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Sovereign risk and the impact of crisis: Evidence from Latin America

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ABSTRACT

We utilize the default by Argentina in 2001 and the Global Financial Crisis in 2008, as natural experiments, to monitor the complex interactions between sovereign bonds when subjected to endogenous and exogenous shocks. By forming pairs of Latin American sovereign bonds, bundled into similar maturity class, the analysis highlights the complex nature of risk shifting, and the temporal nature of the volatility transmission and sharing mechanisms in the lead up to, and after, a crisis period. The results show that shorter maturity groups and longer maturity groups behave in fundamentally different ways in terms of volatility transmission, while one or two leading countries act as regional benchmarks. The dynamics are consistent with temporal but segmented investor preferences, with the arrival of crisis contributing to a breakdown in the previous relationships. In addition, there is additional economic benefit from utilizing knowledge of the volatility structure underlying the historic transmission channels to improve the portfolio outcomes of market participants.

1. Introduction

This paper investigates how international bond markets respond to changes in risk by examining the volatility linkages between U.S. dollar denominated bonds issued by Latin American countries of different maturity and ratings class. We utilize the Argentine 2001 default, which is a crisis endogenous to the Latin American region, and the Global Financial Crisis (GFC) of 2008, which is exogenous to the region, as natural experiments to test the impact of these events on sovereign risk dynamics and investor preferences. The use of U.S. dollar denominated bonds facilitates investigation within this region, while also avoiding any premium applied by investors concerned with foreign exchange risk, in addition to the usual credit and liquidity risks.

When a country issues bonds internationally they are termed "sovereign bonds" by financial market participants.[1] Such issues are typically denominated in U.S. dollars and have English common law as the governing law of the transaction, a feature that also clarifies concerns over legal jurisdiction in the event of bankruptcy. In summary, sovereign bonds represent a homogeneous asset class of varying maturity that only differ by the credit quality of the issuer, and rarely contain the option features that complicate the pricing and analysis of corporate bonds in domestic markets, especially those in the United States (e.g., Longstaff and Schwartz, 1995; Jacoby, Liao and Batten, 2009).

While the focus of this study is on Latin American sovereign bond issues, the findings have wider application to financial markets generally. In addition to providing insights into theories on regional term structure and investor preferences, we also contribute to an existing literature on asset market linkages where the focus has typically been on linkages within, or between, equity markets.[2] The Latin American market is an important segment of the international bond market and the key economies within the region are integrated with strong economic and financial market linkages, although the degree of integration between the countries has changed along with the regional links to the broader international economy (e.g. Baumann, 2008). At this time and prior to the Argentina default, Latin American governments traditionally relied more on the direct issuance of international bonds than the

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[1] Henceforth for simplicity in this study we will refer to a bond issued by a sovereign state in the international markets as a sovereign bond.

[2] The existing empirical literature on the linkages across equity markets includes: Chan, Chan and Karolyi (1991), Karolyi (1995), Lin, Engle and Ito (1994), amongst others.

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international bank lending that characterized developing economies in Asia or Europe (BIS, 1999). The high level of dependency by Latin American economies on the international debt market as a source of finance is attributable to inadequate domestic savings, and under-developed domestic banking and bond markets. Seeking funds in the international bond market remains an important source of finance for these emerging economies – and many others – to support domestic economic activities. Nonetheless, it also makes these same economies vulnerable to changes in investor preferences that occur especially during periods of crisis.

The debt sustainability of an issuer is closely linked to transfer risk[3] and manifests in the form of sovereign risk when government bonds are denominated in foreign currency. Among others, Longstaff and Schwartz's (1995), show that for a corporation, default occurs when the value of the firm , V, reaches the threshold value K. At the sovereign level, Claessens and Pennacchi (1996) attribute this threshold to an index that captures the repayment capacity of the sovereign issuer. Under the Debt Sustainability Framework (DSF), developed jointly by the International Monetary Fund (IMF) and World Bank, this default threshold is gauged using the present value of a country's income stream and expenditure in addition to any initial debt. Specifically, for a country to be solvent, the external debt must be less than, or equal, to the present value of future non-interest current account balances. We later show how from both an individual country and regional level, changes in creditworthiness affect the volatility transmission process, with the yield curve dynamics associated with one or two leading countries shaping the intraregional dynamics. The dynamic nature of these volatility transmission relationships has important implications for the risk management of international portfolios containing sovereign bonds.

Clearly, the incentive for market participants to monitor and manage cross-market volatility becomes stronger when underlying asset volatility increases, as it does during periods of crisis. Consequently, another feature of this paper is that we monitor the complex interactions in the sovereign bond portfolios bundled into different maturity baskets before and after the Argentine default and the GFC. Thus, in addition to addressing the question of how volatility in one market leads to volatility in another market during crisis, we are able to identify the temporal nature of the volatility structure by showing how these interactions affect the regional term structure. These results confirm the temporal dependence of the investigated Latin American sovereign bonds and the volatility channels that are present within the region.

Utilizing the information obtained from the cross-market volatility structure, optimal portfolio weights are estimated both in-sample and out-of-sample. This portfolio approach offers insights that are relevant to both investors and issuers of sovereign international bonds[4]. For example, an investor seeking to manage, or hedge, the level of risk in a sovereign bond portfolio can rebalance individual asset positions based upon information on the direction, and magnitude, of volatility. In fact, we later show how daily optimal portfolio weights evolve when accounting for volatility linkages of sovereign bonds in a multivariate framework. This perspective would help alleviate concerns of financial market participants, whose focus is typically either on the market timing of investment, or issuance of new securities.

[3] Bouchet, Clark and Groslambert (2003) argue that transfer risk is a risk that feeds into sovereign risk. What it means is that when a country issues debt in foreign currency in the international market, the repayment capacity is inextricably linked to the country's ability to maintain foreign exchange reserve at the required level depending on its external obligations.

