Interdependence or Contagion? A Model Switching Approach with a Focus on Latin America

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Abstract

Empirical research analysing contagion has become increasingly fragmented. Different definitions of contagion have resulted in different methods being deployed to analyse financial transmission channels. This paper devises a novel econometric strategy where the nature of interdependencies, magnitude of interdependencies and transmission channels selected for inclusion can change over time. We thus appeal to multiple definitions of contagion, distinguishing between: interdependence, contagion through interdependence and abrupt contagion through changing linkages. Using our approach we analyse different crisis episodes in Latin America. Results generally indicate interdependence not contagion during the currency crises of the 1990s and Argentine crisis of 1998 - 2002. During the global financial crisis, results indicate abrupt contagion from the US to Argentina and Brazil. Mexico, however, experiences contagion through existing interdependencies with the US. Results also show that macroeconomic and uncertainty channels play a role during different crises not just financial channels. By establishing whether or not different interdependencies and transmission channels are present during different crises our model switching approach provides new insights.

Keywords: Bayesian Panel VAR, time-varying parameter model, contagion, financial crisis, Latin America.

JEL Codes: C11, C30, C52, F0, F40, G15.

1 Introduction

Contagion first gained attention in the late 1990s following a series of crises in emerging markets. More than a decade later, the global financial crisis and European sovereign debt crisis have illustrated the importance of establishing which interdependencies and transmission channels are relevant during different crises. The literature attempting to do so is already extensive. Successive surveys have summarised: different definitions of contagion (see reviews by Pericoli and Sbracia, 2003 and Forbes, 2013), different theories of contagion and early empirical methods for measuring contagion (see e.g. Claessens et al., 2000; Dungey et al., 2005 and Forbes and Rigobon, 2001a, 2001b) and the challenges associated with different empirical methods (Rigobon, 2002, 2016).

Nonetheless, despite this substantial body of research, two fundamental questions remain unresolved. First, how should we define contagion? In Forbes' survey (2013) eleven different academic definitions were listed. Second, how can we measure and test for contagion? Different definitions of contagion have resulted in different methods being deployed. It has become common practise for studies to adhere to a single definition of contagion which coheres with the method used. For instance, studies exploiting breaks in the data (e.g. using correlation breakdowns or regime switching models) often refer to "shift contagion" (see Forbes and Rigobon, 2002) where linkages between countries abruptly change or heighten. Another important issue when empirically analysing contagion is which variables to consider. With some definitions of contagion emphasising financial contagion in asset markets, the empirical literature focuses almost exclusively on financial transmission channels. This strategy risks isolating empirical work from theories of contagion which consider both real and financial transmission channels (Rigobon, 2016).

In response to the challenges above, our paper devises a novel econometric strategy to analyse contagion. A model switching approach is used where the model dimension, model parameters and shrinkage parameters can change over time. Put differently, we allow the nature of interdependencies, magnitude of interdependencies and transmission channels selected for inclusion to change over time. We, therefore, pull together different strands of the literature in three respects. First, our framework acknowledges different theories of contagion, accounting for macroeconomic and uncertainty transmission channels as well as financial transmission channels. This allows us to analyse the relative importance and evolution of different transmission channels during different crises. Second, by incorporating a range of model features, we nest a number of different approaches to measuring contagion. We, therefore, move away from attempting to measure contagion using a single indicator. Rather, we report a range of indicators, building a holistic, but nuanced picture of interdependence and contagion over time. Third, our comprehensive approach allows us to appeal to multiple definitions of contagion, distinguishing between: interdependence (existing linkages between countries which do not heighten during crises), contagion through interdependence (existing linkages between countries which heighten during crises) and abrupt contagion (linkages between countries which abruptly change during crises).

To illustrate our approach we focus on different crisis episodes in Latin America, a region which lay at the centre of early research on contagion and continues to experience considerable economic turbulence. Our data spans 1988:01 - 2016:08. We consider the three largest economies in the region, Argentina, Brazil and Mexico, denoted the LA-3, whilst also accounting for linkages with the US. For each Latin American (LA) country, we estimate a set of nearly 30,000 different Bayesian vector autoregressions (VARs) and panel vector autoregressions (PVARs) with time-varying coefficients, time-varying volatilities and exogenous variables. We thus denote our models as TVP-VAR-Xs and TVP-PVAR-Xs respectively. We switch between these different models, selecting the optimal model at each point in time.

Incorporating time-varying coefficients and time-varying volatilities has a number of advantages. First, we allow the magnitude of interdependencies to change over time. Specifically, we allow the magnitude of correlations between countries and the magnitude of volatility spillovers between countries to evolve over time. Or, using the terminology of the PVAR literature (see Canova and Ciccarelli, 2013), we allow dynamic interdependencies (DIs) and static interdependencies (SIs) to be time-varying. Second, heteroskedasticity, a common feature of financial data, can falsely lead to the conclusion that contagion is present (Rigobon, 2016). By distinguishing between time-variation in the coefficient and covariance matrices we surmount this empirical challenge.

Each of our models has different characteristics. By selecting the optimal model at each point in time, relevant interdependencies and transmission channels are revealed. First, our models are characterised by different shrinkage parameters, allowing different groups of variables to be included/excluded. This allows for switching between models which include/exclude different transmission channels. Second, to capture different types of interdependencies, our set of models are characterised by different dimensions. This allows for switching between small "domestic" TVP-VAR-Xs, medium sized "bilateral" TVP-PVAR-Xs and "regional" TVP-PVAR-Xs. Across all dimensions, the variables associated with the LA country of interest are endogenous and US variables are exogenous. Importantly, however, we allow the variables associated with other LA countries to enter exogenously into our TVP-VAR-Xs and endogenously into our TVP-PVAR-Xs. This strategy is pursued in order to reveal and distinguish between DIs (i.e. correlations) and SIs (i.e. volatility spillovers). While interdependencies are possible in all our models, in our TVP-VAR-Xs only DIs can be selected whereas in our TVP-PVAR-Xs both DIs and SIs can be selected.

This paper relates to different strands of the econometric literature. First, our model switching strategy combines and extends insights from the dynamic model selection literature. In particular, we build on the dynamic model learning strategy of Beckmann et al. (2018) by introducing dimension switching (see Koop, 2014 and Koop and Korobilis, 2013). We also tailor our shrinkage parameters so that different transmission channels can be included/excluded. Second, our approach draws on insights from the PVAR literature. Koop and Korobilis (2016) consider the existence of DIs and SIs in a constant parameter setting using variable selection methods. However, our approach allows us to establish the existence and magnitude of DIs and SIs over time.[1]

In terms of the contagion literature, our model switching approach relates to studies which use regime switching methods and time-varying parameters (TVP). Regime switching methods can capture crisis and non-crisis regimes without arbitrarily specifying when break dates occur (see, among many others, Gravelle, 2006 as an early example and Casarin et al., 2018 and Chan et al., 2018 for recent examples). However, if only focussing on two regimes, it may be difficult to discern between times when linkages between countries are weak and when they are strong (Ciccarelli and Rebucci, 2007). In response, Ciccarelli and Rebucci (2007) devise a TVP model which can be used in the presence of heteroskedasticity and omitted variables.

Our approach incorporates both the abrupt change seen in regime switching models and gradual change seen in TVP models. We achieve this by estimating the degree of model switching and time-variation in parameters at each point in time following Beckmann and Schüssler (2016) and Beckmann et al. (2018). Moreover, while we allow for model switching we are not restricted to focussing on two regimes.

We also draw inspiration from Ehrmann et al. (2011) and Beirne and Gieck (2014) who go beyond analysing individual asset prices movements. Instead, they jointly consider interest rates, stock prices, government bond yields and exchange rates. We move one step further incorporating macroeconomic and uncertainty variables into our framework.

Turning to our results (see Table 1 for a summary), we tend to find evidence of interdependence rather than contagion during the Mexican currency crisis of 1994, Brazilian currency crisis of 1999 and Argentine crisis. During these crises, financial interdependencies are most crucial, although macroeconomic interdependencies also play a role in the Mexican peso crisis and Argentine crisis. In Mexico, and to a lesser extent Argentina, volatility spillovers in exchange rates and stock markets are also important during the above crises.

[1] Koop and Korobilis (2019) also adapt dynamic model averaging/selection methods to estimate PVARs. However, their focus is on forecasting in a high-dimensional context rather than understanding the nature and evolution of interdependencies between countries.

In contrast, during the global financial crisis there is evidence of abrupt contagion spreading from the US to Brazil and Argentina. In particular, we find that US uncertainty abruptly affects both countries. The US excess bond premium, an indicator of financial distress, also becomes important while changes in US macroeconomic fundamentals affect Brazil more than Argentina. Importantly, movements in US uncertainty variables and the excess bond premium do not only affect stock prices in Argentina and Brazil. Instead, they also have a significant impact on industrial production. During the global financial crisis, contagion is also seen from the US to Mexico, but through pre-existing macroeconomic and financial interdependencies. US uncertainty variables also affect Mexico before and during the crisis. Overall, we demonstrate that contagion has only manifested in the recent global financial crisis. Our results also illustrate the importance of moving beyond financial variables to consider a wider range of transmission channels.

	Interdependence	Contagion via Interdependence	Abrupt Contagion
Mexican Currency Crisis (1994)	✓ F, M		
Brazilian Currency Crisis (1999)	✓ F		
Argentine Crisis (1998 - 2002)	✓ F, M		
Financial Crisis (2007 - 2009)		✓ F, M, U	✓ F, M, U

Table 1: Summary of Key Findings

Note: F, M and U correspond to financial, macroeconomic and uncertainty transmission channels. The table indicates which of these channels were present during different crises. For brevity, we refer to LA stock price and exchange rate channels under the broader term of financial transmission channels.

In the section that follows, we critically review and contrast different definitions of contagion. We then outline our empirical strategy in section 3, describing how our data and model switching approach relates to different definitions of contagion. Section 4 presents our results, first providing a comparative overview and then delving deeper into historical episodes of crisis. Section 5 summarises our key conclusions.

2 Definitions of Contagion

Many attempts have been made to adequately define contagion with Forbes' survey (2013) revealing a broad spectrum of opinions. Forbes' survey also illustrates the trade-off between academic definitions of contagion and definitions likely to be favoured by policymakers. The former must be sufficiently precise to guide empirical work while the latter tend to be broader in order to encompass a wider range of crises. For instance, a looser but widely applicable definition of contagion is "when an extreme negative event in one country affects others" (Forbes, 2013, p.24). This can be contrasted with five academic definitions presented by Pericoli and Sbracia (2003, p.574-575) which continue to be widely cited in the literature. We reproduce them here to aid further discussion:

> Definition 1. *Contagion is a significant increase in the probability of a crisis in one country, conditional on a crisis occurring in another country.*
>
> Definition 2. *Contagion occurs when volatility of asset prices spills over from the crisis country to other countries.*
>
> Definition 3. *Contagion occurs when cross-country comovements of asset prices cannot be explained by fundamentals.*
>
> Definition 4. *Contagion is a significant increase in comovements of prices and quantities across markets, conditional on a crisis occurring in one market or group of markets.*
>
> Definition 5. *(Shift-)contagion occurs when the transmission channel intensifies or, more generally, changes after a shock in one market.*

While the above definitions appear diverse, they do share some common aspects. First, many definitions tend to provide an indication of the method required to measure and test for contagion. Definition 2, for instance, refers to volatility spillovers. This becomes a natural definition to work with when using methods which allow for time-varying volatility such as

GARCH models. Definitions 3 and 4, on the other hand, make reference to comovements and may prove appropriate when examining how correlations among variables change over time. Finally, shift-contagion, discussed in definition 5, implies a break in the data generating process, making it popular among studies which deploy regime switching models or consider correlation breakdowns. The fact that there is often a direct relationship between definitions and methods may seem beneficial to empirical researchers, particularly when contrasted with the looser definition provided by Forbes (2013). However, it may be undesirable to focus on a single or narrow range of indicators to determine whether contagion is present.

The second feature shared by some definitions is the reference made to transmission channels. In definitions 2 and 3 financial markets are key. Definition 3 further requires that for comovements in asset prices to be indicative of contagion they should not be driven by changes in fundamentals. This caveat can be traced back to early work by Calvo and Reinhart (1996) who distinguish between "fundamentals-based" contagion and "true" contagion. Fundamentals-based contagion refers to shocks transmitted through pre-existing real and financial linkages while true contagion marks a change in conventional linkages. Over time, the literature has redefined fundamentals-based contagion simply as interdependence.

Despite definitions of contagion which stress fundamentals, recent empirical studies focus on financial markets. This may be driven by definitions which emphasise asset prices as well as a desire to capture the "fast and furious" contagion outlined by Kaminsky et al. (2003, p.55). Empirically, this rules out including macroeconomic time series which cannot be captured at a daily or weekly frequency. This failure to account for different transmission channels has resulted in the distinction between interdependence and contagion becoming more difficult to quantify empirically.

The third common feature across some definitions of contagion is the reference made to the strength of linkages between countries. Definitions 4 and 5 stress that there is a "significant increase" or "intensification" in linkages between countries if contagion is present. Similarly, Kaminsky et al. (2003, p.55) only consider the effects of a common external shock contagious if there is " 'excess comovement' in financial and economic variables across countries". These definitions express the same sentiment: if, following a shock, linkages are stronger than during "normal times" contagion is present. However, it is difficult to precisely pin down what should be considered "normal" or "in excess" (Rigobon, 2016). What is considered the "normal state" of the economy may vary over time as an economy develops or undergoes structural change. These issues are especially potent in emerging markets where greater economic turbulence and change is experienced.

3 Empirical Strategy

We begin this section by describing our data, emphasising how a wider range of variables can be included to capture different transmission channels. We then provide details of our econometric methods. We consider how different model specifications, shrinkage parameters and discount factors can be used to analyse how the relevance and strength of different interdependencies and transmission channels evolve over time. We then describe how we estimate our different models and select the optimal model at each point in time. Finally, we summarise how our model switching approach relates to multiple definitions of contagion.

3.1 Capturing Different Transmission Channels

We collect monthly data spanning 1988:01 - 2016:08 on Argentina (ARG), Brazil (BRA), Mexico (MEX) and the US. Our study, therefore, captures severe contagion which has long-lived consequences lasting months rather than days. This marks an important shift from the recent literature which focusses on high frequency data. Importantly, however, using monthly data allow us to introduce measures of macroeconomic fundamentals into our model and consider macroeconomic linkages between countries. Additionally, we can now also consider macroeconomic and financial uncertainty originating from the US. Accounting for a wider range of variables will aid us later when distinguishing between: interdependence, contagion through interdependence and abrupt contagion through a change in linkages.

