that the spillover estimates from a monetary policy tightening in the US obtained from the GVAR model are negative. If higher-order spillovers and spillbacks are better captured by the spillover estimates obtained from the GVAR model we would expect $\widehat{\beta}_1 < 0$ and $\widehat{\beta}_3 < 0$, as the former should be more pronounced for economies which are strongly integrated with the rest of the world overall. At the same time, if direct bilateral spillovers are captured equally well by the two-country VAR models and the GVAR model we would expect $\widehat{\beta}_2 > 0$ and $\widehat{\beta}_4 > 0$, as the former should be more important for economies for which the US accounts for a large share of the spillover-receiving economies' overall integration with the rest of the world. In addition to economies' integration patterns I also consider a dummy variable equalling unity for Mexico and Canada and thereby reflecting contiguity with the US: Recall that the results in Sections 2 and 3 suggest that the relationship between bilateral and multilateral integration on the one hand and differences in spillover estimates across the two-country VAR and GVAR models may have a non-linear shape; moreover, as can be seen in Figure 8 economies neighbouring the US exhibit very large values for their bilateral integration with the US that does not appear to be aligned with the relationship of the variables for the other economies.

Table 4 reports the results from various regressions of Equation (59). The baseline results presented in the first column suggest that the differences in the spillover estimates between the two-country VAR models and the GVAR model are related to differences in economies' integration patterns: In line with the results in Sections 2 and 3 the two-country VAR models produce spillover estimates which are systematically smaller (in absolute terms) than those obtained from the GVAR model for economies which are more integrated overall, and for economies in which the US accounts for a smaller share in their overall global integration. In particular, when trade and financial integration variables are entered simultaneously the coefficient estimates for overall financial integration and the share of trade accounted for by the US are statistically significant; the coefficient estimates for overall trade integration and the share of financial integration accounted for by the US are only qualitatively consistent with the results in Sections 2 and 3. When the variables reflecting trade and financial integration are entered in separate regressions, the coefficient estimates for multilateral and bilateral integration patterns are all (at least marginally) statistically significant and in line with the results from Sections 2 and 3. As the lack of individual significance when the variables are included jointly is likely to be due to the high correlation between financial and trade integration in the data, in the following I consider the principal components of multilateral (bilateral) trade and financial integration patterns. Specifically, when I run the regression in Equation (59) with the principal components of economies' multilateral and bilateral integration patterns the coefficient estimates are highly statistically significant and consistent with the results from Sections 2 and 3.

4.4 Corroborating Evidence

4.4.1 Robustness

In contrast to the two-country VAR models, the GVAR model accounts for the fact that euro area monetary policy is carried out at the euro area-wide rather than at the country level. The differences in the spillover estimates could be driven by this conceptual inconsistency in the two-country VAR models. However, Table 5 suggests that the results are very similar to those from the baseline if euro area economies are dropped from the sample. The results are also very similar to those from the baseline when standard errors are clustered at the monetary policy shock level j and when I apply robust regression (`rreg` in Stata). The results are also similar if I consider the value of the impulse response of output to a US monetary policy shock after seven quarters rather than the trough spillover, even if the estimates are less precise.

In the baseline I pool the spillover estimates obtained from separate estimations of the two-country VAR models and the GVAR model using the monetary policy shock time series constructed by Romer and Romer (2004), Bernanke and Kuttner (2005), Sims and Zha (2006) as well as Barakchian and Crowe (2013). Table 6 reports the results for the regression of the difference between the spillover estimates across the two-country and the GVAR models on economies' integration patterns for each individual monetary policy shock time series. While the estimates are typically less precise, they are overall consistent with those from the pooled sample. Importantly, the baseline results do not seem to be driven by a particular monetary policy shock time series.

4.4.2 Exchange Rate Regime

Direct expenditure-reducing spillovers through a drop in US demand for domestic goods are alleviated if economies' exchange rate can depreciate vis-à-vis the US dollar and trigger expenditure-switching. Therefore, other factors held constant, direct trade spillovers from the US should be smaller for economies with a flexible exchange rate regime relative to economies with a fixed exchange rate. As a result, ceteris paribus, having the US account for a larger share in an economy's overall trade integration should reduce by less the difference in the spillover estimates between the two-country VAR models and the GVAR model for economies with a flexible exchange rate than for economies with a fixed exchange rate. Similarly, as flexible exchange rates insulate at least to some extent domestic financial conditions from those in the US (the famous "trilemma", see Obstfeld et al., 2005), direct financial spillovers from the US should be smaller in economies with a flexible exchange rate; as a result, ceteris paribus, having the US account for a larger share in an economy's overall financial integration should reduce by less the difference between the spillover estimates in the two-country VAR models and the GVAR model for economies with a flexible exchange rate than for economies with a fixed exchange rate.

The data are mostly consistent with these hypotheses. Specifically, Table 7 reports results from the regression of Equation (4) with interactions between the bilateral trade and financial integration variables and an economy's exchange rate regime included.[13] With the interaction terms included the coefficient estimate for the relative importance of the US in economies' overall trade integration is statistically significant with the expected sign (higher values of the exchange rate regime variable indicate more flexible regimes); and the interaction with the exchange rate regime is also statistically significant with the expected sign. The results for financial integration in the first regression are at best only marginally statistically significant. However, when only financial integration variables are considered the coefficient estimates have the expected signs, but only the coefficients of the levels of the variables and not the interaction are statistically significant. That the coefficient estimates for financial and trade integration are not both statistically significant in the same regression might again be due to their strong correlation. This is consistent with the results reported in the last column in Table 7, in which the principal components of multilateral and bilateral integration patterns are considered. In this case, the coefficient estimates of bilateral integration patterns and the interaction with the exchange rate regime are both statistically significant.

[13]The data for the exchange rate regime are taken from Ilzetzki et al. (2010). I adjust the data so that euro area economies have a flexible exchange rate regime.

4.4.3 Distance to the US

One could also argue that differences in the spillover estimates between the two-country VAR models and the GVAR model may be related to economies' geographic distance to the US. Specifically, conditional on controlling for bilateral and multilateral integration patterns, spillovers for economies farther away from the US should occur less through direct bilateral channels, thereby increasing the differences across the spillover estimates obtained from the GVAR and the two-country VAR models. While the coefficient estimate for geographic distance to the US reported in Table 8 has a negative sign in line with this hypothesis, it is estimated very imprecisely.

4.4.4 Trade Network Centrality

Economies which are more central in the global trade network may be subject to larger higher-order spillovers, exacerbating the differences between the spillover estimates obtained from the two-country VAR models and the GVAR model. The results from a regression that includes a measure of economies' centrality in the global trade network reported in Table 8 are consistent with this hypothesis: The coefficient estimate for centrality in the global trade network is negative and statistically significant.[14]

4.4.5 Higher-order spillover susceptibility index

[To be written.]