[4] Outstanding of international bonds worldwide were US$20.9 trillion in March 2015 (BIS, 2015). Of these, US$1.6 trillion were issued by governments and so are classified as sovereign bonds (BIS, 2015).

For example, our analysis highlights the impact of shifting maturity and risk preferences on the regional term structure. Prior to the 2001 default of Argentina, the regional term structure was not only stratified based upon credit worthiness implied by credit ratings, but also by standard macroeconomic measures such as debt service. While other studies have demonstrated regional spillover effects due to rating changes (e.g. Bissoondoyal-Bheenick et al., 2014), we show that during periods of stability, the regional bond markets were largely driven by the risk structure of the issuer having the highest credit quality (in our case Mexico). This single issuer effectively provided the regional benchmark for other issuers. However, immediately before and immediately after the default of Argentina, which is treated as an endogenous shock to the region, idiosyncratic risks dominate. This situation contrasts to the pricing dynamics during the exogenous shock from the GFC, when the region tended to respond as a connected system.

This paper contributes to the existing literature in a number of dimensions. First, while it is closely related to a group of papers that examine sovereign risk premiums[5] our portfolio approach and later assessment of the economic advantages of risk shifting across sovereign bond portfolios is novel in the context of the sovereign risk literature. The investigation undertaken in this paper provides evidence of a definite incentive for investors to better understand cross-border volatility dynamics before, during and after crisis.

Second, unlike other recent studies that investigate price effects and impacts associated with derivatives (such as CDS), where the sovereign bond is the underlying asset (Pan and Singleton,2008; Longstaff, Pan, Pedersen and Singleton, 2011; Sharma and Thuraisamy, 2013; Westerlund and Thuraisamy 2016 amongst others), we utilize changes in the prices based on the bid–ask spread of actual U.S. dollar denominated sovereign bonds to provide additional insights into the role of bond market liquidity (e.g. Elton and Green, 1998; Jovanovic and Rousseau, 2001; Angel Lafuente and Serrano, 2015; amongst others) in explaining the regional dynamics and the volatility transmission process.

Third, we are able to contribute to the broader literature on the macroeconomic and microeconomic impacts of financial market crisis (e.g. Demyanyk and Van Hemert, 2011) and the modeling of financial turmoil (e.g. Huixin, 2012). Historically, credit shocks in an economically and geographically integrated region affect the first and second-order moments of asset price returns, with the latter being shared between regional economies. Therefore, by investigating the cross-market dynamics of Latin American sovereign bonds around both endogenous and exogenous shocks, we unravel the direction of second-order moments and the change in the covariance structure of seemingly related markets, and do so in a regional setting.

Overall, this approach is able to provide vital information on the channels transmitting volatility across these regional bond markets. The paper is organized as follows: Section 2 further introduces previous studies, while Section 3 outlines the data used in this study. Section 4 covers the method used in this study. We discuss the results from the study in Section 5, and Section 6 concludes the paper.

2. Previous studies

The benefit of modeling time-varying, second-order moments of asset returns through a multivariate modeling framework is both efficient and relevant when compared to modeling through a univariate process (see Bauwens, Laurent and Rombouts, 2006 for

[5] For example, Bernoth et al. (2013), who investigate the European government bond market; Hernandez and Valdes (2001) who examine the contagion of Mexico, Thailand, Russia and Brazil using sovereign spreads as the measure of crisis, and Martinez et al. (2013) and Csonto (2014) also investigate factors affecting sovereign bond spreads.

more details). The transmission of asset-market movements in the first and second moments of returns is typically investigated using a number of different methodologies, including the Generalized Autoregressive Conditional Heteroskedasticity (GARCH) framework. Within this framework, univariate as well as multivariate settings are utilized to better understand the spillover between various asset classes and financial markets. For example, King and Wadhwani (1990), Hamao, Masulis and Ng (1990), Engle, Ito and Lin (1990), Wang, Meng Rui and Firth (2002), Lin, Engle and Ito (1994) and Karolyi (1995), Ewing and Malik (2005), Gande and Parsley (2005), Bubak, Kocenda and Zikes (2011), Chang (2009), Chang, McAleer and Tansuchat (2011), El Hedi Arouri, Jouini and Nguyen (2011), Martinez et al. (2013), Narayan (2015), Clements, Hurn and Volkov (2015) are some of the many studies that examine the empirical linkages across equity, currency and commodity markets and sectors within individual markets.

Examining the inter-market dependencies and directions of spill-over of returns and volatility of dually-listed stocks in the equity markets of Hong Kong and the UK, Wang, Meng Rui and Firth (2002) provide evidence of bi-directional spillover. Lin, Engle and Ito (1994) investigate the transmission of return and volatility between New York and Tokyo using an aggregate shock model and a signal extraction process and their evidence suggests that the local return is influenced by the return innovations in the foreign market. In addition, they show that the signal extraction process weakly outperformed the GARCH-M model and the aggregate shock model. Karolyi (1995) highlights the importance of properly measuring volatility for regulatory mechanisms, pricing of securities and trading strategies. Ewing and Malik (2005), in an intra-market setting, document the importance of accounting for volatility shifts when testing volatility transmissions. Testing the forecast error variance of sectoral equity return in the US, Narayan (2015) documents the time-varying nature of credit market shocks and their influential role during the GFC. Similarly, El Hedi Arouri, Jouini and Nguyen (2011) test the extent of volatility transmission between oil and stock market sectors in Europe and the U.S. They find significant spillover between oil and the oil sector stock returns in Europe, with this volatility sharing being bi-directional in the U.S.