Our choice to focus on Latin America, and the LA-3 in particular, is motivated by several factors. First, Latin America was prominent in early studies of contagion but has received relatively less attention in recent years. Latin America has, however, experienced numerous crises which differ in nature. This makes it an important and useful region should we wish to compare and understand different types of contagion. Second, we wish to demonstrate the applicability of our approach even when using data which is susceptible to structural breaks and greater time-variation. Third, we focus on the LA-3 in particular since these economies are unlikely to be affected by their smaller neighbours, reducing the risk of omitted variables bias. We do, however, account for the US which we would expect to have important effects on the LA-3, particularly Mexico.

Following Beirne and Gieck (2014) and Ehrmann et al. (2011), we begin by including different asset prices in our model. For all LA economies we include measures of the real effective exchange rate and the stock price index. Due to a lack of data, we omit government bond yields. To account for macroeconomic fundamentals we also include the following measures for each LA country: industrial production, inflation and short-term interest rates. Notably, it is important to obtain accurate inflation data given episodes of hyperinflation during the sample period.

For the US, we include measures of: the stock price index, industrial production, inflation and the short-term interest rate. During times when the interest rate is at the zero lower bound, the shadow interest rate developed by Wu and Xia (2016) is used so that we can capture the effects of unconventional monetary policy. Additionally, we include measures of US macroeconomic and financial uncertainty constructed by Ludvigson et al. (2019). This reflects recent research on the link between uncertainty and contagion (see e.g. Kannan and Koehler-Geib, 2011), a strand of the literature still in its infancy. We also include the US excess bond premium, an indicator of financial distress developed by Gilchrist and Zakrajšek (2012). Non-fuel commodity prices and the oil price are also included in the model. These are particularly important in our context, given the prominence of non-fuel commodities in Argentina's and Brazil's exports. Mexico's reliance on non-fuel commodities, over our sample period, is considerably less. All three countries, however, are oil producers. Traditionally, Brazil has been a net importer, Argentina has been relatively self-sufficient and Mexico has been a net exporter.

Variable	Transmission Channel	Abb.	Transf.
Real industrial production index	Macro fundamentals of country i	MF	Δ ln
Inflation (% MOM)	Macro fundamentals of country i	MF	levels
Short-term interest rate	Macro fundamentals of country i	MF	Δ
Real effective exchange rate	Exchange rate of country i	FX	Δ ln
Stock price index	Stock price index of country i	SP	Δ ln
Real industrial production index	Macro fundamentals of country i	MF	Δ ln
Inflation (% MOM)	Macro fundamentals of country i	MF	levels
Short-term interest rate	Macro fundamentals of country i	MF	Δ
Stock price index	Financial indicators of US	F	Δ ln
Excess bond premium	Financial indicators of US	F	levels
Macroeconomic uncertainty	Uncertainty indicators of US	U	levels
Financial uncertainty	Uncertainty indicators of US	U	levels
Non-fuel commodity price index	Commodity prices	$COMM$	Δ ln
Oil price	Commodity prices	$COMM$	Δ ln

Table 2: Assigning Variables to Transmission Channels

Each variable is assigned a category according to the transmission channel it characterises. We have thirteen categories in total. There are three categories per LA country: macroeconomic fundamentals, the stock price index and the exchange rate. These account for macroeconomic and financial interdependencies. There are four categories relating to the US and commodities: macroeconomic fundamentals, financial indicators, uncertainty indicators and commodity prices. We can also think of these four categories as representing global transmission channels through which extra-regional shocks are transmitted. With the exception of commodity prices, we follow the transformations recommended by McCracken and Ng (2016) to achieve stationarity. All variables are also standardised.

Details regarding the variables, the transmission channel they belong to, the abbreviation associated with each transmission channel and data transformations are summarised in Table 2. Information relating to the LA-3 can be found in the upper section while details relating to the US and commodities can be found in the lower section. Further details on how data was sourced and selected, particularly for the LA-3, can be found in Appendix B.

3.2 Analysing the Evolution of Different Interdependencies and Transmission Channels

For each LA country, we estimate 29,952 TVP-VAR-Xs and TVP-PVAR-Xs. Our models are carefully chosen to reflect a wide array of possible restrictions in terms of interdependencies between countries. Moreover, the number of models under consideration exceed that considered in previous studies using dynamic model selection/averaging methods.[2]

Our characterisation of the model space adapts and extends the methods in Beckmann et al. (2018). However, we emphasise where our approach differs. Each of our models is characterised by four elements. First, unlike Beckmann et al. (2018), we define the model specification for each model. This describes the dimension of the model and the way in which other countries' variables enter the model. We follow Koop (2014) and Koop and Korobilis (2013) by allowing for dimension switching. Specifically, we can switch between "domestic", "bilateral" and "regional" models over time. By allowing different models to have different specifications for which variables are exogenous and endogenous, we can also switch between models which allow for DIs (i.e. correlations) and models which allow for both DIs and SIs (i.e. volatility spillovers). Thus the nature of interdependencies can evolve over time.

Second, each model is characterised by a set of shrinkage parameters, γ. These determine which endogenous coefficients and exogenous variables are included/excluded from

[2]Koop and Korobilis (2013) allow for 216 models in their forecasting exercise while Beckmann et al. (2018) consider 9,216 in their study of exchange rate predictability.

each model. Beckmann et al. (2018) assign a shrinkage parameter to each exogenous variable. However, we assign a shrinkage parameter to each group of variables belonging to the same transmission channel (see Table 2). Switching between models with different shrinkage parameter values allows us to identify which transmission channels are selected for inclusion/exclusion at each point in time.

Third, our models are characterised by a discount factor, λ, which determines the degree of time-variation in the coefficient matrix. Fourth, our models are characterised by a second discount factor, δ, which determines the degree of time-variation in the covariance matrix. Thus we can switch between models which have different degrees of time-variation in the coefficient and covariance matrices.

To begin formalising these ideas, let us write a single TVP-VAR-X in state space form

$$y_t = x_t \beta_t + \varepsilon_t, \quad \varepsilon_t \sim N(0, \Sigma_t), \tag{1}$$

$$\beta_{t+1} = \beta_t + u_t, \quad u_t \sim N(0, \Omega_t), \tag{2}$$

where y_t for $t = 1, ..., T$ is an $M \times 1$ vector containing observations on M time series variables. The matrix β_t is an $M \times k$ matrix where each row contains an intercept, N (lagged) exogenous variables and p lags of each of the M variables. This means that there are $k = M(1 + pM + N)$ elements in β_t. To reflect the relatively fast nature of contagion we include the first lag of exogenous variables in all our models. Similarly, we set $p = 4$ so our models capture short-term movements in variables spanning months rather than years. Deviance information criteria also confirm that shorter lag lengths of 2, 3 and 4 are preferred to lag lengths between 5 and 12. Thus a lag length of 4 reflects a conservative choice.

Denoting the LA country under consideration as country 1, we describe our five possible model specifications in Table 3. Across all specifications, the variables associated with the LA country of interest are endogenous and US variables are exogenous. This follows Canova (2005) who verifies that current and lagged values of Latin American variables do not influence the US. We then specify whether we have (i) a domestic TVP-VAR-X where other LA variables, US variables and commodity prices enter the model exogenously or (ii) a bilateral/regional TVP-PVAR-X where other LA variables are endogenous and US variables and commodities are exogenous. In the former case, we only have DIs (i.e. correlations) between countries: lagged country 2 and 3 variables can affect country 1 variables. In the latter instance, SIs (i.e. volatility spillovers) are also present: we can have non-zero correlations between the reduced-form errors of different countries.

Exogenous variables can enter the domestic TVP-VAR-X in different ways. Model specification 1 differs from specification 2 by only allowing exogenous LA regressors to enter equivalent equations. For instance, country 2 and 3 stock prices can only enter country 1's stock price equation. Put differently, each exogenous LA variable can only affect a specific market rather than the entire economy. We find that this specification is necessary to capture certain crises.

	Dimension	Endogenous Variables	Exogenous Variables	Exogenous Variables Enter	Linkages	No. of TCs
1.	Dom. VAR	Country 1	Countries 2,3,US	LA: Equiv. equations US: All equations	DIs	10
2.	Dom. VAR	Country 1	Countries 2,3,US	All equations	DIs	10
3.	Bil. PVAR	Countries 1,2	US	All equations	DIs, SIs	7
4.	Bil. PVAR	Countries 1,3	US	All equations	DIs, SIs	7
5.	Reg. PVAR	Countries 1,2,3	US	All equations	DIs, SIs	10

Table 3: Model Specifications

Note: TVP-(P)VAR-X has been abbreviated to (P)VAR for clarity. Country 3 is larger than country 2 as measured by GDP. TCs denotes transmission channels. The US denotes US variables and commodity prices.

A final point noted in Table 3 is the number of potential transmission channels through which shocks can be transmitted. For each model specification, shocks can be transmitted from country 2 and/or 3 via the following transmission channels: macroeconomic fundamentals, stock prices and the exchange rate. Thus if countries 2 and 3 are both included in a model they account for six transmission channels. US and commodity price shocks can also be transmitted via the following four global transmission channels: macroeconomic fundamentals, financial indicators, uncertainty indicators and commodities.

Having established a framework which allows us to assess how the nature of interdependencies evolve over time, we now develop an approach to assess the relative importance of different transmission channels over time. Since our estimation procedure is Bayesian, this can be achieved through setting a prior for the initial conditions:

$$\beta_0 = N(0, \Omega_0). \tag{3}$$

The prior mean on our VAR coefficients is set to zero. The diagonal elements, γ, of our prior covariance matrix, Ω_0, determine the degree of shrinkage associated with different groups of coefficients. If a shrinkage parameter is set to 0.01 the associated coefficients undergo moderate shrinkage and remain in the model. If instead a shrinkage parameter is set to 0 the associated coefficients are excluded from the model. Moreover, if the coefficients belong to an exogenous variable it is removed entirely from the model. Like Koop (2014) we are not required to rescale our shrinkage parameters since we standardise our variables.

We build on Beckmann et al. (2018) who use 10 independent shrinkage parameters to determine the degree of shrinkage associated with 10 groups of coefficients. Recall that the LA country under consideration is denoted country 1. We can include/exclude groups of coefficients from country 1 VAR equations (i.e. equations 1 - 5) by allowing different models to have different sets of shrinkage parameters. For any given model specification, 7 - 10 transmission channels will be of interest as shown in Table 3. We, therefore, assign a minnesota shrinkage parameter, γ_j, to each group of coefficients belonging to the same transmission channel (i.e. for $j = 1, .., TC$ where $TC \in \{7, 10\}$). We allow $\gamma_j \in \{0, 0.01\}$ thus different models reflect different assumptions about which transmission channels are relevant. Switching between models with different shrinkage parameter values allows us to include/exclude different transmission channels at each point in time.

In practise, we must also specify shrinkage parameters for: intercepts, coefficients associated with country 1 own lags and country 1 cross lags. Denoting the coefficients associated with country 1 variables as "domestic" and other coefficients as "foreign", the shrinkage parameters associated with country 1 VAR equations are summarised in Table 4. The upper part of the table is required when estimating all 5 model specifications. Additionally, we require the second and third part of the table when estimating model specification 1. For model specification 2, we require the third part of the table. To estimate model specifications 3, 4 and 5 we require the third and fourth part of the table. Moreover, we specify that for country 2 and 3 equations coefficients on own lags have shrinkage parameter 0.01 and coefficients on all cross lags have shrinkage parameter $\frac{0.01}{2r^2}$ $r = 1, ...p$.

Coefficients	Values of γ
Intercept	0.01
Coefficients on own lag $r = 1, ..., p$	0.01
Coefficients on domestic cross lags $r = 1, ..., p$	$\frac{0.01}{Dr^2}$
Coefficients on first group of equation-specific exogenous variables	0 or 0.01
...	
Coefficients on last group of equation-specific exogenous variables	0 or 0.01
Coefficients on first group of exogenous variables	0 or 0.01
...	
Coefficients on last group of exogenous variables	0 or 0.01
Coefficients on first group of foreign cross lags $r = 1, ..., p$	0 or $\frac{0.01}{r^2}$
...	
Coefficients on last group of foreign cross lags $r = 1, ..., p$	0 or $\frac{0.01}{r^2}$

Table 4: Shrinkage Parameters for Country 1 VAR Equations, Equations 1 - 5

Note: $D = 1$ if we have a domestic TVP-VAR-X whilst $D = 2$ if we have a bilateral or regional TVP-PVAR-X.

In addition to a model specification and a set of shrinkage parameters each model is characterised by two discount factors. The first discount factor, δ, must lie in the interval $0 < \delta \leq 1$ and determines the degree of time-variation in the covariance matrix. We use the following grid - $\delta \in \{0.8, 0.88, 0.96\}$ - where low values are associated with greater time-variation and high values are associated with a lower degree of time-variation. Since we work with heteroskedastic financial data we do not nest a model with constant covariance.

The second discount factor, λ, must also lie in the interval $0 < \lambda \leq 1$ and determines time-variation in the coefficient matrix. The following grid is used - $\lambda \in \{0.96, 0.99, 1\}$ - with high and low values having the same interpretation as above. In this case, we do nest the constant coefficient case since it is a possibility. Thus we can switch between models which have different values of δ and λ allowing the degree of time-variation to evolve over time.

3.3 Estimation Procedure

Having outlined the four features which characterise each model, we now describe our estimation procedure. We deploy the same algorithm as Beckmann et al. (2018), updating the parameters for each period using the Kalman filter. Here, we discuss important steps in the procedure, but for further details the reader is referred to Beckmann et al.'s Online Appendix. Let $y^s = (y_1, ..., y_s)'$ denote observations from $t = 1, ..., s$ and $t|t-1$ denote estimates of this period's parameters using information available last period. The key ingredient required to evaluate each model is the predictive density

$$\hat{y}_t | y^{t-1} \sim t(y_{t|t-1}, x_t \Omega_{t|t-1} x_t' + Q_{t|t-1}), \tag{4}$$

where $\hat{y}_t = x_t \beta_{t|t-1}$.