4.4.6 Involvement in Global Value Chains

Finally, for economies further upstream in the global value chain the extent of higher-order spillovers and spillbacks should be more limited. As a result, the spillover estimates obtained from two-country VAR models should be closer to those from the GVAR model for these economies. Moreover, economies which participate more in global value chains as measured by the share of domestic value added in gross exports should exhibit smaller spillovers due to multilateral channels. The data are consistent with these hypothesis. Table 8 reports the results from a regression in which a measure of economies' position in global value chains (higher values reflect an upstream position in global value chains) and the share of domestic value added in gross exports are entered as additional explanatory variables (higher values

[14] The data for centrality are taken from the CEPII database. The variable used is the principle component of degree, eigenvector, closeness and strength centrality.

reflect a higher share of domestic value added).[15] The coefficient estimates are statistically significant and have the expected signs.

5 Conclusion

Due to the increasing global trade and financial integration cross-country spillovers have become a major element of economic policy thinking over the last decades. Estimating the magnitude of spillovers for different economies is thus an important branch of research in international macroeconomics and finance. The analysis in this paper suggests that spillover estimates from easy-to-implement bilateral, two-country models are in general less accurate than those from technically more demanding multilateral models. In particular, the accuracy of the spillover estimates obtained from bilateral models depends on spillover-receiving economies' global integration patterns: Stronger overall susceptibility to developments in the rest of the world accentuate the inaccuracy in the spillover estimates obtained from bilateral models; and strong bilateral trade and financial integration with the spillover-sending economy improve accuracy. The analysis in this paper also suggests that the differences in the spillover estimates between bilateral and multilateral models can be economically significant in practice. Spillover estimates from bilateral models should thus be taken with caution, and more resources should be devoted to the development of multilateral multi-country models.

[15] I calculate the index for the position in global value chains using the World Input-Output Database as

$$gvc_i^{pos} \equiv log\left(1 + iv_i/e_i\right) - log\left(1 + fv_i/e_i\right), \quad (60)$$

where iv_i represents the indirectly exported value added of country i embodied in other economies exports, fv_i the value added from foreign sources embodied in economy i's gross exports, and e_i gross exports. The data for the domestic value added share of exports are taken from Johnson and Noguera (2012).

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A Tables

Table 1: Response Surface Regression for the Difference in the Bias of the Peak Spillover Estimate obtained from the Multilateral and Bilateral Model

	(1)	(2)	(3)	(4)	(5)
$[\gamma_\ell]_2$	-0.010***	-0.010***	-0.008**	-0.014***	
	(0.00)	(0.00)	(0.04)	(0.00)	
w_{21}	0.023***	0.023***	0.053***	0.045***	
	(0.00)	(0.00)	(0.00)	(0.00)	
$\log(T)$		-0.002***	-0.002***	-0.002***	-0.002***
		(0.00)	(0.00)	(0.00)	(0.00)
$\log(N)$		0.006***	0.006***	0.006***	0.006***
		(0.00)	(0.00)	(0.00)	(0.00)
$[\gamma_\ell]_2$ squared			-0.002	-0.002	
			(0.54)	(0.52)	
w_{21} squared			-0.043***	-0.043***	
			(0.00)	(0.00)	
$[\gamma_\ell]_2$ x w_{21}				0.017***	
				(0.00)	
$\log([\gamma_\ell]_2)$					-0.004***
					(0.00)
$\log(w_{21})$					0.007***
					(0.00)
Constant	-0.012***	-0.025***	-0.030***	-0.027***	-0.017***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Observations	324	324	324	324	324
Adjusted R^2	0.52	0.88	0.91	0.92	0.91

p-values in parentheses

Robust standard errors.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 2: Response Surface Regression for the Difference in the RMSE of the Peak Spillover Estimate obtained from the Multilateral and Bilateral Model

	(1)	(2)	(3)	(4)	(5)
$[\gamma_\ell]_2$	-0.011***	-0.011***	-0.001	-0.001	
	(0.00)	(0.00)	(0.92)	(0.85)	
w_{21}	0.030***	0.030***	0.096***	0.095***	
	(0.00)	(0.00)	(0.00)	(0.00)	
$\log(T)$		0.001*	0.001**	0.001**	0.001**
		(0.07)	(0.03)	(0.03)	(0.04)
$\log(N)$		0.006***	0.006***	0.006***	0.006***
		(0.00)	(0.00)	(0.00)	(0.00)
$[\gamma_\ell]_2$ squared			-0.011*	-0.011*	
			(0.09)	(0.09)	
w_{21} squared			-0.094***	-0.094***	
			(0.00)	(0.00)	
$[\gamma_\ell]_2$ x w_{21}				0.002	
				(0.78)	
$\log([\gamma_\ell]_2)$					-0.004***
					(0.00)
$\log(w_{21})$					0.009***
					(0.00)
Constant	-0.014***	-0.039***	-0.050***	-0.050***	-0.026***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Observations	324	324	324	324	324
Adjusted R^2	0.55	0.75	0.86	0.86	0.84

p-values in parentheses

Robust standard errors.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 3: Correlation Between Trough Output Spillovers from US Monetary Policy obtained from the GVAR and Two-country VAR Models Using Different Monetary Policy Shock Measures

	(1) B&K	(2) R&R	(3) B&C	(4) S&Z	(5) Pooled
Two-country VAR peak IRF	0.57***	0.22**	0.53**	-0.46	0.23***
	(0.00)	(0.02)	(0.03)	(0.46)	(0.01)
Constant	-0.51***	-0.96***	-0.31***	-2.57***	
	(0.00)	(0.00)	(0.00)	(0.00)	
B&K dummy					-0.61***
					(0.00)
R&R dummy					-0.96***
					(0.00)
B&C dummy					-0.32***
					(0.00)
S&Z dummy					-2.50***
					(0.00)
Observations	54	52	54	54	214
Adjusted R^2	0.32	0.06	0.12	-0.01	0.74

p-values in parentheses
Robust standard errors.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 4: Determinants of Differences in Estimates of Trough Output Spillovers from US Monetary Policy obtained from the GVAR and Two-country VAR Models

	(1) Baseline	(2) Trade int.	(3) Fin. Int.	(4) PCs
Trade rel. to GDP	-0.24	-0.54		
	(0.53)	(0.11)		
Share of trade with US	3.88**	4.19***		
	(0.03)	(0.00)		
GFAL rel. to GDP	-0.19*		-0.22**	
	(0.08)		(0.02)	
Share of US in overall fin. integration	0.01		1.78***	
	(0.99)		(0.00)	
Contiguity dummy	-2.05***	-2.13***	-0.81***	-1.39***
	(0.00)	(0.00)	(0.00)	(0.00)
Multil. integration				-0.14**
				(0.04)
Bil. integration				0.25***
				(0.00)
Observations	214	214	214	214
Adjusted R^2	0.11	0.10	0.09	0.10

p-values in parentheses

Robust standard errors.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Determinants of Differences in Estimates of Trough Output Spillovers from US Monetary Policy obtained from the GVAR and Two-country VAR Models—Robustness