Engle, Ito and Lin (1990) test the notion of “meteor showers” versus “heat waves” using yen-dollar exchange rate data to study the cause of volatility clustering. Differentiating between country-specific and cross-market effects due to spillovers, they find evidence supporting the “meteor shower” hypothesis, thereby confirming volatility persistence arising from private information. Clements, Hurn and Volkov (2015) extend this study to an investigation of equity and bond markets and also confirm the meteor shower effect. Kearney and Patton (2000) find reduction in volatility transmission with temporal aggregation and they argue that markets tend to transmit volatility during active phases rather than during calm phases. The volatility dynamics between spot and futures have also been investigated by Chan, Chan and Karolyi (1991), Gannon (2005), Au-Yeung and Gannon (2005), Chuliá and Torró (2008), to name but a few of the many studies in this area. Chng (2009) examining the cross-market trading dynamics between seemingly unrelated commodities underpinned by the automobile industry, reports a common exposure to this industry. Chang, McAleer and Tansuchat (2011), testing the hedging effectiveness of crude oil spot and futures, also demonstrate the effectiveness of diagonal BEKK model, which is used in this study for the out-of-sample forecasting exercise.

Despite the size and growth of fixed income markets, an understanding of the empirical linkages across bond markets is far from complete. This is more so in the case of risky sovereign international bonds issued by emerging market issuers. Studies on the volatility dynamics of fixed income markets include Edwards and Susmel (2003), Batten and In (2006), Cifarelli and Paladino (2004), In (2007) and Chuliá and Torró (2008). For example, Batten and In (2006) examine the linkages in the sovereign spreads due to interest rate and asset factors and find that there is an asymmetric interaction between high-grade yen Eurobonds. Cifarelli and Paladino (2004) examine the impact of the Argentine default in an intra-regional setting in Latin America and Asia by modeling the second moment of sovereign spreads. They find signs of contagion having long-lasting effects in Latin America and a less persistent effect in Asia.[6] This finding could be attributed to the institutional nature of these two markets and the neutral impact of the Argentine default on other regions. Gande and Parsley (2005) find asymmetric response effect of sovereign spillover following sovereign rating changes with the dominance of common information spillover. Thuraisamy and Gannon (2013) model the long run dynamics across five markets in Latin America using sovereign international bonds and find credit quality driven sub-regional links. The pre-Argentine default window is characterized by heterogeneous behavior across the clusters. Generally, the Mexican market and the Colombian market co-move during the pre-crisis. More importantly, the shorter maturity clusters have a clear and consistent pattern of credit quality driven linkages. However, these linkages are weaker in the longer maturity clusters. Riedel, Thuraisamy and Wagner (2013) model sovereign risk in Latin America conditional on unobservable endogenous credit cycle. They find that the determinants of spread during crisis states have higher sensitivity to changes in sovereign risk.

3. Data

The Latin American region is one that is known for its asset market volatility with international investors typically requiring a country risk premium when investing in these markets (e.g. Warnes and Warnes, 2014). Importantly, there is also a dependence on international financing. Given the issues associated with the nature of governance in Latin American countries the importance of country level governance as a predictor of equity return is evident in Narayan, Sharma and Thuraisamy (2015). At a corporate level, firms tend to rely on internal financing due to limited development of domestic bond markets (e.g. Maquieira et al., 2012). While many firms are family owned and controlled (e.g. González et al., 2012), the presence of institutional investors has been shown to positively affect firm value (e.g. Camila De-la-Hoz and Pombo, 2016): a finding that highlights the role that corporate governance and reporting plays in impeding regional financial market development. To identify relevant bonds, we searched for key US dollar denominated sovereign bonds with no call provision, adequate liquidity and at least two years of remaining maturity. The search revealed 22 bonds belonging to Argentina, Brazil, Chile, Colombia, Mexico and Venezuela. Since there was only one bond maturing in 2009 for Chile, we excluded it from the analysis. The Argentina sample period, which represents an endogenous crisis period, is from March 31, 1999 to September 15, 2004 (1446 daily observations) for the whole sample and equal-sized sub-sample windows of 713 observations each for the pre and-post crisis periods. These subsamples are based around the official default date of Argentina on December 23, 2001. The sample period for the Global Financial Crisis (GFC), which illustrates an exogenous shock, commences on September 16, 2004 and ends September 14, 2012 (2028 daily observations). Although the origin of the GFC can be traced back to late 2006, the full

[6] Also see Yanus (2013), Mink (2015), Wang et al. (2014) and Mollah et al. (2016) discussion of contagion in emerging stock markets and how emerging markets respond to global risks (Zinna, 2014; Samargandi and Kutan, 2016).