Since Ω_t is unobserved we use our discount factor λ to produce an approximation

$$\Omega_{t|t-1} = \frac{1}{\lambda} \Omega_{t-1|t-1}. \tag{5}$$

Similarly, since Σ_t is unobserved, we specify that it follows an Inverse Wishart distribution with δn_{t-1} degrees of freedom and scale matrix S_{t-1}

$$\Sigma_{t|t-1} \sim IW(\delta n_{t-1}, S_{t-1}), \tag{6}$$

with expected value

$$E(\Sigma_{t|t-1}) := Q_{t|t-1} = \frac{S_{t-1}}{\delta n_{t-1} + M - 1}, \tag{7}$$

and where the degrees of freedom and scale matrix are initialised as follows using

$$n_0 = \frac{1}{1-\delta}, \tag{8}$$

$$S_0 = I_M, \tag{9}$$

both of which are common choices in the literature.

After estimating the parameters for each of our 29,952 models we must select the optimal model at each point in time. We do so using dynamic model learning (see Beckmann and Schüssler, 2016 and Beckmann et al., 2018), selecting the model with the highest discounted joint log predictive likelihood at each point in time. Since they have a different number of dependent variables, the predictive likelihoods (i.e. the predictive density for the dependent variables evaluated at the actual outcome) from VARs of different dimensions are not directly comparable (Koop, 2014). We, therefore, use the predictive likelihood for the country 1 variables which are common to all models. The discounted joint predictive likelihood (DPL) can be calculated as

$$DPL_{t|t-1,j} = \prod_{i=1}^{t-1} [p_j(y_{t-i}|y^{t-i-1})]^{\alpha^i}, \tag{10}$$

where $[p_j(y_{t-i}|y^{t-i-1})]^{\alpha^i}$ denotes the predictive likelihood of model j in period i.

It can be seen that at time τ the DPL utilises information on past model performance from $t = 1, ..., \tau - 1$. Thus, at any given point in time, model j receives a higher DPL if past model performance has been effective as measured by the predictive likelihood. The extent to which past model performance is considered is determined by the discount factor α which can adopt a range of values reflecting different degrees of model switching: $\alpha \in \{0.001, 0.01, 0.1, 0.2, 0.4, 0.6, 0.8, 0.9, 0.95, 1\}$. Model performance k periods ago receives approximately α^k as much weight as last period's model performance when calculating the DPL. For example, if $\alpha = 0.4, 0.6, 0.9$ or 0.95, model performance 6 months ago receives approximately 1%, 5%, 53% and 74% as much weight respectively. If $\alpha = 1$ we simply have Bayesian model selection using marginal likelihoods. Our grid, therefore, spans rapid to moderate model switching.

It should be emphasised that at each point in time, τ, we select the value of α which produces the model with the highest product of predictive likelihoods from $t = 1, ..., \tau$. This allows us to select the degree of model switching using a real-time data-driven approach. For a given value of α, we then calculate the DPL for each of our models. By having two discount factors which control time-variation in model parameters, λ and δ, and a discount factor, α, which later determines the degree of model switching we capture both gradual and abrupt time-variation.

3.4 Relating Our Model Switching Approach to Multiple Definitions of Contagion

In section 2, we demonstrated that different definitions of contagion typically have three features in common: they provide an indication of which method should be used to analyse contagion, they make reference to specific transmission channels and they make reference to an increase in the magnitude of linkages between countries. In selecting our data and devising our model switching approach, we have considered these three aspects in order to appeal to multiple definitions of contagion.

First, we appeal to multiple definitions by incorporating a number of different methods for measuring contagion into our approach. In particular, we can jointly consider DIs between countries via the coefficient matrix (i.e. correlations), SIs between countries via the covariance matrix (i.e. volatility spillovers) and sudden shifts in linkages indicated by model switching. Our approach thus allows us to combine the insights that would be obtained from using GARCH models, regime switching models and analysing correlation breakdowns.

Second, we have included a wide range of transmission channels and devised a means to assess their changing relevance. This allows us to establish when crises spread through pre-existing linkages between countries or through a sudden change in linkages. We can thus appeal to definitions of contagion which focus on asset markets as well as definitions which distinguish between fundamentals-based contagion (i.e. contagion through interdependence) and true contagion (i.e. contagion through an abrupt change in linkages).

Third, by allowing for time-varying parameters, we can analyse magnitude: the extent to which DIs and SIs intensify or weaken over time. This appeals to definitions of contagion which stress that linkages between countries should intensify. When recording DIs in bilateral and regional TVP-PVAR-Xs, where all LA variables are endogenous, we record the values associated with first lags to retain comparability with our other model specifications.

By assessing the relevancy of different transmission channels and the evolution and magnitude of DIs and SIs we distinguish between: interdependence, contagion through interdependence and abrupt contagion. If linkages are present between countries prior to a crisis and these do not change during a crisis, we call this interdependence. If, however, linkages are present between countries prior to a crisis and they increase in magnitude during a crisis, we call this contagion through interdependence. If the nature of linkages between countries abruptly change during a crisis, with different transmission channels becoming relevant, we call this abrupt contagion. Importantly, DIs can intensify when coefficients are constant if a transmission channel is selected for inclusion following several periods of exclusion.

We explore DIs and SIs rather than estimating impulse response functions for a number of reasons. First, our model specifications have been devised to illustrate different interdependencies, but make it difficult to compare impulse responses over time. This is exacerbated by the fact that specifications are often chosen in which other country variables are exogenous and only enter specific equations. DIs and SIs are, however, comparable over time. Second, our results indicate that it would be difficult to impose a causal ordering on our countries and variables without making unrealistic identifying assumptions. This is unsurprising given that we focus on countries which have experienced considerable economic turbulence over the sample period. We, therefore, follow Canova and Ciccarelli (2013) and Koop and Korobilis (2016) in extracting economically relevant information from the reduced-form of our TVP-VAR-Xs and TVP-PVAR-Xs. However, when examining the magnitude of DIs and SIs we interpret our results with caution since we have not disentangled causality.

4 Results

We begin by presenting a timeline of events in our countries of interest. We then provide a comparative overview of our results. Focussing on January 1990 onwards, we then select and examine in detail three crisis episodes.[3] In considering these episodes, we analyse whether interdependence, contagion through interdependence or abrupt contagion were present. Notably, results presented are for the transformed variable unless otherwise stated. We do not consider the role played by the 1997 Asian financial crisis or 1998 Russian financial crisis.

4.1 Timeline of Events

To aid interpretation of our results, we provide a timeline of recessions (see Figure 1 where a non-zero event indicates a recession for the respective country) and key economic and financial events (see Table 5) in the LA-3 and US from 1990 - 2016. We briefly summarise the experience of each of the LA-3 economies as follows.

Argentina experienced considerable economic turbulence from 1998 - 2002. This culminated in banking, sovereign debt and currency crises. Thereafter, Argentina experienced

[3]For clarity, we focus on three episodes but there are undoubtedly others we could consider.

high growth rates with a quick recovery following the global financial crisis. In subsequent years currency controls were imposed, inflation rose with official figures being discredited and Argentina selectively defaulted after failing to reach an agreement with holdout investors.

In Brazil, the 1990s began with a severe recession and ended with the 1999 currency crisis. Consequently, Brazil abandoned the US dollar peg and adopted inflation targeting. Despite pursuing more conventional policies, Brazil has experienced modest growth rates compared to Argentina. Recently, the fall in commodity prices, rising fiscal deficit and political crisis led to Brazil entering its worst recession over the sample period.

Relative to Argentina and Brazil, Mexico has pursued increased trade and, to a lesser extent, financial openness. The North American Free Trade Agreement came into effect in January 1994. Nonetheless, after recovering from a currency crisis in 1994, Mexico has continued to experience sluggish growth rates and mild recessions. The exception was the recession following the global financial crisis which was short but deep.

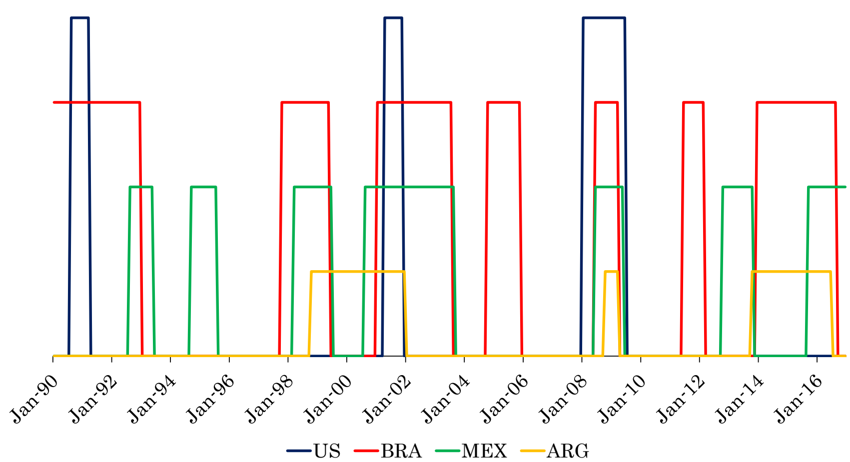


Figure 1: Recessionary Periods in the LA-3 and US: 1990 - 2016

Sources: NBER and OECD recession indicators for the US, Brazil and Mexico were obtained from St Louis Fed data. Dates are approximate for Brazil prior to 1996 and Argentina.

As shown in Table 5, we can split our sample into three distinct periods which we examine in subsequent sections. First, we focus on currency crises experienced by Mexico and Brazil in the 1990s, the subject of early contagion research. Second, we analyse whether interdependence and contagion were present in the Argentine crisis from 1998 - 2002. Last, we consider the global financial crisis which inspired a new wave of literature on contagion. Before considering each of these, however, we present a comparative overview of our results.

Date	Description
1994, Dec	Brazilian banking crisis begins.
1994, Dec	Mexican banking crisis begins.
1994, Dec	**Mexican currency crisis: peso is devalued and allowed to float.**
1996	Mexican banking crisis ends.
1998	Brazilian banking crisis ends.
1999, Jan	**Brazilian currency crisis: real is devalued and allowed to float.**
2000, Mar	Dotcom bubble bursts.
2001, Nov	**Argentine banking crisis begins.**
2001, Dec	**Argentine sovereign debt crisis: intention to default announced.**
2002, Jan	**Argentine currency crisis: peso is devalued and allowed to float.**
2003	**Argentine banking crisis ends.**
2007, Feb	First signs of the subprime mortgage crisis.
2007, Jul	**Global liquidity crisis begins.**
2007, Dec	US banking crisis begins and is followed by banking crises worldwide.
2008, Sep	Lehman Brothers files for bankruptcy.
2011, Nov	Argentina imposes currency controls.
2014, July	Argentine selective default.
2015, Dec	Argentina lifts currency controls allowing peso to float freely.

Table 5: Selected Economic and Financial Events in the LA-3 and US: 1990 - 2016

Sources: Information on banking crises, sovereign debt crises and currency crises was extracted from Laeven and Valencia (2013) and the corresponding database on systemic banking crises. We exclude crises which Laeven and Valencia (2013) consider borderline.

4.2 A Comparative Overview

We first consider which types of interdependencies are important over time. To do so, for each country, we examine which model specification is selected at each point in time. This is shown in the top panels of Figures 2 - 4 (all figures can be found in Appendix A). Recall that model specifications 1 and 2 involve TVP-VAR-Xs where only DIs (i.e. correlations) are present between countries. Model specifications 3 - 5 involve TVP-PVAR-Xs where both DIs and SIs (i.e. volatility spillovers) are present. Results from all three countries indicate that model specifications 1 and 2 are selected more frequently than 3, 4 and 5. Additionally, for Argentina and Brazil model specification 1, which only allows for cross-market linkages between countries, is often sufficient to capture interdependencies. Thus DIs are, on average, more important than SIs.

TVP-PVAR-Xs, where SIs are present in addition to DIs, tend to be selected during crisis periods. More specifically, they tend to be selected during domestic crises. In Argentina, TVP-PVAR-Xs are selected during 2002, 2008 and 2014 - 2015. These dates correspond to the Argentine crisis, global financial crisis and Argentine selective default respectively. In Brazil, TVP-PVAR-Xs are not selected in the 2000s until a severe recession is experienced. In Mexico, however, TVP-PVAR-Xs and thus SIs are selected throughout the sample.

For each country, we then consider which transmission channels are selected for inclusion at each point in time. This is shown in the second panels of Figures 2 - 4. Figures 5 - 10 provide a further breakdown, detailing how often transmission channels associated with different countries are included. To compute how many times each transmission channel is included we simply count how often the corresponding shrinkage parameter is non-zero throughout the sample. Notably, we cannot directly compare how often LA channels are included relative to global channels. This is because model specification 1 allows each exogenous LA variable to either enter a single equation or none. By contrast, across all specifications, each exogenous US/commodity price variable can either enter all equations or none.

If we consider the Argentine results, other countries' variables are selected for inclusion less frequently than when we model Brazil and Mexico. When modelling Argentina, the LA channels included least frequently are Brazilian and Mexican macroeconomic fundamentals. However, Brazilian macroeconomic fundamentals are included more regularly during 2001

- 2004, 2008 - 2010 and, to a lesser extent, 2014. These correspond to the Argentine crisis and subsequent recovery, the global financial crisis and the Argentine selective default respectively. US uncertainty and financial channels are the global channels included most frequently. This validates the importance of including uncertainty measures. We find that US transmission channels are included more regularly from 1990 - 1992, 2001 - 2003, 2007 - 10 and 2013 onwards. Commodities also play a role during these periods, particularly near the end of the sample when commodity prices slumped.

In our Brazilian results, Argentine stock prices, the exchange rate and macroeconomic fundamentals are the LA channels included most frequently followed by Mexican stock prices and the exchange rate. However, we find evidence of Mexican macroeconomic fundamentals entering the model from 1990 - 1998, appearing abruptly in 2008 and then from 2010 onwards. These correspond to Brazil and Mexico experiencing recessions and banking crises, the global financial crisis and Brazil moving in and out of recessions respectively. Like in Argentina, we also find that US financial and uncertainty channels are the global channels included most frequently. These channels are included more frequently in the early 1990s, 1998 - 2001 and 2008 - 2010. These correspond to a Brazilian recession, a Brazilian currency crisis and the global financial crisis. We also see commodity prices take on a prominent role near the end of the sample as the drop in prices contribute to the most recent Brazilian recession.