	(1) Baseline	(2) No EA	(3) Cluster	(4) rreg	(5) Fix h
Multil. integration	-0.14**	-0.13*	-0.14*	-0.22***	-0.09
	(0.04)	(0.09)	(0.06)	(0.00)	(0.22)
Bil. integration	0.25***	0.25***	0.25**	0.18***	0.14
	(0.00)	(0.00)	(0.01)	(0.00)	(0.12)
Contiguity dummy	-1.39***	-1.42***	-1.39***	-1.12***	-0.74*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.07)
Observations	214	167	214	214	213
Adjusted R^2	0.10	0.09	0.10	0.16	0.02

p-values in parentheses

Robust standard errors.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 6: Determinants of Differences in Estimates of Trough Output Spillovers from US Monetary Policy obtained from the GVAR and Two-country VAR Models—Regressions for Individual Monetary Policy Shock Time Series

	(1) Pooled	(2) B&K	(3) R&R	(4) B&C	(5) S&Z
Multil. integration	-0.14**	-0.11	0.11	-0.32***	-0.22**
	(0.04)	(0.45)	(0.49)	(0.00)	(0.01)
Bil. integration	0.25***	0.22	0.41***	0.08	0.29**
	(0.00)	(0.17)	(0.01)	(0.42)	(0.02)
Contiguity dummy	-1.39***	-1.19	-2.12***	-0.93	-1.37**
	(0.00)	(0.11)	(0.00)	(0.13)	(0.01)
Observations	214	54	52	54	54
Adjusted R^2	0.10	0.03	0.12	0.14	0.15

p-values in parentheses

Robust standard errors.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 7: Determinants of Differences in Estimates of the Trough Output Spillovers from US Monetary Policy obtained from the GVAR and Two-country VAR Models—Taking into Account Economies' Exchange Rate Regime

	(1)	(2)	(3)	(4)
Trade rel. to GDP	-0.35	-0.57		
	(0.38)	(0.11)		
Share of trade with US	12.10***	10.41***		
	(0.00)	(0.00)		
GFAL rel. to GDP	-0.14		-0.18*	
	(0.18)		(0.07)	
Share of US in overall fin. integration	-2.85		4.02*	
	(0.40)		(0.07)	
Contiguity dummy	-0.99	-1.41***	-0.75***	-1.10***
	(0.14)	(0.01)	(0.00)	(0.00)
ER regime	0.03	0.07**	0.06	-0.00
	(0.64)	(0.01)	(0.23)	(0.94)
Share of trade with US x ER regime	-1.07**	-0.73**		
	(0.01)	(0.01)		
Share of US in overall fin. integration x ER regime	0.39		-0.22	
	(0.24)		(0.29)	
Multil. integration				-0.11
				(0.12)
Bil. integration				0.70***
				(0.00)
Bil. integration x ER regime				-0.05**
				(0.02)
Observations	214	214	214	214
Adjusted R^2	0.13	0.12	0.08	0.12

p-values in parentheses

Robust standard errors.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 8: Determinants of Differences in Estimates of Trough Output Spillovers from US Monetary Policy obtained from the GVAR and Two-country VAR Models—Taking into Account Distance to the US and Trade Network Position Characteristics

	(1)	(2)	(3)	(4)
Multil. integration	-0.24***	-0.31***	-0.22***	-0.48***
	(0.00)	(0.00)	(0.00)	(0.00)
Bil. integration	0.15**	0.16***	0.16***	0.26***
	(0.02)	(0.01)	(0.00)	(0.01)
Contiguity dummy	-1.11**	-0.95**	-1.11***	-1.84***
	(0.02)	(0.01)	(0.00)	(0.00)
Distance to US	-0.10			
	(0.62)			
Centrality		-0.09*		
		(0.08)		
Higher-order spillover susceptibility score			-34.52**	
			(0.01)	
GVC position				16.82***
				(0.00)
VAX ratio (aggregate)				-4.99***
				(0.00)
Observations	214	178	214	130
Adjusted R^2	0.16	0.23	0.18	0.19