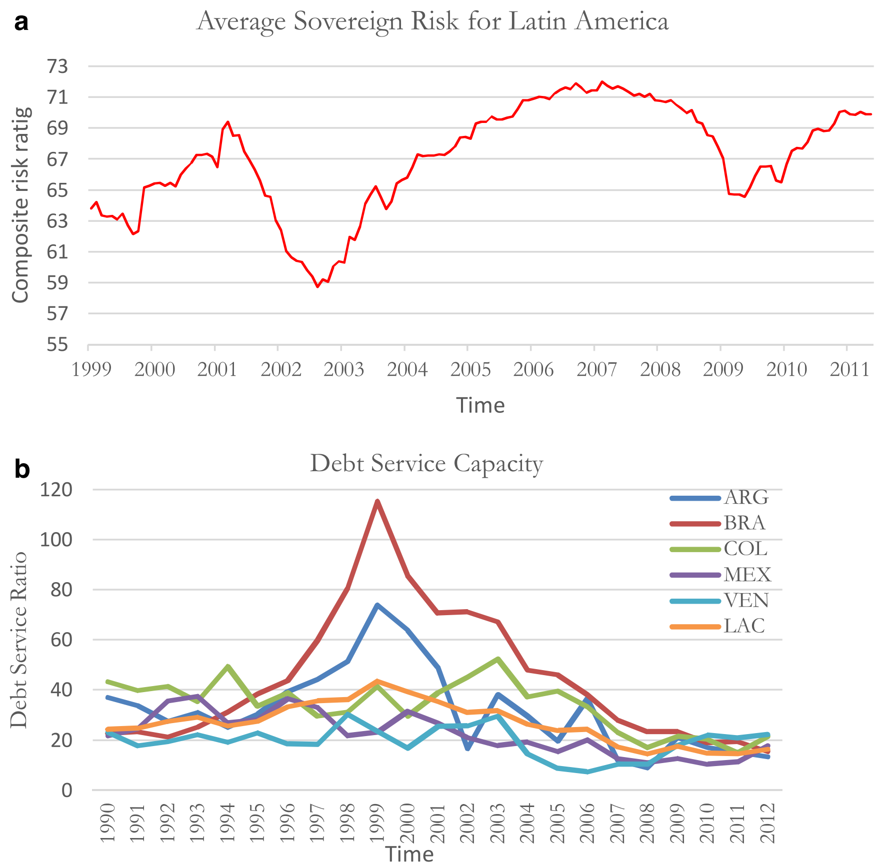

Fig. 1. (A): Average ICRG sovereign risk for Latin American sovereign issuers. The figure plots the average score (from 100 = the lowest risk) of the International Country Risk Guide (ICRG) composite risk rating for Argentina, Brazil, Colombia, Mexico and Venezuela for the period from February 1999 March to July 2011. The composite rating is derived from (1) political, (2) economic and (3) financial risk ratings produced by ICRG using the subjective assessment of ICRG editors. The declining scores, from the middle of 2001, demonstrate the subjective assessment by ICRG about the individual Latin American countries covered in this study with respect to the degree of stability in terms of political risk, the economic strengths and weaknesses in terms of economic risk and the in individual country's capacity to generate adequate foreign currency to meet its financial obligations. The increasing sovereign risk within the region in the lead-up to the sovereign default of Argentina in December 2001 reflects the subjective assessment by ICRG editors. **(B) Debt sustainability index for key Latin American countries.** This diagram represents the country's capacity to service its debt commitment for the Latin American countries covered in this study. Debt service ratio is the ratio total debt service to revenue earned. Total debt service is measured as the sum of principal repayments and interest actually paid in currency, goods, or services on long-term debt, interest paid on short-term debt, and repayments. During the latter part of 1990 s and in the lead up to the Argentine default most of the countries in the region experience sharp rise in debt service ratio revealing vulnerability with respect to capacity index.

extent of the crisis was only revealed when Lehman Brothers filed for Chapter 11 protection on September 15, 2008. Accordingly, we subsample this data as pre and-post GFC with equal-sized windows of 1014 observations each based around 15 September 2008. While analysis of the impact of the GFC on other emerging markets and regions outside Latin America is outside the scope of this paper, a number of authors have also investigated spillover effects in bond and stock markets, including Sugimoto, Matsuki and Yoshida's (2014) analysis of African stock markets, Zinna's (2014) and Csontó (2014) analysis of other sovereign bond markets, and Kenourgios and Padhi (2012) and Daugherty et al.'s (2015) analysis of frontier markets, amongst others.

The database for the Argentina sample of 1446 daily observations includes 21 U.S. dollar denominated sovereign bonds divided into five different maturity baskets covering 2007, 2008, 2009, 2020 and 2027 baskets. Given the maturity status of the sample of bonds, we cluster them into two distinct groups – the shorter maturity group consisting of the 2007, 2008 and 2009 baskets and the longer maturity group consisting of the 2020 and 2027 baskets. The Argentine crisis sample includes all five baskets of varying maturities, while the second GFC-crisis sample (due to the expiry of various issues) includes only the longer maturity group. The Argentine default changed the correlation structure between regional assets and the level of intra-regional risk (see Kaminsky and Schmukler, 2002; Christopher, Kim and Wu, 2012; Kenourgios and Padhi, 2012, amongst others).

The 21 bonds were then paired, based on near maturity baskets of 2007, 2008, 2009, 2020 s and 2027 s. The daily bid closing prices of these sovereign bonds were obtained from Thomson Reuters and Bloomberg. Specifically, daily logarithmic returns of our sample were used to test the nature of the volatility dynamics in the Latin American region. Sample selection criteria ensured that only the US dollar denominated Eurobonds with a duration exceeding two years of final maturity and adequate liquidity entered our sample. We also ensured that there were no call provisions attached to these bonds as these provisions will likely distort the results. For example, when controlling for call provisions and taxes, Jacoby, Liao and Batten (2009) find an insignificant relationship between spreads and riskless yield in the Canadian corporate bond market – raising considerable concern on the current understanding of the relationships. The specific sample periods were also chosen to provide the maximum number of series and daily yield observations.

The economic context of these crisis events is revealed in Fig. 1a and b. Fig. 1a plots the average International Country Risk Guide (ICRG) composite sovereign risk for Latin American bond issuers for the period 1999–2011,[7] while Fig. 1b reports the change in the macroeconomic position. The left hand side axis of Fig. 1a reports the average sovereign risk score implied by the composite risk rating measure. The aggregate score for the Latin American region is derived as the average composite sovereign risk score for Argentina, Brazil, Colombia, Mexico and Venezuela for the period from February 1999 March to July 2011. ICRG derives the composite rating from (1) political, (2) economic and (3) financial risk ratings produced by the subjective assessment of its country editors. The declining scores, from the middle of 2001, demonstrate the assessment by ICRG about the individual Latin American countries covered in this study with respect to the degree of stability in terms of political risk, the strengths and weaknesses in terms of economic risk and the in individual country's capacity to generate adequate foreign currency to meet its financial obligations. The declining scores, from the middle of 2001 to 2003, demonstrate deterioration in the economic conditions of the region and an associated increase in sovereign risk after the default of Argentina in December 2001. Fig. 1b plots the capacity to service its international debt for selected countries: the ratio of total debt service to revenue earned, with total debt service measured as the sum of principal repayments and interest actually paid in currency, goods, or services on long-term debt, interest paid on short-term debt, and repayments. Fig. 1b to a degree, provides more or less the mirror image of Fig. 1a and shows the relationship between deterioration in macroeconomic fundamentals and investor perceptions of risk (e.g. the sovereign risk score declined and the debt service ratio increased in the lead up to the Argentine default).