Mexico's results present a different, less predictable pattern. Argentine and Brazilian transmission channels do not tend to undergo long periods of exclusion. Moreover, US variables are included more frequently than when modelling Argentina and Brazil. These indications of greater interdependence are unsurprising given Mexico's higher levels of trade and financial openness. Argentine stock prices, the Brazilian exchange rate and Argentine macroeconomic fundamentals are the LA channels most frequently included. This is interesting given that Brazil is larger than Argentina but may reflect the greater economic turbulence seen in Argentina. US financial indicators and commodities are the global channels included most often. The latter reflects the important role of oil prices in Mexico.

Turning to the third panels of Figures 2 - 4, we recall that the discount factor λ (plotted in blue) determines the degree of time-variation in the coefficient matrix and the extent to which DIs evolve over time. The discount factor δ (plotted in red) determines the degree of time-variation in the covariance matrix and the extent to which SIs evolve over time. Lower values reflect greater time-variation. Importantly, if a TVP-VAR-X is selected, no SIs are present and we simply have volatility spillovers between domestic variables. Across all three economies, we find greater time-variation in covariance matrices than in coefficient matrices which are often constant for several years. This coheres with Koop and Korobilis (2013) who find limited time-variation in coefficient matrices. That said, during times of crisis there are departures from the constant coefficient case. This is most evident during domestic crises, for instance, in Mexico, Brazil and Argentina during their respective currency devaluations.

In the fourth panels of Figures 2 - 4, we plot the discount factor α. Lower values reflect a greater degree of model switching. For Argentina and Brazil a value of 0.4 is selected across most of our sample indicating rapid model switching. In Mexico we see a value of 0.2 from late 1995 - mid 2009 increasing to 0.4 following the global financial crisis. This shows that the interval $\alpha \in [0.95, 1]$, commonly used in early studies which did not estimate α, is unsuitable in our context. This also emphasises the importance of allowing for model switching to capture the evolution of different interdependencies and transmission channels.

Figures 11-19 show the evolving magnitude of DIs and SIs. Figures 11, 12 and 17 pertain to Argentine estimations; 13,14 and 18 to Brazil; and 15, 16 and 19 to Mexico. In terms of DIs, for brevity, we focus on the standard deviation responses of industrial production and stock prices to a one standard deviation increase in selected predictors, all things held constant. For SIs, the standardised covariance matrices are transformed so that we have the correlation of reduced-form shocks. Again, for brevity, we focus on cross-market SIs. For instance, we look at volatility spillovers between stock markets in different countries. We delay detailed discussion of intensifying and weakening DIs and SIs to subsequent sections.

In summary, we find evidence of regional business cycles with stronger ties between (i)

Argentina and Brazil, our Southern American countries and (ii) the US and its neighbour Mexico. We also find that Mexico, our most open economy in terms of trade and finance, is the most vulnerable to external conditions on a consistent basis. We further find that interdependencies tend to be driven by DIs rather than SIs, particularly during non-crisis periods, with the exception of Mexico which sees more volatility spillovers. We overturn the possible misconception that macroeconomic linkages between countries are more consistent over time compared to financial linkages. Rather, other countries' macroeconomic fundamentals are sometimes abruptly included during times of crisis. Across economies, US financial conditions followed by uncertainty tend to be the most frequently included global channels. Our discount factors show the importance of allowing for rapid model switching and time-varying volatility rather than time-varying coefficients. However, departures from the constant coefficient case can be important when DIs evolve during times of crisis.

4.3 Early Currency Crises: 1990 - 2000

For clarity and brevity, we do not refer to specific figures in the following sections. However, all results are in Figures 2 - 19. We first consider currency crises experienced by Mexico and Brazil starting with the Mexican peso crisis. In December 1994, pressures on the exchange rate and banking system led to the sudden devaluation of the peso against the US dollar. We consider the effects of the crisis on Argentina and Brazil. We also discuss which linkages proved important in Mexico.

First, we consider Argentine results, analysing whether the Mexican crisis affected Argentina. Before and after the devaluation, the model specification predominantly selected is 1. Thus we have no SIs and only allow for cross-market linkages between Mexico and Argentina.[4] Put differently, Mexican stock prices only enter the Argentine stock price equation and so on. Mexican macroeconomic fundamentals are consistently included in our model of Argentina from August 1993, even before the Mexican economy entered a recession. DIs

[4]Model specification 2 is also selected during this period. However, when this occurs, all LA transmission channels are excluded from the model.

from the Mexican stock market to the Argentine stock market are present from July 1992 - May 1994 and from January - June 1995 immediately following the devaluation.

While DIs from Mexican industrial production to Argentine industrial production are positive from May 1992 - February 1995 they do not increase in magnitude following the Mexican crisis. Similarly, DIs from the Mexican stock market to the Argentine stock market do not significantly intensify following their re-inclusion following the devaluation. We, therefore, find evidence of macroeconomic and financial interdependence between Mexico and Argentina during the currency crisis. With Mexican stock markets becoming relevant after several months of exclusion there is weak evidence of contagion confined to stock markets.

Next we consider the effect of the Mexican devaluation on Brazil. Prior to the devaluation, specifications 1, 2, 4 and 5 are selected. If we examine SIs between Mexico and Brazil, however, they tend to either remain stable or weaken over time. Following the devaluation, model specifications 1 and 2 are selected. All three Mexican transmission channels are included relatively consistently before and after the Mexican devaluation.

We see a slight intensification of DIs from Mexican industrial production to Brazilian industrial production from April - September 1994. DIs from the Mexican stock market to Brazilian industrial production are strong, but have periods of intensification before and after the devaluation. Finally, DIs from the Mexican stock market to the Brazilian stock market show no sign of intensifying following the devaluation. We thus find evidence in favour of financial, and to a lesser extent macroeconomic, interdependence rather than contagion.

Finally, we consider Mexico, assessing which linkages proved important before and after the devaluation. Model specifications 1,2,4 and 5 are selected prior to the devaluation. Model specification 1 is then selected from December 1994 - August 1995. SIs between Mexico and Argentina tend to intensify from May 1994 to November 1994 especially in stock markets. These SIs did not come through in the Argentine results suggesting that the volatility spillovers are more important for Mexico. In terms of DIs, Brazilian and Argentine exchange rates and Argentine stock prices are present on a more consistent basis after the devaluation. In contrast, all US transmission channels are included in the model before the crisis with US financial indicators remaining important after the crisis.

Evolving DIs play a role from February 1994 - February 1996. During this time, constant coefficient models are no longer selected. All US DIs intensify in the build up to the crisis. DIs from US industrial production to Mexican industrial production are particularly high in April and May 1994 and are included till December 1994. Similarly, DIs from US macroeconomic and financial uncertainty indicate that a rise in these variables leads to a decline in Mexican industrial production from October 1993 - December 1994. DIs from the US stock market indicate a lack of comovement with Mexican industrial production, but positive comovement with the Mexican stock market. These findings show that external conditions, particularly those in the US, become more important in the build up to the Mexican devaluation. After the devaluation, a more specific set of external conditions - US, Argentine and Brazilian financial indicators and exchange rates - are selected for inclusion.

We next consider the 1999 Brazilian currency crisis. In 1994 the Real Plan was implemented, partly to stabilise hyperinflation. The Real was pegged to the dollar and inflation gradually subsided as the 1990s progressed. However, by January 1999 the Real had become significantly overvalued and was suddenly devalued. We consider the effects of the crisis on Argentina and Mexico. We also explore which linkages proved important in Brazil.

First, we consider the effect on Argentina. From November 1997 - December 2000 model specification 1 is selected. Brazilian stock prices and, to a much lesser extent, exchange rates are included before and after the devaluation. If we examine DIs from the Brazilian to the Argentine stock market, however, they are negative, suggesting a lack of synchronicity between financial markets. Therefore, over this time period, where both Brazil and Argentina were in crisis, we find little evidence of interdependence or contagion.

Then we consider Mexico which itself entered a recession in March 1998. Model specifications 1,2,4 and 5 are all selected in the run up to the Brazilian devaluation. During the month of the devaluation, model specification 4 is selected. In terms of volatility spillovers, SIs between Brazil and Mexico intensify between October 1998 and November 1998 before dropping back down slightly in January 1999. This intensification is most noticeable between stock markets. Thereafter SIs are excluded with model specifications 1 and 2 being selected until January 2001. We find that all three Brazilian transmission channels tend to be included, albeit intermittently, before and after the crisis.

DIs from the Brazilian stock market and industrial production to Mexican industrial production, however, generally indicate a lack of comovement. By contrast, DIs from the Brazilian stock market to the Mexican stock market indicate comovement from October 1997 - November 1999. The period October 1998 - March 1999 was the exception with the positive correlation between stock markets breaking down. Given DIs from the Brazilian to the Mexican stock market and volatility spillovers between the two markets we find some evidence of financial interdependence which temporarily weakens following the devaluation.

Finally, let us consider the experience of Brazil during the crisis. From October 1994 - February 2015 we switch between model specifications 1 and 2. All three Argentine transmission channels feature intermittently from January 1998. In contrast, having been excluded from the Brazilian model for more than a year, all three Mexican and US transmission channels are included with the onset of the devaluation in January 1999.

Mirroring Mexico during the peso crisis, DIs to Brazil evolve during the crisis. From November 1998 - April 1999 coefficients are no longer constant and instead vary over time. If we consider the magnitude of interdependencies, DIs from Argentine industrial production to Brazilian industrial production are stronger than those from Mexican or US industrial production. However, these DIs do not increase in magnitude. DIs from the Argentine and Mexican stock markets to the Brazilian stock market and industrial production intensify markedly during the crisis. However, of these DIs, only those from the Argentine stock market were positive indicating comovement. A rise in the US excess bond premium in February and March 1999 corresponded to a marked fall in Brazilian industrial production. We thus find that existing interdependencies with Argentina continue to be included throughout the devaluation whilst US transmission channels suddenly become important in 1999.

4.4 The Argentine Crisis: 1997 - 2003

We now consider the Argentine crisis. The economy entered a recession in October 1998. In December 2001, amidst rioting and a bank freeze on deposits, Argentina defaulted on its sovereign debt. Then in January 2002 the peso was suddenly devalued. We consider the effects of the crisis on Brazil and Mexico. We also examine which linkages proved important in Argentina.

First, we consider the effect on Brazil. Model specifications 1 and 2 are selected during the Argentine crisis. All Argentine transmission channels are regularly selected for inclusion between February 1998 - February 2002. Given the Brazilian devaluation in January 1999, we focus on results from the 2000s when examining the magnitude of DIs to clearly distinguish between the two crises. DIs from Argentine industrial production to Brazilian industrial production are positive but do not intensify. Starting in February 2002, Argentine industrial production is not selected for inclusion for 20 months, Similarly, DIs from the Argentine stock market to the Brazilian stock market remain positive until August 2002 before being excluded for 17 months. Thus we find strong evidence of macroeconomic and financial interdependence which wanes following the sovereign debt and currency crisis.

Next we turn to Mexico. All model specifications are selected during the Argentine crisis. If we examine volatility spillovers, SIs between Mexican and Argentine exchange rates and Mexican and Argentine stock prices heighten between 1998 - 2002. During this period, Mexico also experienced two recessions. All Argentine transmission channels are included intermittently with stock prices included most often. DIs from Argentine industrial production to Mexican industrial production indicate a lack of comovement until February 2002. At this point, DIs, although small, become positive. DIs from the Argentine stock market to Mexican industrial production show slight intensification. DIs from the Argentine stock market to the Mexican market are of a larger magnitude, showing intensification in the months from May 2000 - December 2001. Overall, we have evidence of financial interdependence and some evidence of abrupt contagion resulting from volatility spillovers.

Finally, we consider Argentina itself. Prior to the default and devaluation, model specifications 1 and 2 are selected. After the devaluation, from April 2002 - December 2002, model specifications 1, 2, 4 and 5 are selected. At these points, SIs intensify particularly between the Argentine and Brazilian stock market. In terms of DIs, initially Brazilian exchange rates and stock prices are selected for inclusion. However, in 2001 Brazilian macroeconomic fundamentals become important. From June 1999 - May 2000, Mexican transmission channels are not selected for inclusion. Thereafter, all three Mexican transmission channels are intermittently included until October 2002. Similarly, US transmission channels and commodities are abruptly included in 2001 and 2002.

Some DIs to Argentina evolve during the crisis. Models with constant coefficients are no longer selected from August 2001 - June 2002. DIs from Brazilian industrial production to Argentine industrial production intensify between February - May 2001. DIs from US industrial production to Argentine industrial production peak rapidly between January - June 2002. An increase in US macroeconomic uncertainty has a pronounced negative effect on Argentine industrial production from October 2001, peaking in June 2002. In contrast, DIs from the US stock market and excess bond premium to the Argentine stock market and industrial production indicate a lack of comovement. Thus existing macroeconomic interdependencies with Brazil remain important during the crisis. US macroeconomic fundamentals and uncertainty abruptly become important following the default and devaluation.

4.5 The Global Financial Crisis: 2006 - 2010

Finally, we examine the global financial crisis. Following the collapse of the US subprime mortgage market, a global liquidity crisis ensued with countries facing banking crises worldwide. For each LA economy, we examine linkages with the US before and after the crisis. If contagion is detected, we also explore how the LA economies affect one another.

First, we consider Argentina. Model specifications 1 and 2 are selected during the crisis. Thus volatility spillovers are rarely relevant. The exception is July 2008 when model specification 4, a bilateral TVP-PVAR-X with Brazil, is selected. US financial and uncertainty transmission channels are briefly included in May and June 2007 as the liquidity crisis unfolds. US uncertainty then re-enters the model intermittently from March 2008 - February 2009. US financial indicators and macroeconomic fundamentals briefly reappear from July - September 2008 and in March 2009.

DIs evolve to a lesser extent: departures from the constant coefficient case are seen from August - September 2007 as well as November - December 2008. We now examine the magnitude of DIs from US uncertainty to the Argentine stock market and industrial production. In both cases, a rise in uncertainty between 2007 - 2008 has a negative effect. Financial uncertainty, in particular, has a larger negative effect on industrial production. A rise in the excess bond premium also negatively affects industrial production but only in 2008 and 2009. We thus find strong evidence in favour of abrupt contagion, initiated by a rise in US financial uncertainty in 2007. We also find evidence that macro-financial linkages play a part in the spread of contagion. Changes in US uncertainty and later financial conditions affect Argentine industrial production.