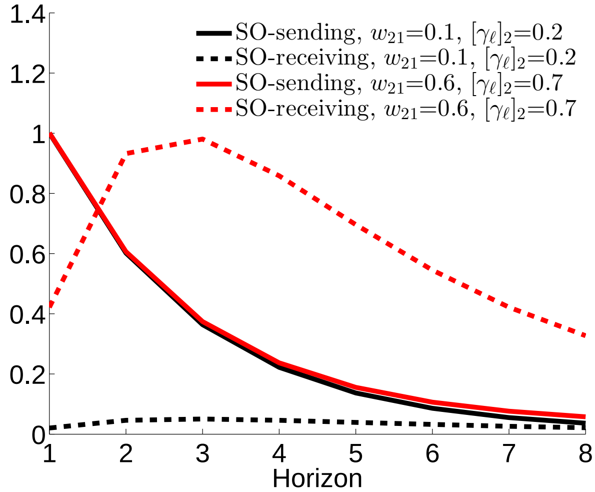
p-values in parentheses

Robust standard errors.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

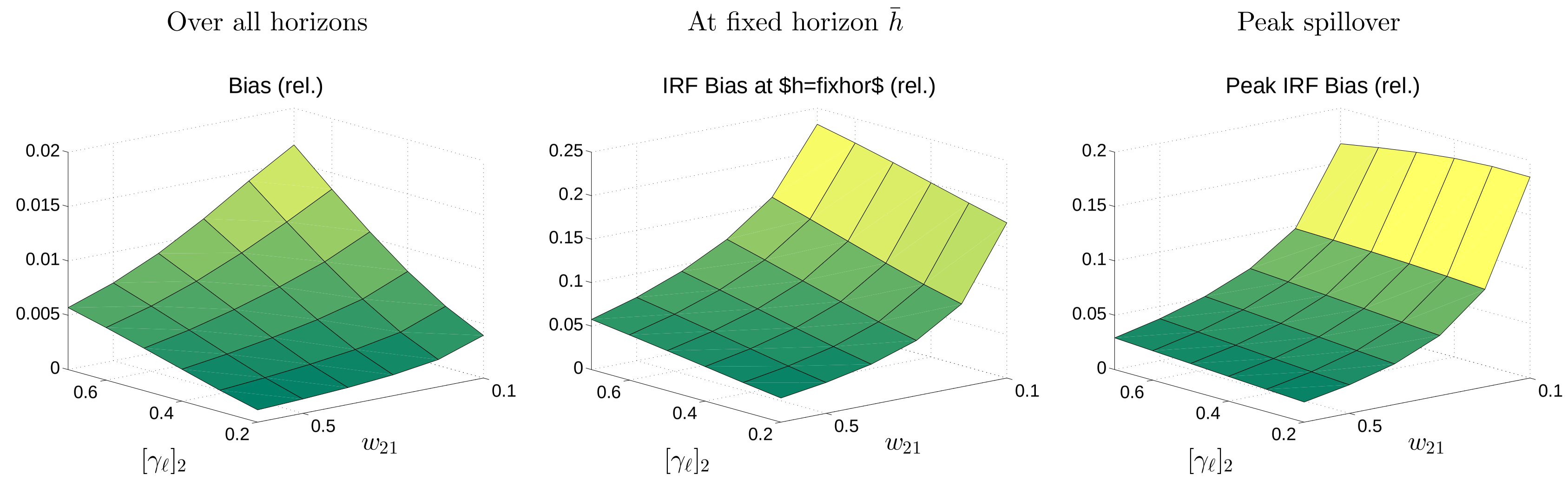
B Figures

Figure 1: Impulse Response Functions of Spillover-sending and Spillover-receiving Economy



Note: The figure displays the impulse response functions to a shock in the spillover-sending economy for the spillover-sending and the spillover-receiving economies for different values of w_{21} *and* $[\boldsymbol{\gamma}_\ell]_2$, $\ell = 0, 1$.

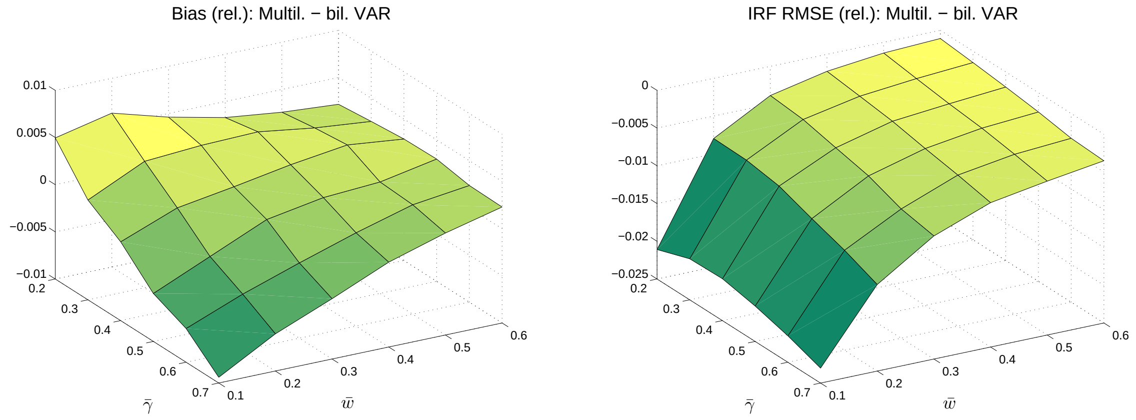
Figure 2: Asymptotic Bias of the Spillover Estimates for the Bilateral Model



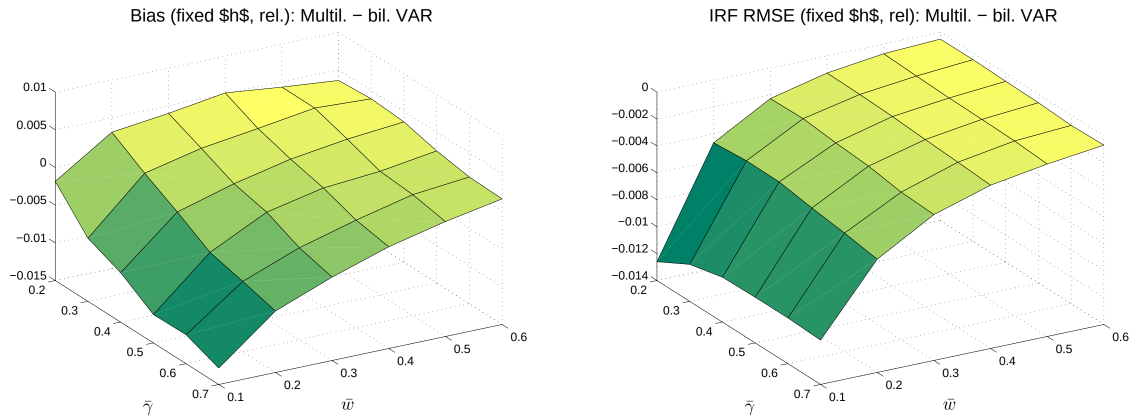
Note: The panels depict the asymptotic bias of spillovers estimates obtained from the bilateral model for different values of w_{21} and $[\boldsymbol{\gamma}_0]_2$.

Figure 3: Difference in Bias and RMSE of Spillover Estimates between the Multilateral and the Bilateral Model