Sovereign bonds are more liquid and actively traded than corporate bonds, which are often privately placed with institutional investors. In order to understand the regional dynamics of Latin American sovereign bonds issued in international markets, the analysis is limited to the most liquid bonds denominated in U.S. dollars. The search revealed 22 Latin American sovereign bonds belonging to Argentina, Brazil, Chile, Mexico, Colombia and Venezuela that were U.S. denominated bullet bonds, had consistent and daily pricing and had a maturity of at least 2-years from the end of our sample period. For example, some bonds of shorter maturity expired during the various samples, while others were issued during the period.

4. Method

We utilize a bivariate GARCH framework to determine the nature of cross-market volatility in the Latin American sovereign bond market during the pre- and post-Argentine crisis periods. We later confirm these findings by investigating the impact of the Global Financial Crisis on a similar group of Latin American bonds. The investigation is undertaken by examining different pairs of sovereign bonds, matched in terms of maturity, to determine how the bond volatilities change over time, within a regional setting. This procedure permits the observation of the behavior of volatilities, and co-volatilities, across markets to determine the direct, and indirect, influences of one market over another. This approach demonstrates how seemingly similar markets, albeit with different credit qualities, share volatility. Later, the economic significance of such information for portfolio management is determined. We begin by considering the structural approach to risky bond pricing given by Longstaff and Schwartz's (1995):

$$P(X,r,T) = D(r,T) - wD(r,T)Q(X,r,T) \tag{1}$$

where $P(X,\ r,\ T)$ is the value of a risky bond, $D(r,\ T)$ is the price of a riskless bond, $wD(r,\ T)$ is the present value of the amount that is not received by the bondholder in the event of default and $Q(X,\ r,\ T)$ is the risk-neutral probability of a default. The first difference of the natural logarithm of the risky bond price is represented as part of the return generating process. Suppressing the term $(X,\ r,\ T)$ from the calculation process, the daily continuous return on a risky bond, belonging to a market of bonds, in the bivariate case is simply:

$$R_{1,t} = ln\left(\frac{P_{1,t}}{P_{1,t-1}}\right) \times 100 \tag{2}$$

$$R_{2,t} = ln\left(\frac{P_{2,t}}{P_{2,t-1}}\right) \times 100 \tag{3}$$

We capture the second-order, time dependence of the risky sovereign bond returns of the various Latin American issuers, through the bivariate model of Baba, Engle, Kraft and Kroner (1990) (henceforth simply the BEKK GARCH model), and Engle and Kroner (1995). The model that governs the joint process of conditional mean and conditional variance-covariance is as follows:

$$R_t = \alpha + u_t \tag{4}$$

$$u_t|\Omega_{t-1} \sim N(0, H_t) \tag{5}$$

where the return vector for any pair of markets is defined as $R_t = [R_{1,t} - R_{2,t}]$, the vector of the constant is defined by $\alpha = [\alpha_1, \alpha_2]$, while the residual vector $u_t = [\varepsilon_{1,t}, \varepsilon_{2,\ t}]$ is bivariate and conditionally normally distributed. The conditional covariance matrix is represented by H_t, where $\{H_t\} = h_{ij,t}\ for\ i,j = 1,2$. Ω_{t-1} is the set of information available at time t−1.

The conditional variance-covariance matrix of Engle and Kroner (1995) is stated as follows:

$$H_t = C_0'C_0 + \sum_i^q A'_i\varepsilon_{t-i}\varepsilon'_{t-i}A_i + \sum_i^p G'_iH_{t-i}G_i \tag{6}$$

where C_0, A_i and G_i are parameter matrices of $n \times n$ dimension, with $C_{0,}$ restricted to a lower triangular matrix, while A_i and G_i are two unrestricted parameter matrices.

For Eq. (6), when $n = 2$ and $p = q = 1$, the conditional covariance matrix depends on its immediate past value and the immediate values of ε_t. The conditional variance may then be represented as follows:

$$H_t = C_0'C_0 + A_{11}'\varepsilon_{t-1}\varepsilon_{t-1}'A_{11} + G_{11}'H_{t-1}G_{11} \tag{7}$$

$$H_t = C_0'C_0 + \begin{bmatrix} a_{11}a_{12} \\ a_{21}a_{22} \end{bmatrix}' \begin{bmatrix} \varepsilon_{1,t-1}^2 & \varepsilon_{1,t-1},\varepsilon_{2,t-1} \\ \varepsilon_{1,t-1},\varepsilon_{2,t-1} & \varepsilon_{2,t-1}^2 \end{bmatrix} \begin{bmatrix} a_{11}a_{12} \\ a_{21}a_{22} \end{bmatrix} + \begin{bmatrix} g_{11}g_{12} \\ g_{21}g_{22} \end{bmatrix}' H_{t-1} \begin{bmatrix} g_{11}g_{12} \\ g_{21}g_{22} \end{bmatrix} \tag{8}$$

The parameter matrices for the variance equation are defined as C_0, which is restricted to a lower triangular matrix with two unrestricted matrices, A_{11} and G_{11}. The application of the BEKK-GARCH specification in our analysis is advantageous because of the need to consider the interaction of both the conditional variances and covariance of the two return series. Therefore, this approach allows testing of the null hypothesis that there is no causality effect in either direction. In addition, the BEKK-GARCH model guarantees, by construction, that the covariance matrices in the system are positive definite.