Next, we consider the effect of Brazil and Mexico on Argentina during the crisis. When a bilateral TVP-PVAR-X is selected in July 2008, volatility spillovers between Argentine and Brazilian exchange rates and stock markets heighten. However, volatility spillovers between macroeconomic fundamentals weaken. Turning to DIs, from January 2005 - March 2008, Brazilian transmission channels are included very intermittently. Thereafter, however, Brazilian transmission channels, particularly macroeconomic fundamentals, are more consistently selected for inclusion until 2010. Having not been included in the model since April 2002, Mexican macroeconomic fundamentals are intermittently included from February 2007. Having been intermittently included prior to the crisis, Mexican exchange rates continue to be intermittently included while stock prices are more regularly included from June 2008.

DIs from Mexican industrial production to Argentine industrial production heighten earlier in 2007. However, DIs from Brazilian industrial production to Argentine industrial production intensify to an even greater degree in late 2008 and 2009. These findings suggest that Argentina was not solely affected by the US during the global financial crisis. Instead, Argentina was also indirectly affected through macroeconomic linkages with Mexico and Brazil which abruptly became important. These findings are consistent with Argentina being the last LA-3 economy to enter a recession following the financial crisis.

Turning to Brazil, model specification 1 is selected from May 2004 - September 2011 with three exceptions: model specification 2 is selected in July 2006 and July and August 2008. Thus volatility spillovers play no role in Brazil. Having not been selected for inclusion since October 2001, all US transmission channels are included at some point between September 2008 - March 2009. Macroeconomic fundamentals are included first. Uncertainty becomes more important in 2009. Financial indicators are only included for one period.

As was the case when modelling Argentina, DIs evolve to a lesser extent during the financial crisis: departures from the constant coefficient case are only seen in November 2008 and January 2009. DIs from US industrial production to Brazilian industrial production heighten considerably in November 2008 after the Lehman Brothers collapse. Moreover, the negative response of industrial production to a rise in financial and macroeconomic uncertainty heightens. To a lesser extent, the negative response of industrial production to a rise in the excess bond premium, also heightens. DIs to the Brazilian stock market show similar patterns but are of a smaller magnitude. Thus we have abrupt contagion from the US, particularly in terms of macroeconomic and uncertainty transmission channels. Again, changes in US financial and uncertainty indicators also have real effects.

Now, we examine the effect of Argentina and Mexico on Brazil during the crisis. All Argentine transmission channels are intermittently selected for inclusion before and during the crisis. Mexican transmission channels are included from 2002 onwards, but become more intermittent in 2007. Mexican macroeconomic fundamentals are included more consistently in 2008. DIs from Argentine industrial production to Brazilian industrial production only intensify slightly in August and September 2009. DIs from the Argentine to Brazilian stock market also intensify in January 2009. The magnitude of DIs from Mexico to Brazil are, however, small. We find evidence of interdependencies between Brazil and Argentina and, to a lesser extent, between Brazil and Mexico but these interdependencies do not play a significant role in our largest Latin American economy, Brazil.

Finally, we consider how Mexico was affected during the global financial crisis. Despite showing the greatest tendency to switch between models of different sizes, Mexico only switches between model specifications 1, 2 and 3. Unlike the Argentine and Brazilian cases, US macroeconomic and uncertainty transmission channels do not show abrupt inclusion. Rather, they continue to be included before and after the crisis. US financial indicators are included prior to the crisis but are included more regularly from August 2008 - August 2010.

Evolving DIs play a greater role in Mexico with a departure from the constant coefficient case from September 2008 - March 2009. If we consider DIs from US to Mexican industrial production, there is some intensification from January - March 2009. Macroeconomic uncertainty negatively affects industrial production but does not intensify noticeably. The excess bond premium also negatively affects industrial production, intensifying from August 2008 - August 2010. If we next examine the Mexican stock market, a drop in US industrial production has a severe negative impact in November 2008. The negative effects of a drop in US stock prices or rise in the excess bond premium is smaller although linkages heighten from April - November 2009. The negative effect of a rise in financial uncertainty starts increasing from late 2001 peaking in September 2008. We thus find evidence of contagion in Mexico through existing macroeconomic and financial interdependencies with the US. US uncertainty variables are also important before and during the crisis.

We conclude this section by examining how Argentina and Brazil affected Mexico during the crisis. Bilateral TVP-PVAR-Xs with Argentina are selected from February - November 2009. The magnitude of volatility spillovers between the Argentine and Brazilian stock market and, to a lesser extent, Argentine and Brazilian industrial production heighten over this period. We find that all Brazilian and Argentinean transmission channels are included intermittently before the crisis. Argentinean macroeconomic fundamentals, exchange rates and Brazilian stock prices are included more regularly during the crisis. DIs from Argentine to Mexican industrial production heighten, peaking in November 2008. Similarly, DIs from the Argentine to the Mexican stock market heighten considerably, again peaking in November 2008. In contrast, DIs from Brazilian to Mexican industrial production indicate a lack of comovement while DIs from the Brazilian to the Mexican stock market are small in magnitude. We, therefore, find that Argentina affected Mexico through existing interdependencies during the financial crisis.

4.6 Overarching Trends from our Three Crisis Episodes

During the currency crises of the 1990s, we find evidence in favour of interdependence or even a lack of linkages rather than contagion. In Argentina and, to a lesser extent, Brazil model specification 1, which only allows for cross-market linkages, is often selected. These cross-market interdependencies, where present, tend to be particularly strong in financial markets. Macroeconomic interdependencies also play a role in the Mexican peso crisis. Similarly, when TVP-PVAR-Xs are selected, which is most common in Mexico, volatility spillovers are strongest between exchange rates and between stock markets.

Our results on the Argentine crisis are also more indicative of interdependence than contagion. While financial interdependence also continues to be important in terms of DIs, macroeconomic fundamentals play a more prominent role in terms of interdependencies between Brazil and Argentina. In Mexico and Argentina, as the crisis worsens in late 2001 and early 2002, model specifications 2 - 5 become more important. As seen during the 1990s, the resulting volatility spillovers tend to strengthen in exchange rate markets and stock markets.

In contrast, during the global financial crisis, without exception, we find evidence of contagion from the US to all LA countries. In Argentina and Brazil, we detect abrupt contagion from the US. However, in Mexico results indicate that contagion spreads through existing macroeconomic, financial and uncertainty transmission channels. Unlike previous crises, we also see evidence of macro-financial linkages proving important in the spread of contagion with movements in the US excess bond premium and uncertainty variables, in particular, affecting industrial production across all LA economies. Financial uncertainty dominates in Argentina but in Brazil and Mexico macroeconomic uncertainty plays a greater role in affecting domestic industrial production.

As discussed in section 4.2., we also uncover another indicator of economic distress: departures for the constant coefficient case indicate that the magnitude of DIs are evolving. This occurs during domestic crises in Argentina, Brazil and Mexico. It also occurs, to a lesser extent, in all LA-3 economies during the global financial crisis.

5 Conclusions

Was contagion present? Many studies have sought to definitively answer this question, first in the context of currency crises in emerging economies and more recently following the global financial crisis and European sovereign debt crisis. The existing literature, however, has become increasingly fragmented with different definitions of contagion making reference to different methods. Moreover, although the wider literature acknowledges the importance of macroeconomic transmission channels, financial transmission channels have been the focus of recent empirical studies.

In this paper, drawing on insights from the dynamic model selection literature, we develop a model switching approach to analyse contagion. We allow the nature of interdependencies, magnitude of interdependencies and transmission channels selected for inclusion to change over time. We also account for macroeconomic fundamentals and changes in US uncertainty in addition to various financial indicators. We thus appeal to multiple definitions of contagion, distinguishing between: interdependence, contagion arising from interdependence and contagion arising through an abrupt change in linkages between countries.

Focussing on Latin America, we examine the early currency crises of the 1990s, the Argentine crisis spanning 1998 - 2002 and the global financial crisis. Following currency devaluations in Mexico and Brazil, results indicate interdependence, particularly in financial markets. Macroeconomic interdependencies are also present during the Mexican devaluation. Our results on the Argentine crisis are similar, however, macroeconomic fundamentals play a more prominent role in terms of interdependencies between Argentina and Brazil. During the global financial crisis, the abrupt inclusion of US transmission channels, particularly uncertainty transmission channels, is clearly indicative of abrupt contagion in Argentina and Brazil. Mexico, however, experiences contagion through pre-existing macroeconomic and financial interdependencies with the US. US uncertainty also affects Mexico before and during the crisis. Overall, our findings demonstrate that contagion was only present during the global financial crisis. We also find that macroeconomic and uncertainty transmission channels play a role during some crises not just financial transmission channels.