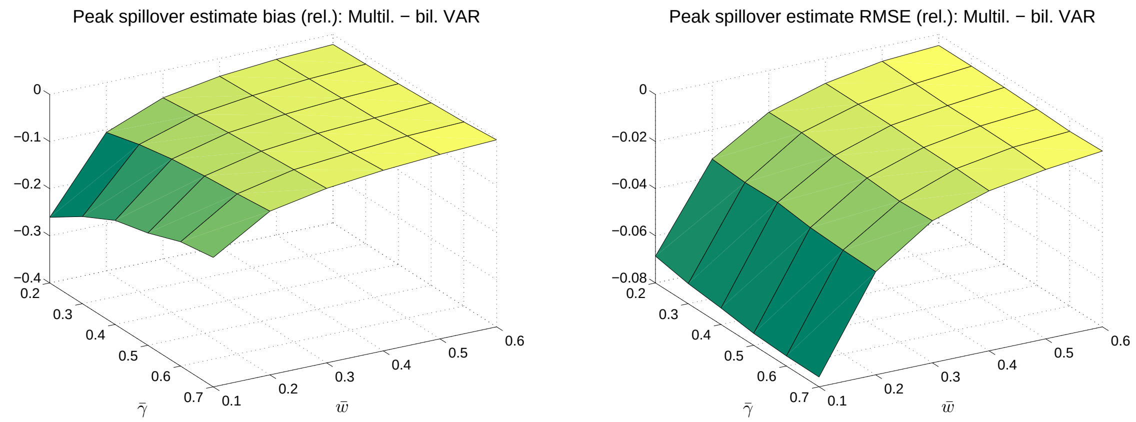
Over all horizons



At fixed horizon $\bar{h}$



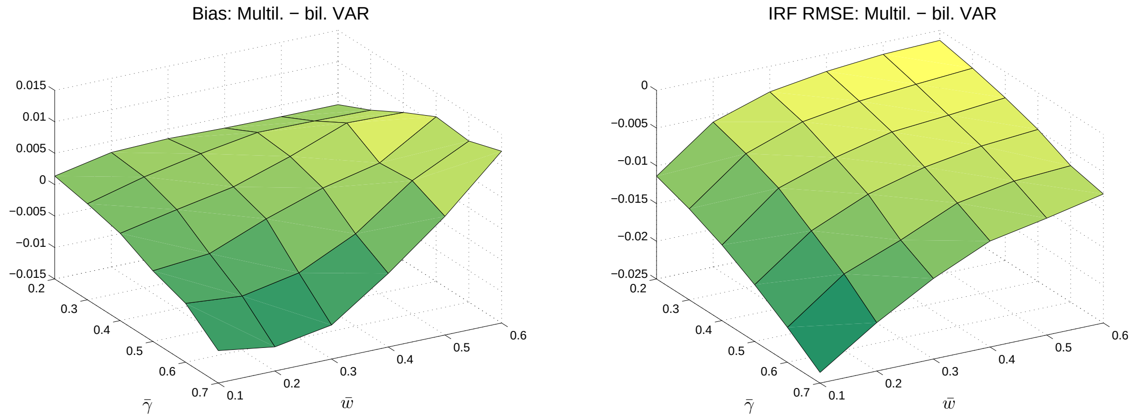
Peak spillover



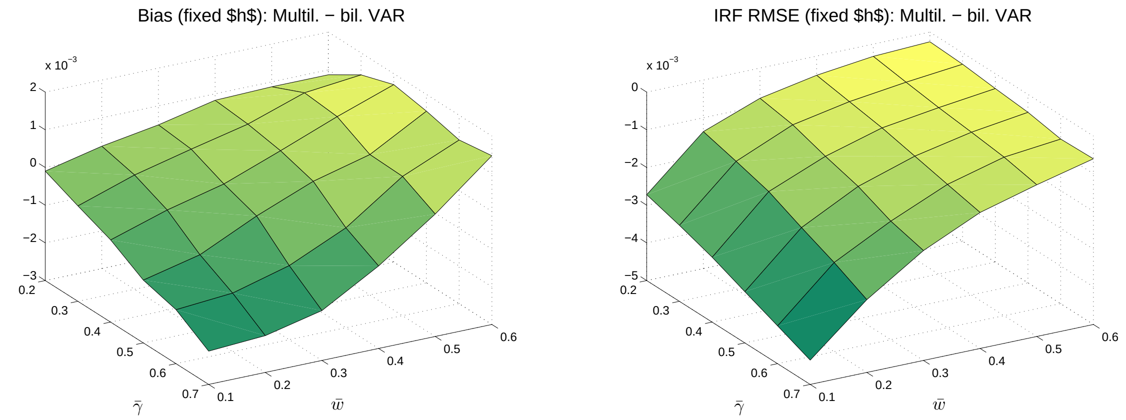
Note: The panels depict the differences in the bias (left-hand side panels) and RMSE (right-hand side panels) in the estimates of the spillovers from the multilateral model and the bilateral model. The differences in the bias and RMSE are plotted for Monte Carlo experiments with different specifications of $\bar{\omega}$ (right-hand side horizontal axes) and $\bar{\gamma}$ (left-hand side horizontal axes).

Figure 4: Absolute Difference in Bias and RMSE of Spillover Estimates between the Multilateral and the Bilateral Model