In order to establish the presence of volatility linkages between different bond markets, the lead–lag relationship is tested. Eqs. (9) and (10), below, impose zero separate restrictions on the off-diagonal terms (a_{12}− g_{12} and a_{21}−g_{21}) of matrices A_{11} and G_{11}. Doing so allows an accurate test of the causality effect from one market to the other. Eqs (9) and (10) test the effect on the log

[7] See: http://www.prsgroup.com/wp-content/uploads/2012/11/icrgmethodology.pdf Accessed November 24 2015.

likelihood value of lagged squared residuals and the lagged conditional variances of market 1 and market 2, respectively to detect volatility transmission.

$$\begin{aligned} h_{11,t} &= c_{11}^2 + a_{11}^2\varepsilon_{1,t-1}^2 + 2a_{11}a_{21}\varepsilon_{1,t-1}\varepsilon_{2,t-1} + a_{21}^2\varepsilon_{2,t-1}^2 \\ &\quad + g_{11}^2 h_{11,t-1} + 2g_{11}g_{21}h_{12,t-1} + g_{21}^2 h_{22,t-1} \\ h_{12,t} &= c_{11}c_{21} + a_{11}a_{22}\varepsilon_{1,t-1}\varepsilon_{2,t-1} + a_{21}a_{22}\varepsilon_{2,t-1}^2 \\ &\quad + g_{11}g_{22}h_{12,t-1} + g_{21}g_{22}h_{22,t-1} \\ h_{22,t} &= c_{21}^2 + c_{22}^2 + a_{22}^2\varepsilon_{2,t-1}^2 + g_{22}^2 h_{22,t-1} \end{aligned} \tag{9}$$

$$\begin{aligned} h_{11,t} &= c_{11}^2 + a_{11}^2\varepsilon_{1,t-1}^2 + g_{11}^2 h_{11,t-1} \\ h_{12,t} &= c_{11}c_{21} + a_{11}a_{12}\varepsilon_{1,t-1}^2 + a_{11}a_{22}\varepsilon_{1,t-1}\varepsilon_{2,t-1} + g_{11}g_{22}h_{12,t-1} \\ &\quad + g_{11}g_{22}h_{12,t-1} + g_{21}g_{22}h_{12,t-1} \\ h_{22,t} &= c_{21}^2 + c_{22}^2 + a_{12}^2\varepsilon_{1,t-1}^2 + 2a_{12}a_{22}\varepsilon_{1,t-1}\varepsilon_{2,t-1} \\ &\quad + a_{22}^2\varepsilon_{2,t-1}^2 + g_{12}^2 h_{11,t-1} + 2g_{12}g_{22}h_{12,t-1} + g_{22}^2 h_{22,t-1} \end{aligned} \tag{10}$$

Having first estimated the unrestricted version (Eq. 8), as well as the restricted versions (Eqs. 9, and 10) of the BEKK model, we use the log likelihood values of these estimations to generate the likelihood ratio tests. As with other studies, the maximum likelihood estimations are optimized by Berndt, Hall, Hall and Hausman (1974) algorithm (henceforth simply the BHHH algorithm), where the conditional log likelihood function $L(\theta)$ for a sample of T number of observations has the following form:

$$L(\theta) = \sum_{t=1}^{T} l_t(\theta) \tag{11}$$

$$l(\theta) = -\log 2\,\pi - 1/2\log|H_t(\theta)| - 1/2\varepsilon_t'(\theta)H_t^{-1}(\theta)\varepsilon_t(\theta) \tag{12}$$

and θ denotes the vector of all the unknown parameters.

In order to test for any volatility transmission between two bond markets, this study uses the likelihood ratio test outlined in Eq. (13), which compares the log likelihood values of the restricted models, Eqs. (9) and (10) separately, with the unrestricted model.

$$D = -2LLR = -2\,\ln\left(\frac{L_0}{L_1}\right) = -2(lnL_0 - lnL_1) \tag{13}$$

where LLR = Log Likelihood Ratio

L_0 = Value of the likelihood function of the restricted model
L_1 = Value of the likelihood function of the unrestricted model

The statistic D in Eq. (13) follows a chi-squared (χ^2) distribution with k degrees of freedom, where k is the number of restrictions in the restricted model. The χ^2 distribution, with 2 degrees of freedom, is used as the critical value for the nested testing, with the 5% χ^2distribution critical value being 5.991. In the relevant tables, the LLR statistics that are equal to or above 5.991, have been assigned the symbol "*" to highlight the statistical significance at the 5% level and above.

Having established the pattern of transmission across the five sovereign markets, the volatility dynamics between the market of high, medium and low risk is established through a tri-variate analysis with particular attention paid to the sub-samples of the pre and-post Argentine crisis periods. When Eq. (6) is allowed to take the value for three markets and $p = q = 1$, the conditional variance Eq. (7) will use the individual elements from the following lower triangular and square matrices to estimate the full BEKK GARCH (1, 1).

$$C = \begin{bmatrix} c_{11} & 0 & 0 \\ c_{21} & c_{21} & 0 \\ c_{31} & c_{32} & c_{33} \end{bmatrix} A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{21} & a_{23} \\ a_{31} & \varepsilon_{32} & \varepsilon_{33} \end{bmatrix}$$
$$G = \begin{bmatrix} g_{11} & g_{12} & g_{13} \\ g_{21} & g_{21} & g_{23} \\ g_{31} & g_{32} & g_{33} \end{bmatrix} \tag{14}$$

where C is restricted to be a lower triangular matrix with two unrestricted matrices, A_{11} and $G_{11.}$ The elements of matrices A and G capture the effects of sovereign risk related shocks on the conditional variances, as well as showing how the conditional variances impact on the current conditional variances.