Appendix A: Figures

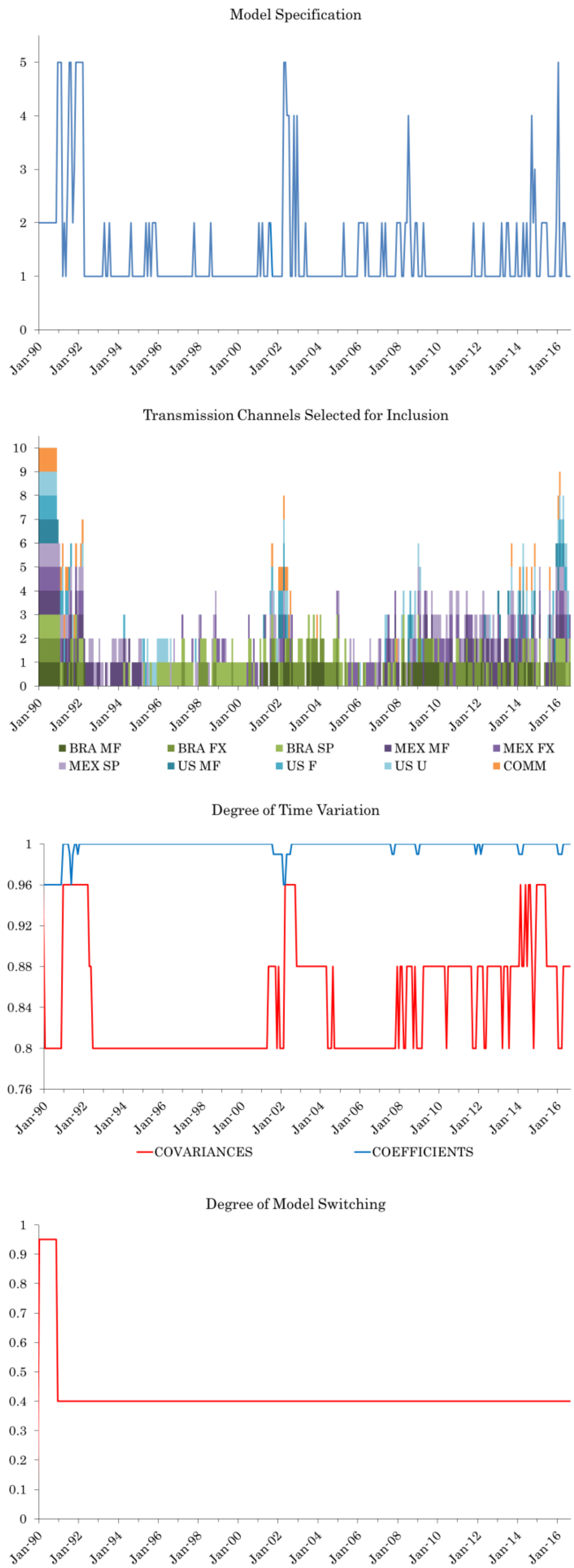


Figure 2: Argentina: An Overview of Key Features

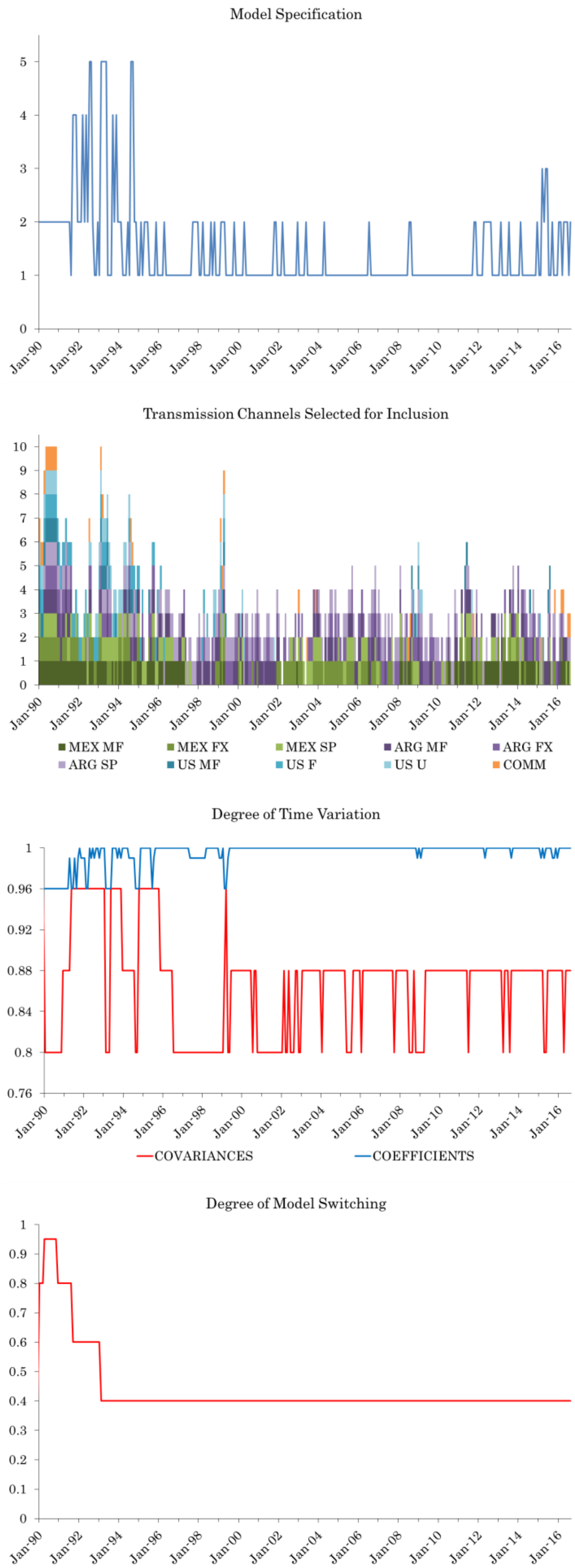


Figure 3: Brazil: An Overview of Key Features

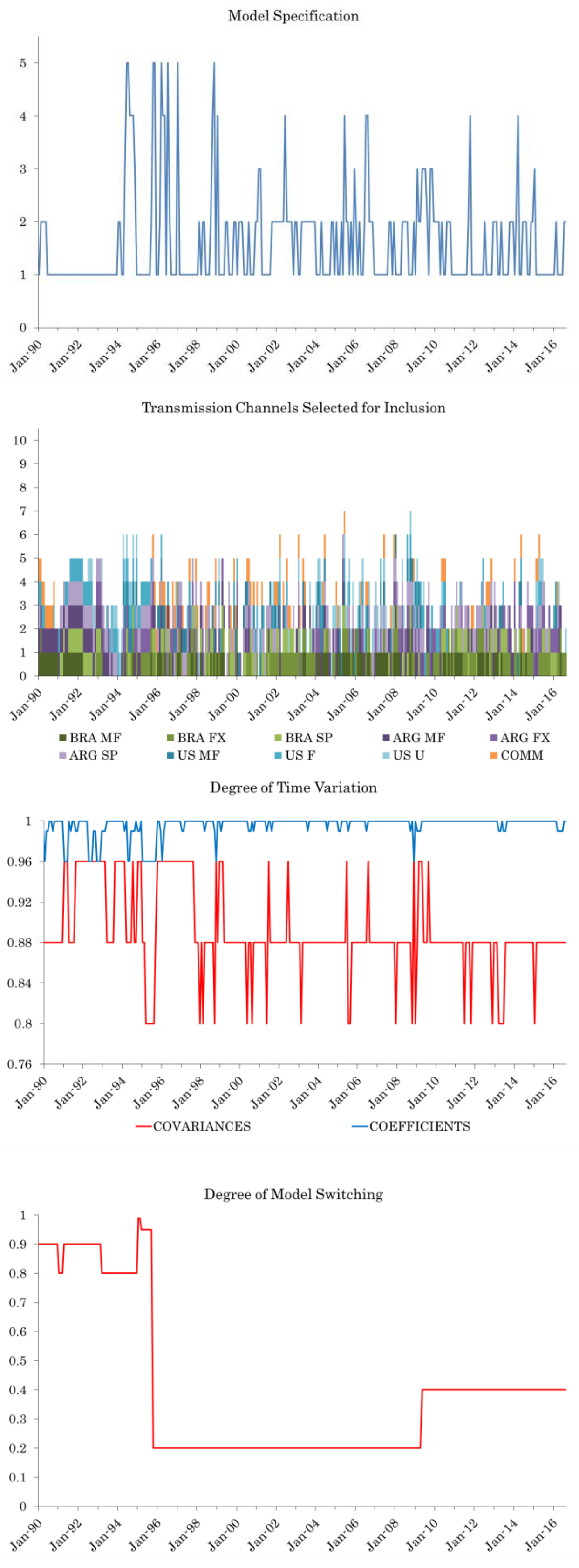


Figure 4: Mexico: An Overview of Key Features

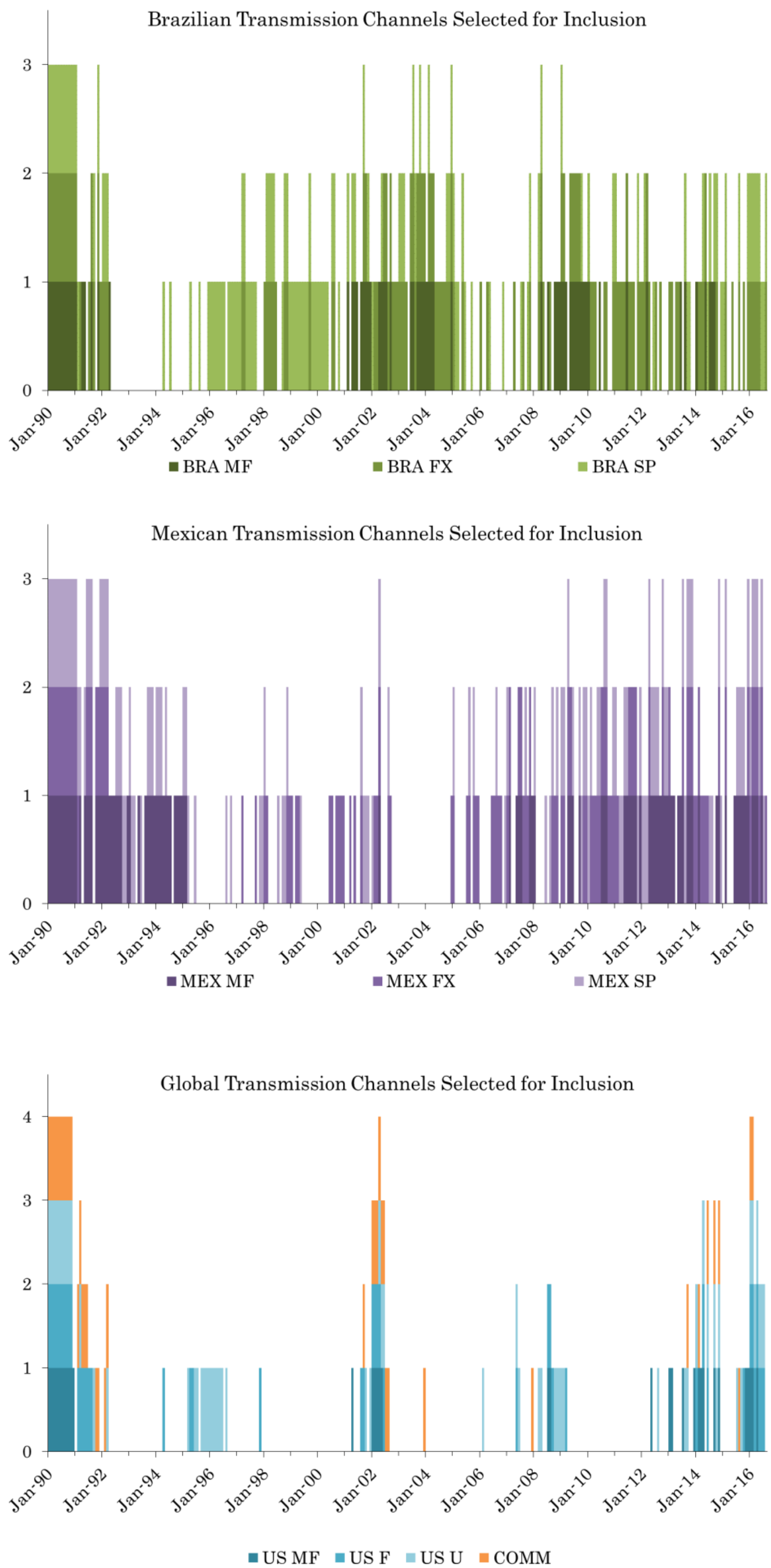


Figure 5: Argentina: Transmission Channels Selected for Inclusion by Country

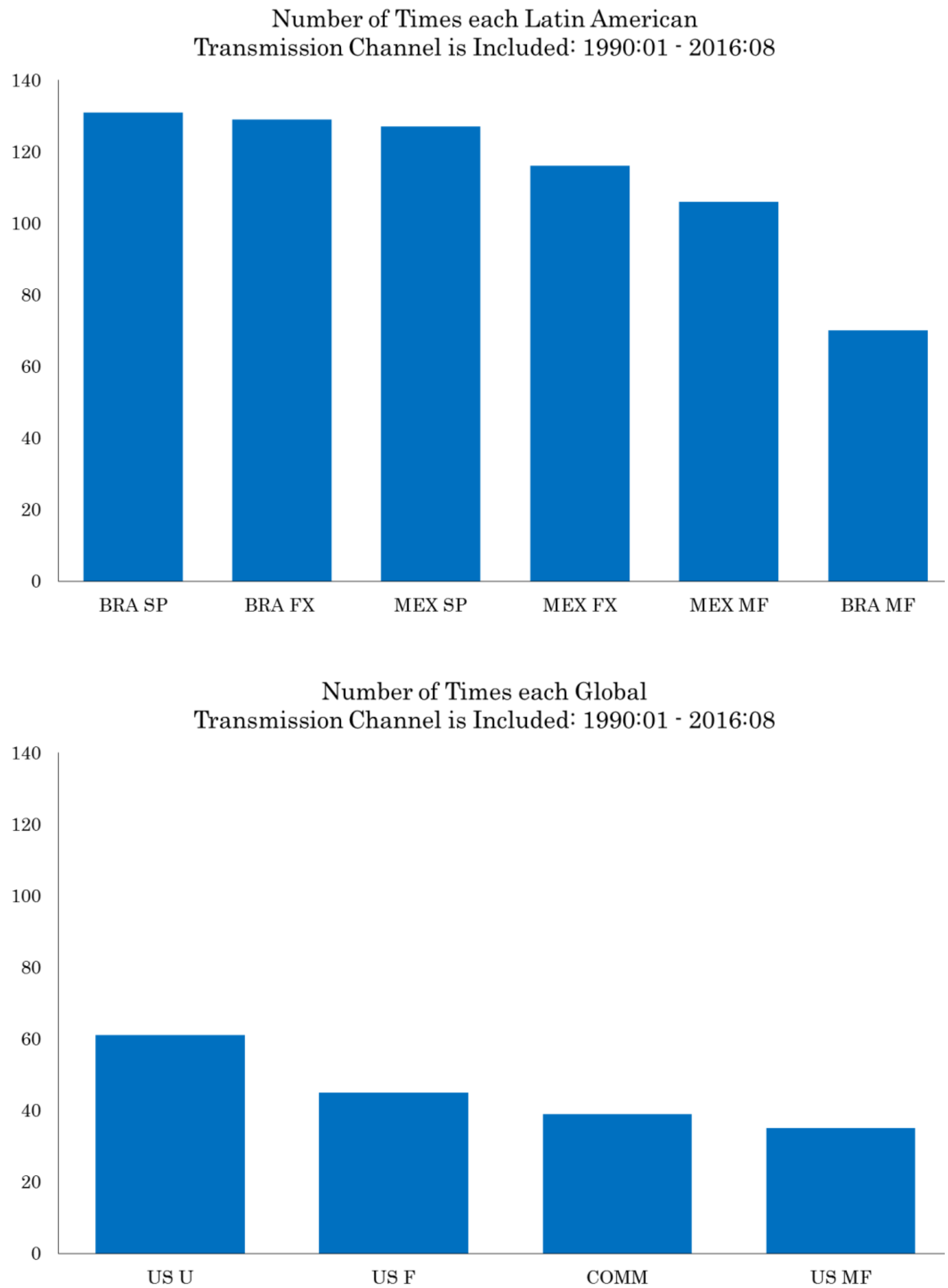
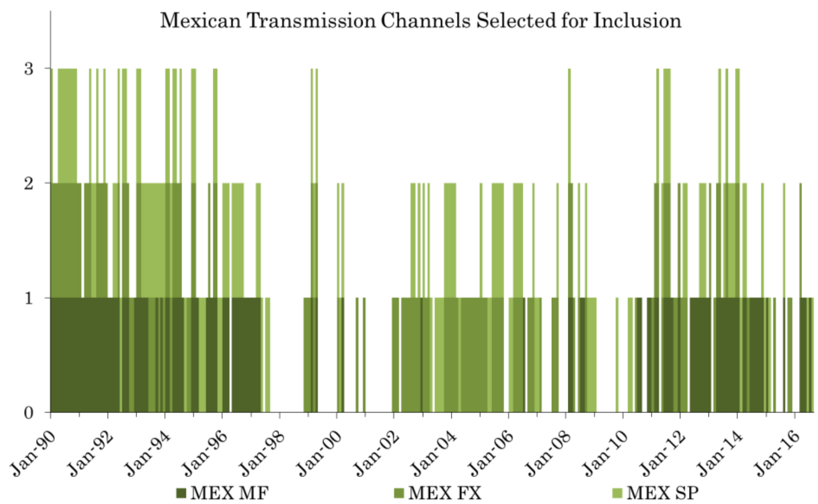
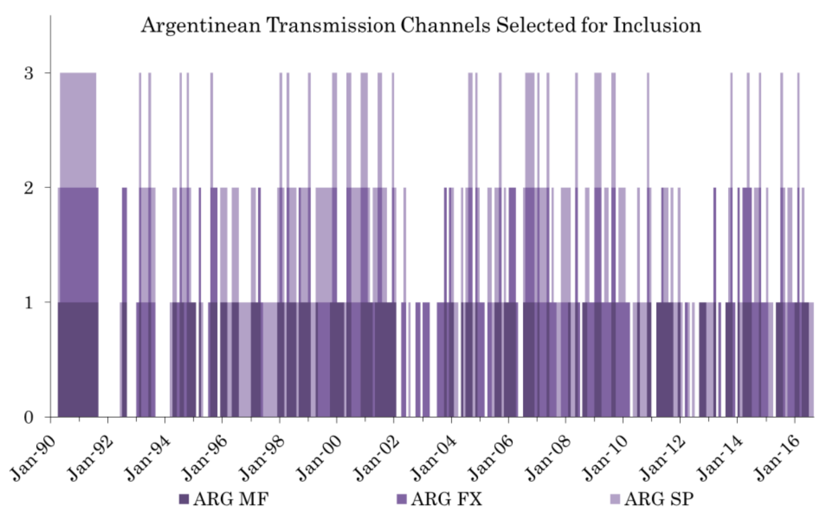