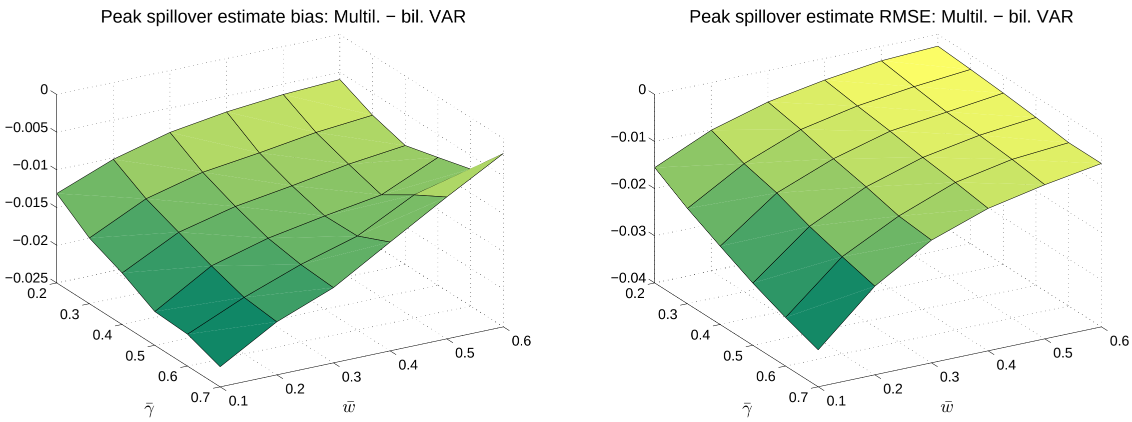
Over all horizons



At fixed horizon $\bar{h}$



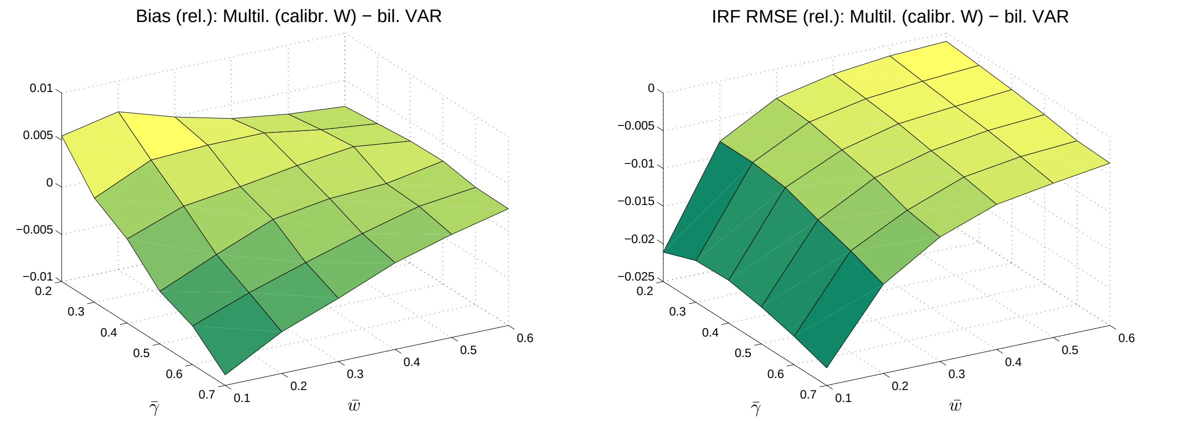
Peak spillover



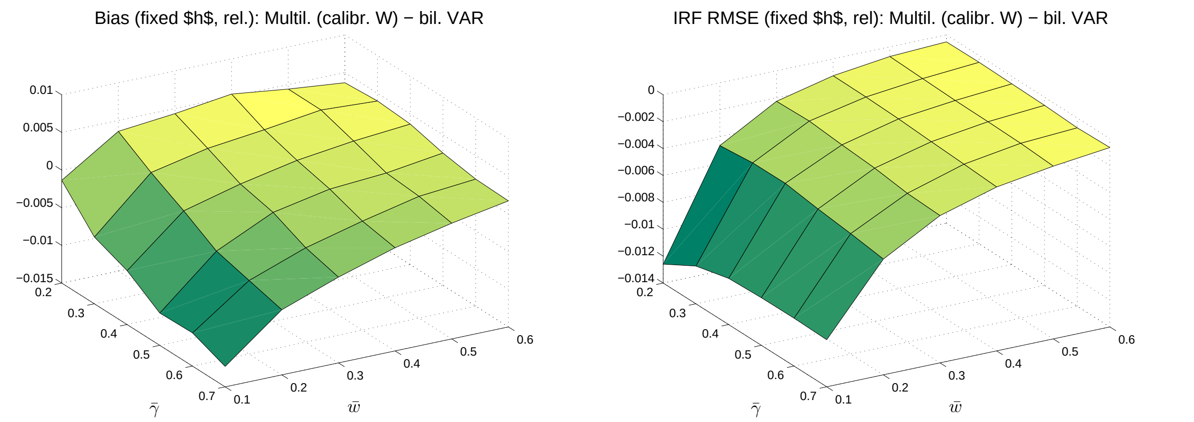
Note: The panels depict the differences in the bias (left-hand side panels) and RMSE (right-hand side panels) in the estimates of the spillovers from the multilateral model and the bilateral model. The differences in the bias and RMSE are plotted for Monte Carlo experiments with different specifications of $\bar{\omega}$ (right-hand side horizontal axes) and $\bar{\gamma}$ (left-hand side horizontal axes).

Figure 5: Difference in Bias and RMSE of Spillover Estimates between the Multilateral with Calibrated Weight Matrix $\boldsymbol{W}$ and the Bilateral Model

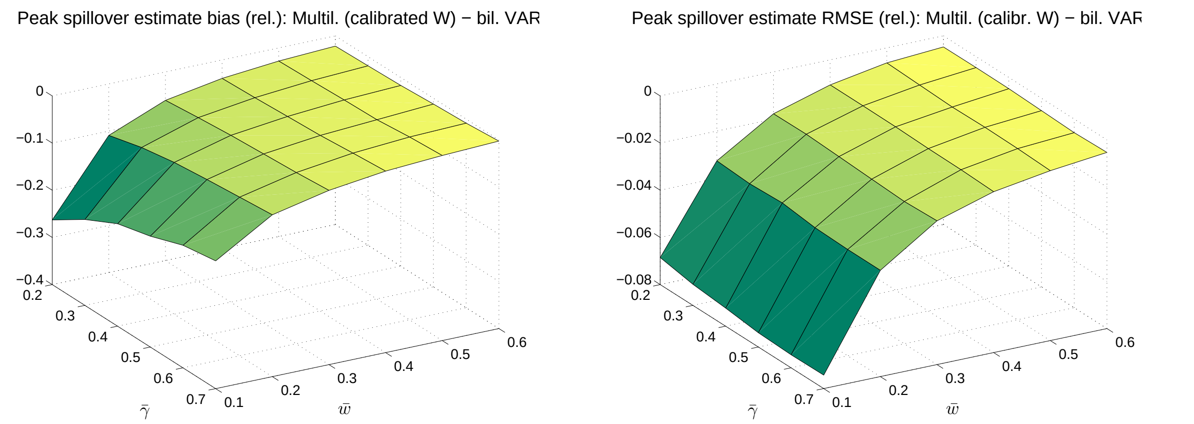
Over all horizons



At fixed horizon $\bar{h}$



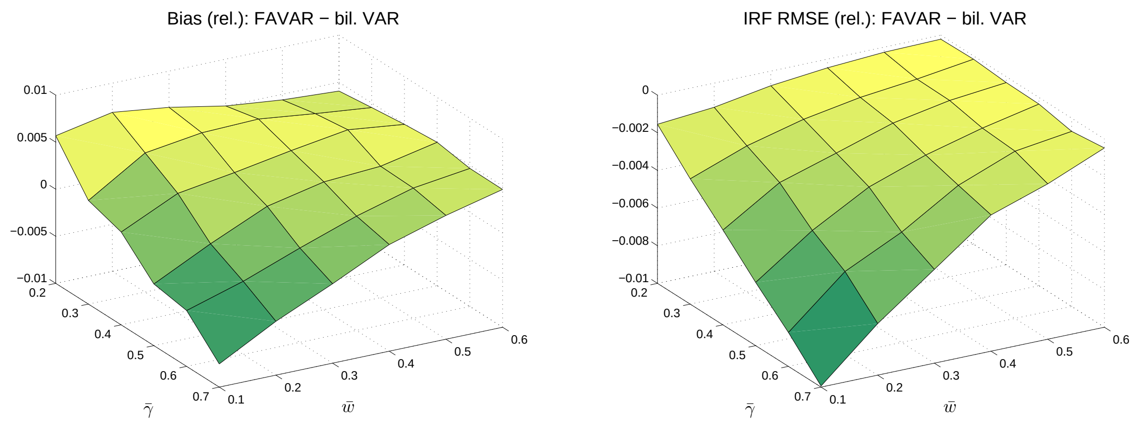
Peak spillover



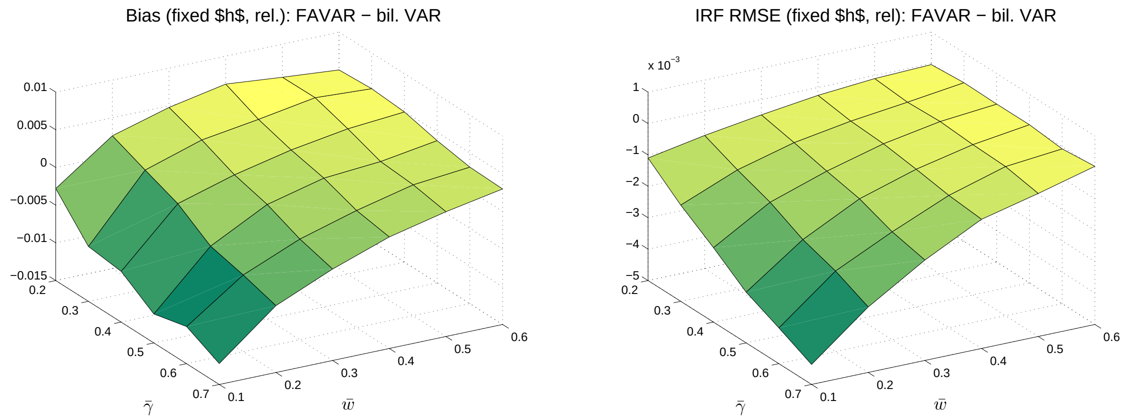
Note: The panels depict the differences in the bias (left-hand side panels) and RMSE (right-hand side panels) in the estimates of the spillovers from the multilateral and the bilateral model. The differences in the bias and RMSE are plotted for Monte Carlo experiments with different specifications of $\bar{\omega}$ (right-hand side horizontal axes) and $\bar{\gamma}$ (left-hand side horizontal axes).