5. Results

In order to investigate the volatility interaction and transmissions between pairs of sovereign bond markets, BEKK-GARCH models with restricted off-diagonal terms are first estimated, then likelihood ratio tests are conducted to assess the direction of causality. These results are reported in a series of Tables numbered from 1 to 8. First, the statistical properties of the bonds are reported in Tables 1 and 2. Then the first set of results of the volatility modeling are reported for the cross-market dynamics of the shorter (Table 3) and long maturities (Table 4). In this table the pairs of sovereign bonds are matched based on maturity, for both the pre-Argentine default and the post-Argentine default. Then, Tables 6 and 7 report the in-sample and out-of sample economic significance analysis for shorter and longer maturities. Finally, robustness test results on the role of illiquidity and the dating of the Argentine crisis are reported in Table 8 and Appendix A.

5.1. Preliminary analysis of bonds

We begin the analysis of the data with the summary statistics followed by a Principal Components Analysis (PCA). The PCA is undertaken to identify the underlying common factors that drive the yield behavior of the baskets of bonds grouped into either shorter or longer maturities. The summary statistics reported in Table 1 have three panels that represent the shorter and longer maturity groups for the Argentine crisis (Panels A and B), and the longer maturity group for the GFC sample (Panel C). The summary statistics on bond returns are reported in columns 2 to 5, while the Augmented Dickey and Fuller test for unit roots and the ARCH LM test are reported in columns 6 and 7 respectively. For brevity, the underlying yields of the series are not reported although the yields of the longer bonds are less volatile than the shorter maturity bonds, with the reverse being the case for the price series as discussed in detail below. This is consistent with studies investigating expectation theories of term structure dynamics (see also Bulkley and Harris, 2015; Chadwick, Fazilet and Tekatli, 2015; Li, 2016).

Examining the statistical results reported in Panels A and B reveals some evidence of idiosyncratic grouping with the Argentine series earning negative returns in all sub-periods and for both the shorter and longer maturity baskets. On-the-other-hand all of the other series earn positive returns during the 1999 to 2004 period. Argentine bond returns also have the largest standard deviation, and in particular the longer maturity bonds (2017 and 2027 maturities) carry the largest standard deviations of 2.45% and 2.37% respectively per day. The next risker bonds in the shorter and longer maturity groups belong to the Brazilian market, followed by Venezuelan sovereign bonds. The Mexican market is the least risky, followed by the Colombian market. One exception, however, is the Colombia 2027 bond that has a standard deviation that is slightly above that of the equivalent maturity Venezuelan 2027

Table 1
Summary statistics.

Bond Series	Mean	Std. Dev.	Skewness	Kurtosis	ADF	ARCH(4)
Panel A: shorter maturity Argentine sample 31 March 1999–15 September 2004						
ar 06	−0.077	2.334	−1.230	17.216	−0.937	183.239***
co 07	0.016	0.662	−0.887	19.938	−0.863	85.707***
mx 07	0.009	0.318	0.533	13.214	−1.442	91.743***
vn 07	0.031	0.936	0.338	9.880	−0.957	23.745***
br 08	0.025	1.444	−4.509	85.440	−1.588	13.385**
co 08	0.015	0.713	−0.473	22.970	−0.835	74.035***
mx 08	0.014	0.350	0.176	9.208	−1.225	55.565***
ar 09	−0.087	2.173	−1.285	15.357	−1.154	89.470***
br 09	0.021	1.413	−1.700	31.053	−1.565	99.109***
co 09	0.021	0.710	−1.816	34.700	−1.169	16.089**
mx 09	0.017	0.372	0.483	9.187	−2.012	75.616***
Panel B: longer maturity Argentine sample 31 March 1999–15 September 2004						
ar 17	−0.096	2.452	−0.997	24.787	−1.540	213.381***
br 20	0.021	1.617	−1.499	22.805	−1.111	106.107***
co 20	0.020	0.853	−2.722	36.558	−1.034	20.231***
mx 16	0.019	0.507	−0.418	8.610	−1.083	48.178***
vn 18	0.026	0.773	−0.078	8.265	−0.399	50.7113***
ar 27	−0.075	2.368	−0.573	17.358	−1.004	257.681***
br 27	0.026	1.535	−1.187	16.625	−1.380	108.154***
co 27	0.012	0.959	−0.159	13.162	−0.935	72.093***
mx 26	0.021	0.630	0.059	8.691	−1.428	82.518***
vn 27	0.033	0.938	0.343	9.822	−0.957	23.744***
Panel C: Longer maturity GFC sample 16 September 2004–14 September 2012						
ar 17	−0.022	3.820	−3.276	89.991	−1.902	21.981***
br 20	0.015	0.557	−0.957	45.664	−2.406	127.196***
co 20	0.013	0.575	−2.039	79.101	−2.126	564.886***
mx 16	−0.003	0.413	−0.014	52.329	−3.214	560.304***
vn 18	−0.007	0.895	−2.935	53.149	−0.965	140.927***
ar 27	−0.017	3.648	−3.571	103.870	−1.722	18.071***
br 27	0.026	0.668	−3.936	82.555	−1.665	77.744***
co 27	0.017	0.968	−0.109	28.234	−2.119	252.673***
mx 26	0.009	0.792	1.033	37.745	−2.157	54.350***
vn 27	−0.006	1.311	0.026	27.103	−1.441	460.109***

In this Table, we report selected descriptive statistics, namely, the mean, standard deviation, skewness, and kurtosis, for bond returns. This is followed by the Augmented Dickey-Fuller (ADF) test for unit roots with the null hypothesis that there is a unit root. The lag length to control for serial correlation is set at 8. Autoregressive Conditional Heteroskedastic (ARCH) effects (lag 4) for individual series are reported in the last column. Panels A and relates to the shorter maturity group around the Argentine default period (sample period 31 March 1999–15 September 2004); Panel B relates to the longer maturity group around the Argentine default (sample period 31 March 1999–15 September 2004); while Panel C relates to the longer maturity group covering the (GFC) Global Financial Crisis (sample period 16 September 2004–14 September 2012). The specific bonds are coded with their respective country abbreviation followed by the year of maturity and are shown in the first column: ar = Argentina; br = Brazil; co = Colombia; mx = Mexico; vn = Venezuela. Thus, the first bond listed, ar 06, is an Argentine sovereign bond maturing in 2006.

bond. The Mexican bond market stands out as generally having positive skewness, a feature that should find favor with bond investors, although the 2016maturityMexican bond displayed slight negative skewness during the Global Financial Crisis (GFC) subperiod. The short and long end of the Venezuelan curve also shows positive skewness, while Argentina, Colombia and Brazil show negative skewness.