Figure 6: Argentina: Transmission Channels Selected for Inclusion by Frequency





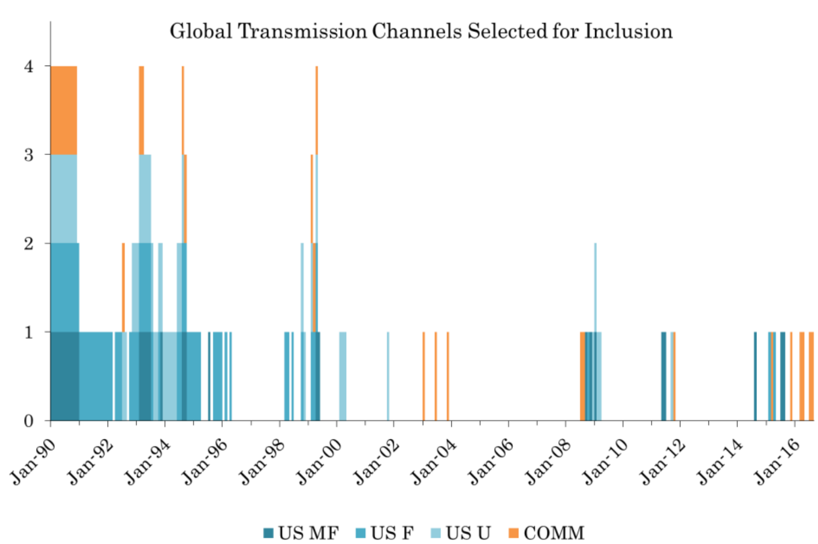


Figure 7: Brazil: Transmission Channels Selected for Inclusion by Country

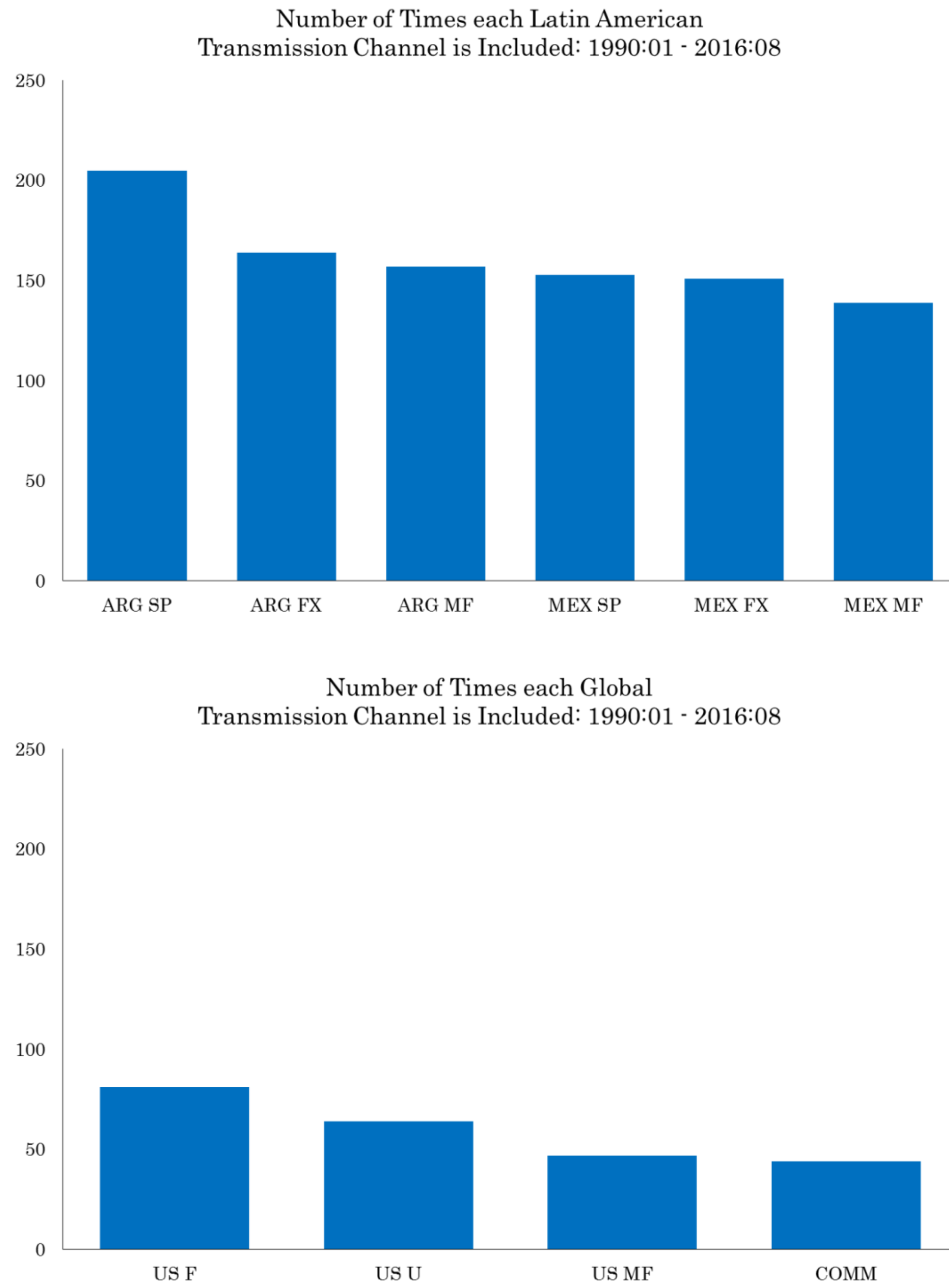


Figure 8: Brazil: Transmission Channels Selected for Inclusion by Frequency

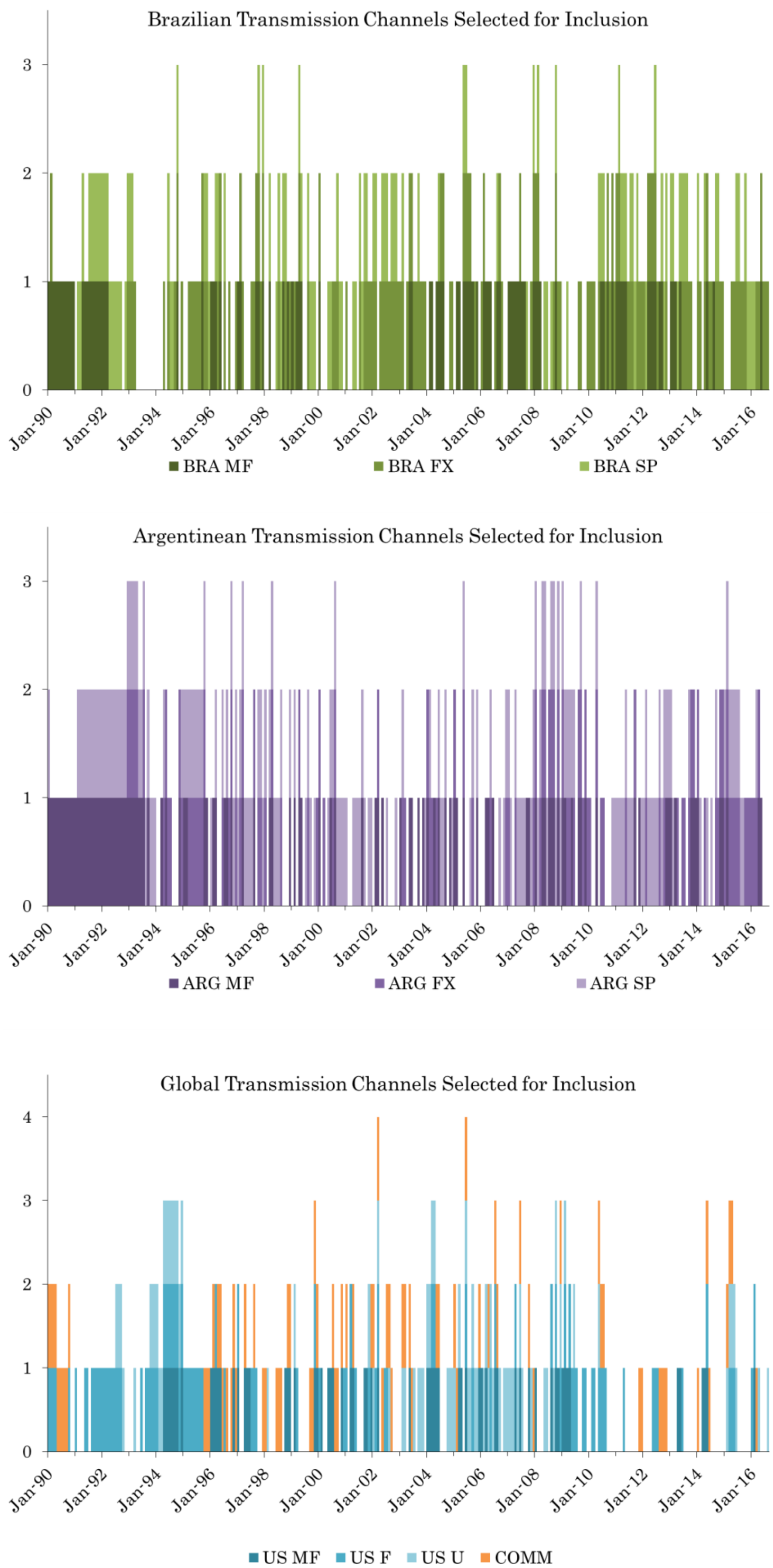


Figure 9: Mexico: Transmission Channels Selected for Inclusion by Country

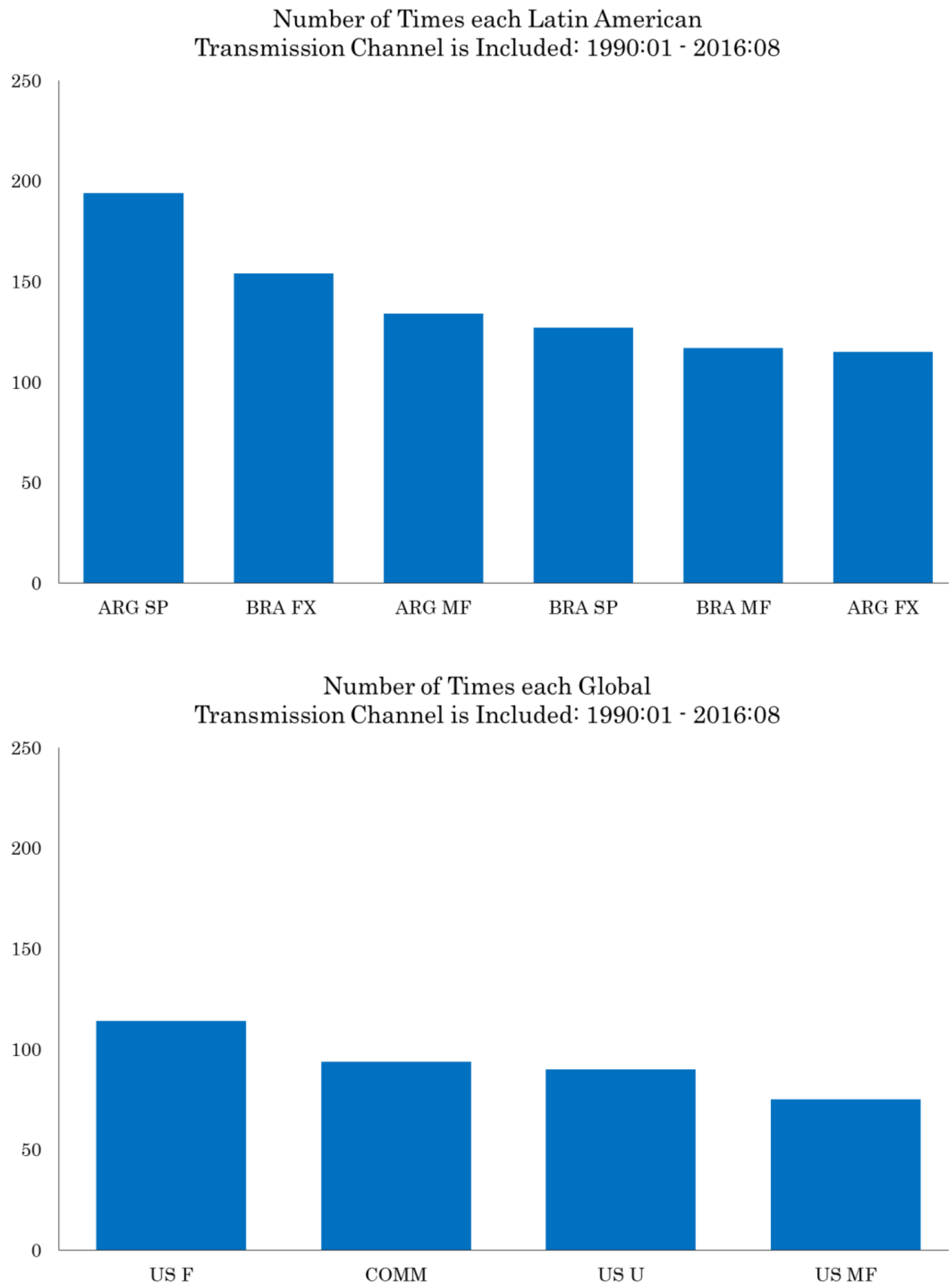


Figure 10: Mexico: Transmission Channels Selected for Inclusion by Frequency

Figure 11: Dynamic Interdependencies: Response of Argentine Industrial Production to a One Standard Deviation Increase in a Predictor

Note: IP = Industrial Production, FX = Exchange Rate, SP = Stock Price, EBP = Excess Bond Premium, FU = Financial Uncertainty, MU = Macroeconomic Uncertainty, OP = Oil Price, COMM = Non-fuel Commodity Price Index

Figure 12: Dynamic Interdependencies: Response of Argentine Stock Markets to a One Standard Deviation Increase in a Predictor

Note: IP = Industrial Production, FX = Exchange Rate, SP = Stock Price, EBP = Excess Bond Premium, FU = Financial Uncertainty, MU = Macroeconomic Uncertainty, OP = Oil Price, COMM = Non-fuel Commodity Price Index

Figure 13: Dynamic Interdependencies: Response of Brazilian Industrial Production to a One Standard Deviation Increase in a Predictor

Note: IP = Industrial Production, FX = Exchange Rate, SP = Stock Price, EBP = Excess Bond Premium, FU = Financial Uncertainty, MU = Macroeconomic Uncertainty, OP = Oil Price, COMM = Non-fuel Commodity Price Index

Figure 14: Dynamic Interdependencies: Response of Brazilian Stock Markets to a One Standard Deviation Increase in a Predictor

Note: IP = Industrial Production, FX = Exchange Rate, SP = Stock Price, EBP = Excess Bond Premium, FU = Financial Uncertainty, MU = Macroeconomic Uncertainty, OP = Oil Price, COMM = Non-fuel Commodity Price Index

Figure 15: Dynamic Interdependencies: Response of Mexican Industrial Production to a One Standard Deviation Increase in a Predictor

Note: IP = Industrial Production, FX = Exchange Rate, SP = Stock Price, EBP = Excess Bond Premium, FU = Financial Uncertainty, MU = Macroeconomic Uncertainty, OP = Oil Price, COMM = Non-fuel Commodity Price Index