Figure 6: Difference in Bias and RMSE of Spillover Estimates between the FAVAR and the Bilateral Model

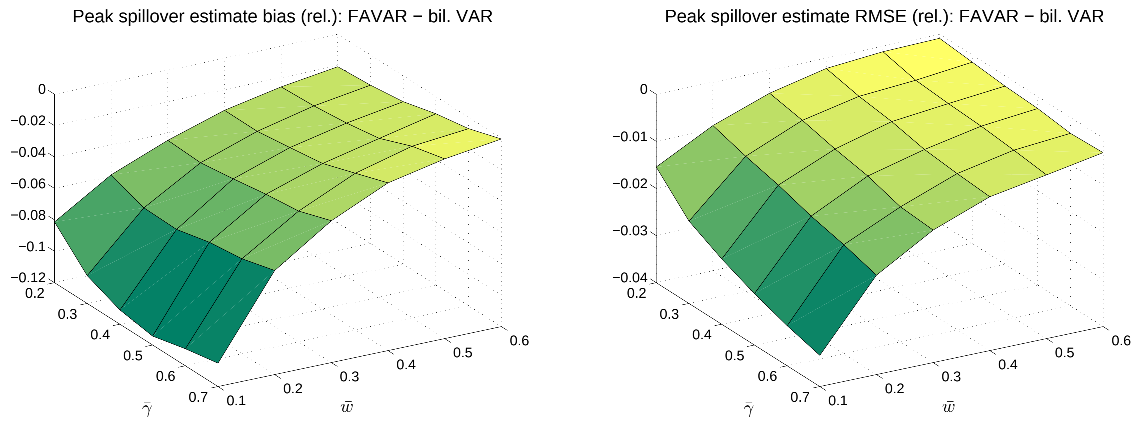
Over all horizons



At fixed horizon $\bar{h}$

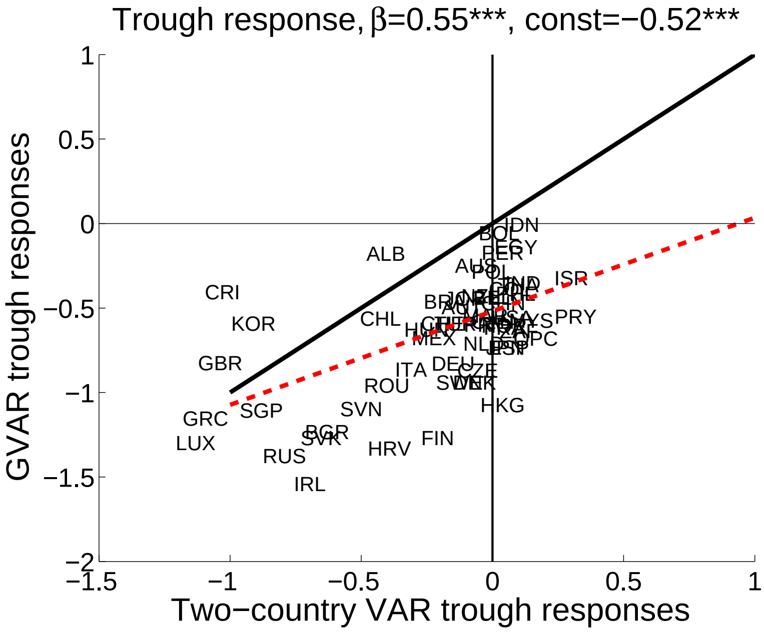


Peak spillover



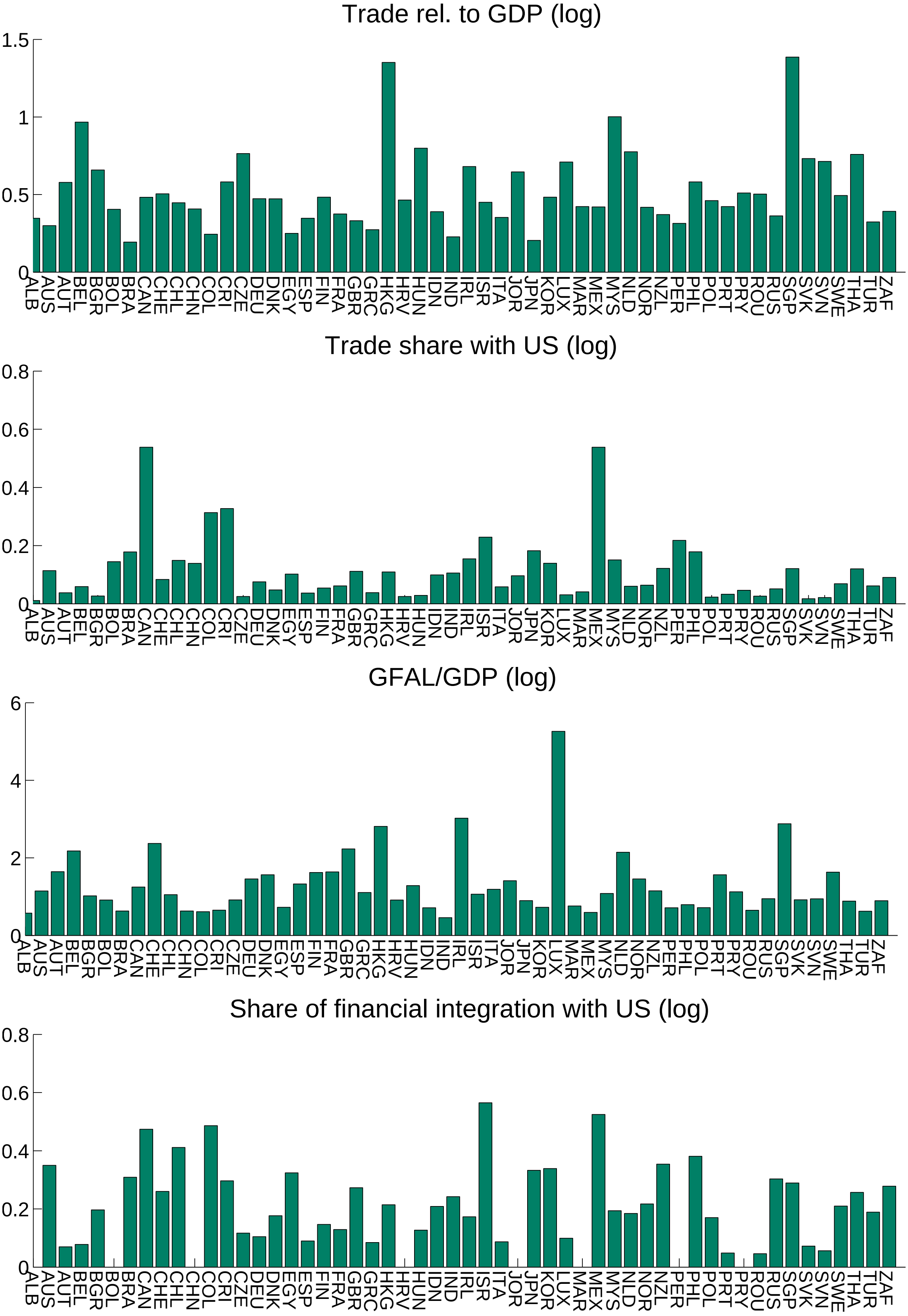
Note: The panels depict the differences in the bias (left-hand side panels) and RMSE (right-hand side panels) in the estimates of the spillovers from the FAVAR and the bilateral model. The differences in the bias and RMSE are plotted for Monte Carlo experiments with different specifications of $\bar{\omega}$ (right-hand side horizontal axes) and $\bar{\gamma}$ (left-hand side horizontal axes).