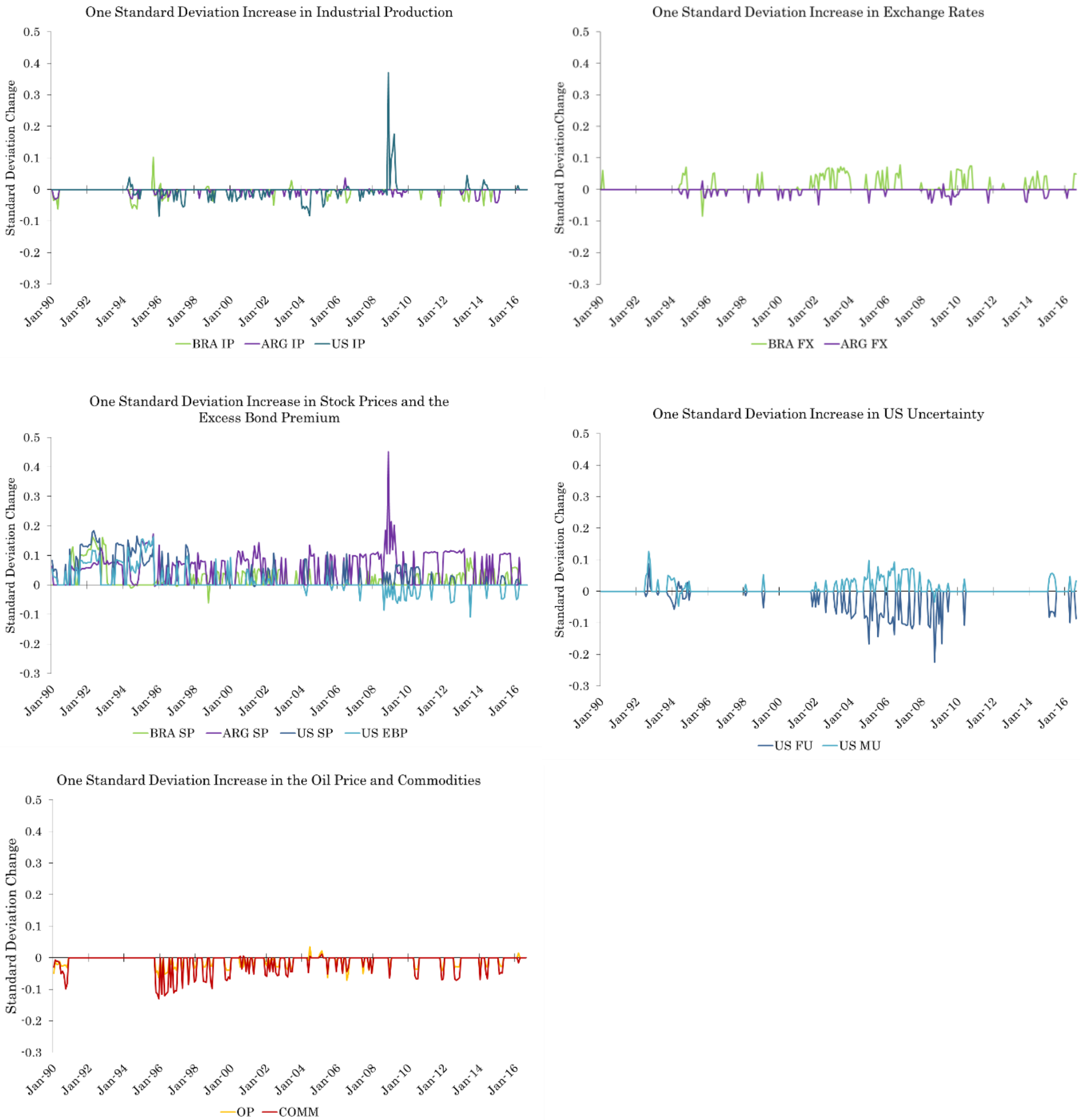


Figure 16: Dynamic Interdependencies: Response of Mexican Stock Markets to a One Standard Deviation Increase in a Predictor

Note: IP = Industrial Production, FX = Exchange Rate, SP = Stock Price, EBP = Excess Bond Premium, FU = Financial Uncertainty, MU = Macroeconomic Uncertainty, OP = Oil Price, COMM = Non-fuel Commodity Price Index

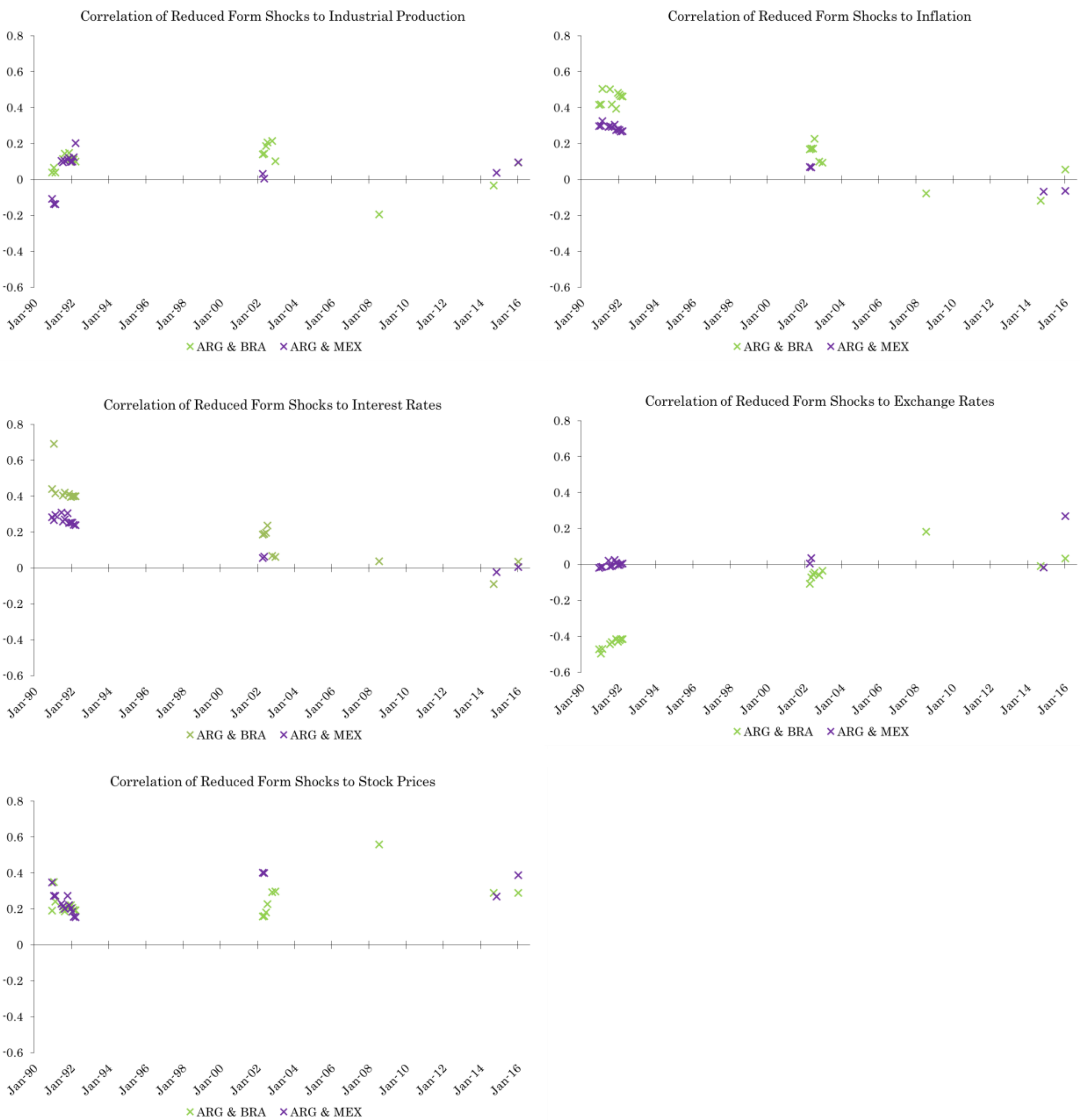


Figure 17: Static Interdependencies: Correlation of Reduced Form Shocks between Argentine Variables and other Latin American Variables

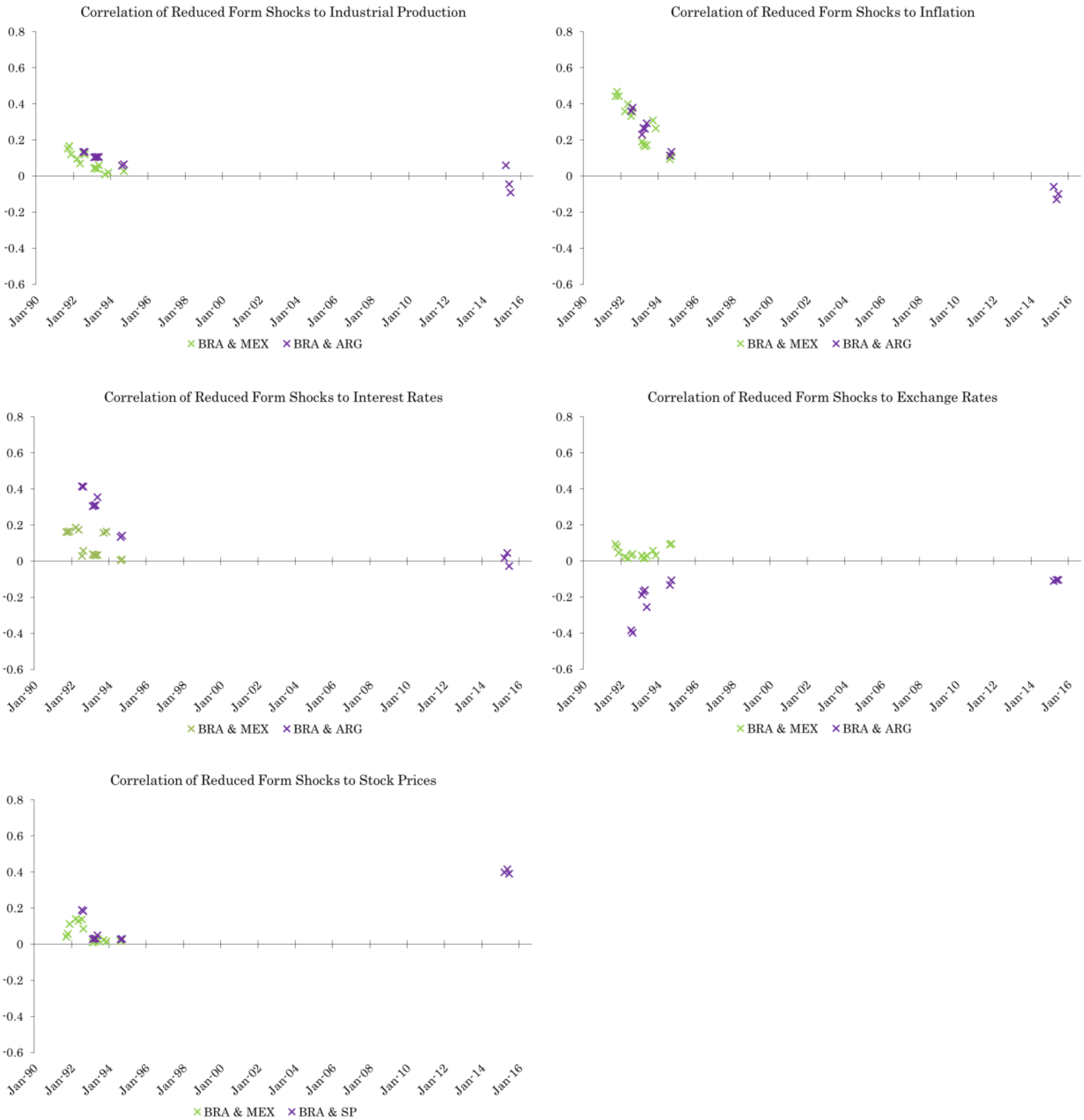


Figure 18: Static Interdependencies: Correlation Reduced Form Shocks between Brazilian Variables and other Latin American Variables

Figure 19: Static Interdependencies: Correlation of Reduced Form Shocks between Mexican Variables and other Latin American Variables

Appendix B: Data Appendix

Data was carefully selected from 10 different sources as described in Table 6. Here, we point out some important features. First, Argentina's official inflation data was discredited in January 2007. In December 2015, the National Institute of Statistics and Censuses of Argentina (INDEC) stopped producing a CPI index. Only in July 2017 did INDEC resume releasing a recognised country wide CPI index. To overcome these issues we use Cavallo and Bertolotto's (2016) chained index which is based on official Argentine data till 2007 and chained to an online price index thereafter.

Second, we sought to obtain accurate short-term interest rate and exchange rate data. For Argentina, the interbank rate was used. For Brazil, the CDI, the interbank rate, was favoured over the SELIC, the base rate, due to longer time series. Finally, for Mexico the 28 day CETES treasury bill rate was used. To capture exchange rate movements we used Darvas' (2012) narrow index of the real effective exchange rate based on 41 trading partners.

Finally, both Argentine and Brazilian stock markets remained undersized and stagnant until the 1990s due to a variety of political and macroeconomic factors. Mexico's stock market also suffered following the 1982 debt crisis. We, therefore, use OECD stock price data which has the longest time series (in terms of non-zero entries) for Brazil. Since the index is recorded to be zero from January to September 1988, we record the log first difference to be zero from February to October 1988. We also use OECD stock price data for Mexico and the US to aid comparability. The OECD does not provide stock price data on Argentina. Instead, data on the MERVAL stock price index was extracted from Bloomberg.

Country	Description	Source
ARG	Real industrial production index	Datastream
	Inflation (% MOM)	Cavallo and Bertolotto (2016)
	Short-term interest rate	Datastream
	Real effective exchange rate	Darvas (2012)
	Stock price index	Bloomberg
BRA	Real industrial production index	Datastream
	Inflation (% MOM)	Datastream
	Short-term interest rate	Datastream
	Real effective exchange rate	Darvas (2012)
	Stock price index	OECD Data
MEX	Real industrial production index	IMF IFS
	Inflation (% MOM)	Datastream
	Short-term interest rate	Datastream
	Real effective exchange rate	Darvas (2012)
	Stock price index	OECD Data
US	Real industrial production index	Datastream
	Inflation (% MOM)	Datastream
	Wu-Xia shadow rate during ZLB/ federal funds rate otherwise	Wu and Xia (2016)/ FRED
	Stock price index	OECD Data
	Excess bond premium	Gilchrist and Zakrajšek (2012)
	Macroeconomic uncertainty	Ludvigson et al. (2019)
	Financial uncertainty	Ludvigson et al. (2019)
WORLD	Non-fuel commodity price index	IMF IFS
	Oil price	IMF IFS

Table 6: Data Sources

Note: IMF IFS = IMF international financial statistics database, FRED = St. Louis Federal Reserve Economic Data, ZLB = zero lower bound.

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