Figure 7: Differences in Spillover Estimates across GVAR and Two-country VAR Models



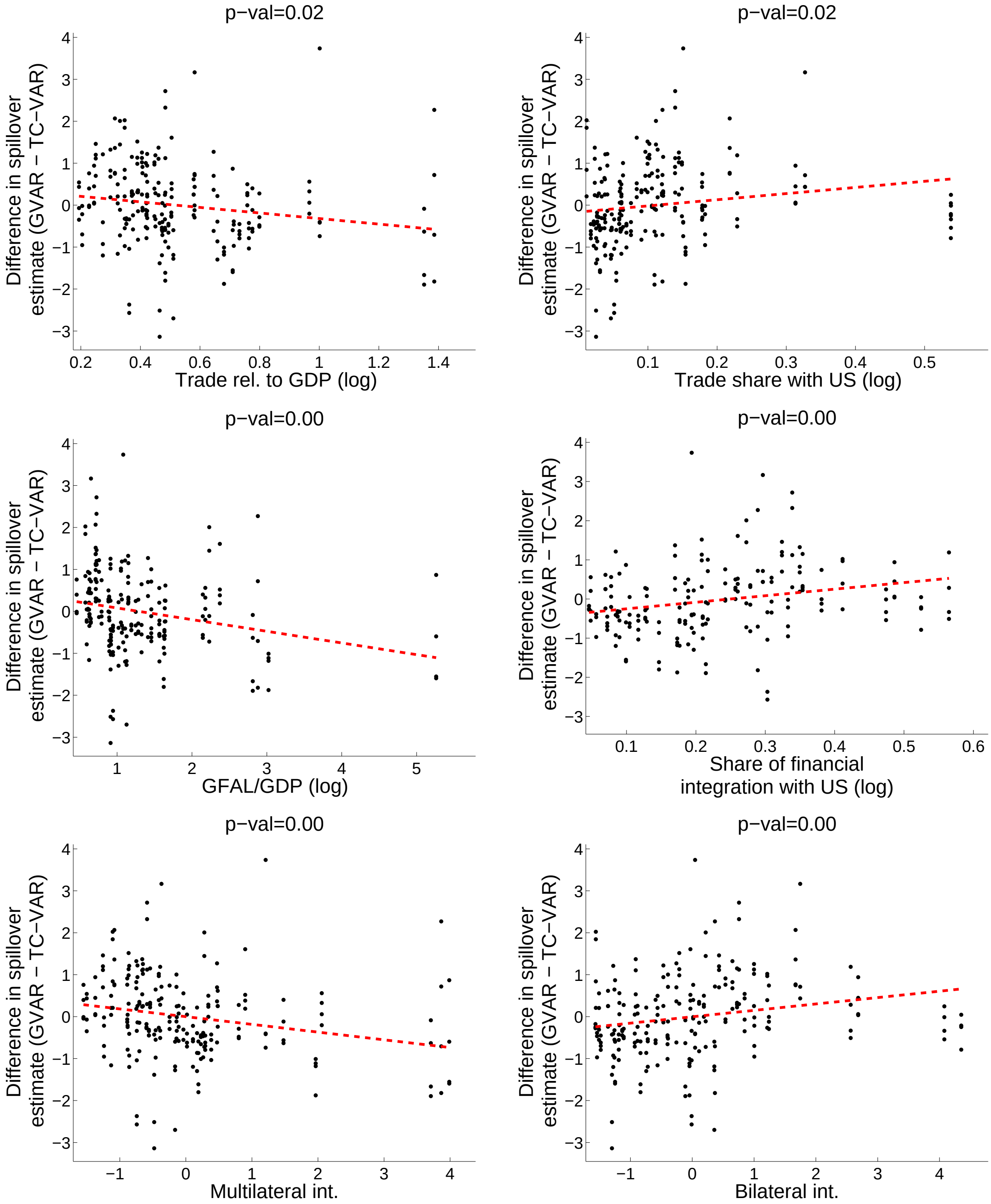
*Note: The figure displays the trough spillover estimates of real GDP to a 100 basis points contractionary US monetary policy shock obtained from two-country VAR models (horizontal axis) and a GAVR model (vertical axis). The black solid line is the 45-degree line and the red dashed line the fit from a linear regression of the trough spillover estimates from the GVAR model on those from the two-country models. The slope and intercept estimates rom this regression are provided in the figure title. *** indicates statistical significance at the 1% significance level. The spillover estimates are based on the monetary policy shocks constructed by Bernanke and Kuttner (2005).*

Figure 8: Economies' Integration Patterns



Note: The panels display the logarithm of one plus trade relative to GDP (top panel), the share of imports from and exports to the US in an economy's total trade (second panel), gross foreign assets and liabilities relative to GDP(third panel), and the share of US financial assets held by an economy's domestic residents and economy's foreign liabilities held by US residents in the economy's total foreign assets and liabilities (bottom panel). The data are time averages over 1999 to 2009. See the main text for further details.

Figure 9: Relationship between Differences in Spillover Estimates between GVAR and Two-Country VAR Models and Economies' Global Integration Patterns



Note: The panels show scatter plots of the differences in the spillover estimates from the GVAR model and the two-country VRA models (vertical axes) and economies' multilateral and bilateral integration patterns (horizontal axes). The red dashed lines represent fitted values from linear regressions of the spillover differences on economies' multilateral and bilateral integration patterns. The p-values from these regressions are provided in the panel titles. The spillover differences are demeaned.