Apart from the Argentine longer bond series, most of the series have lower standard deviations during the 2004–2012 GFC period. Examination of the kurtosis statistic reported in column 5 reveals that the distribution is leptokurtic. Overall, when we look at the shorter and longer maturity bonds reported in Panels A and B, it is evident that the Mexican and Colombian markets seem to represent the least risky segment, while Argentina, Brazil and Venezuela represent a block with excessive risk.

This relation becomes clearer when the term structure of the various countries are plotted in Fig. 2. This figure plots four snapshots that capture the regional term structure at different periods: (a) January 1 2001, which is about 12-months prior to the Argentine default; (b) 6-months prior to the official Argentine default; (c) September 2003; and (d) June 2004. These last two dates capture immediate after-shock periods. Except for Argentina the term structure is largely upward sloping, with bonds of longer maturity having higher yields than those with shorter maturities. These figures also show evidence of a stratification of the term structure of the sovereign yields of key countries in Latin America (Argentina, Brazil, Colombia, Mexico and Venezuela), based on credit quality and maturity, with the Mexican bonds representing the lowest risk threshold(e.g. Fig. 2a).

Fig. 2 also highlights the unstable and time-varying nature of the sovereign term structure. For example, in the post-crisis period the Argentine curve is effectively inverse as short-term credit concerns and risk aversion dominate investor attitudes. These stylized facts are more consistent with liquidity based theories of term structure, which allow for the segmentation of investor preferences (e.g. Elton and Green, 1998; Jovanovic and Rousseau, 2001). Finally, prior to undertaking further analysis it is important to understand the order of integration of the series and the presence of ARCH effects. The ADF test reveals all of the series are nonstationary at levels, except for the Mexican 16 series during the GFC sample. Similarly, the ARCH LM test statistic reported in column 7 reveals significant evidence of heteroskedasticity.

5.2. Principal component analysis (PCA)

Given the nonstationarity of the bond price series at levels, the series are transformed into return form to conduct the PCA analysis. Following Alexander (2001), we normalize each bond series by subtracting the mean and dividing by the sample standard deviation before conducting the analysis. All series are stationary and the columns in the $T \times k$ stationary bond return data matrix $\mathbf{X}$ are mean zero with singular variance. To extract principal components the analysis uses ordinary correlation matrices belonging to the whole and sub-samples separated into pre and-post default

Table 2
Principal components analysis (PCA).

Panel A: Argentine Crisis												
	Whole sample				Pre-Argentine crisis sample				Post Argentine crisis sample			
Shorter maturity bonds	pc1	pc 2	pc3	pc4	pc1	pc 2	pc3	pc4	pc1	pc 2	pc3	pc4
Eigen Value	4.642	1.573	1.276	1.036	5.007	1.778	1.247	0.993	4.559	1.499	1.214	1.054
Cumulative R^2	0.422	0.565	0.681	0.775	0.455	0.617	0.730	0.820	0.415	0.551	0.661	0.757
Eigenvector loadings:												
ar 06	0.157	0.253	0.653	−0.100	0.209	−0.262	0.519	0.061	0.096	0.172	0.663	−0.159
co 07	0.321	−0.465	0.057	−0.114	0.270	0.497	0.123	−0.060	0.348	0.390	−0.169	−0.153
mx 07	0.352	0.299	−0.292	−0.100	0.352	−0.124	−0.407	−0.079	0.342	−0.434	−0.007	−0.064
vn 07	0.050	−0.022	−0.012	0.903	0.034	0.034	−0.199	0.973	0.057	0.100	0.114	0.880
ar 09	0.212	0.268	0.564	−0.027	0.291	−0.245	0.410	0.138	0.107	0.115	0.676	−0.109
br 08	0.314	0.107	−0.007	0.179	0.331	−0.225	0.155	−0.005	0.331	−0.105	0.028	0.168
co 08	0.342	−0.435	0.066	−0.047	0.298	0.477	0.097	0.026	0.360	0.380	−0.159	−0.080
mx 08	0.356	0.319	−0.276	−0.112	0.360	−0.172	−0.364	−0.106	0.347	−0.438	0.026	−0.078
br 09	0.325	0.016	0.093	0.304	0.362	−0.213	0.139	0.047	0.329	0.116	0.041	0.321
co 09	0.340	−0.438	0.039	−0.082	0.290	0.494	0.096	0.013	0.364	0.340	−0.179	−0.133
mx 09	0.371	0.254	−0.275	−0.061	0.362	−0.103	−0.383	−0.085	0.371	−0.361	0.025	−0.015
Longer maturity bonds	pc1	pc 2	pc3	pc4	pc1	pc 2	pc3	pc4	pc1	pc 2	pc3	pc4
Eigen Value	4.790	1.401	0.952	0.936	5.406	1.266	0.935	0.743	4.650	1.305	1.014	0.894
Cumulative R^2	0.479	0.619	0.714	0.808	0.541	0.667	0.761	0.835	0.465	0.596	0.697	0.786
Eigenvector loadings												
ar 17	0.209	0.647	−0.028	0.151	0.288	−0.359	0.483	0.083	0.156	0.638	0.139	0.124
br 20	0.357	−0.025	0.077	−0.082	0.363	−0.126	0.003	−0.260	0.361	0.047	−0.056	0.097
co 20	0.325	−0.244	−0.172	0.504	0.229	0.590	0.315	−0.041	0.364	−0.036	0.094	−0.533
mx 16	0.354	−0.043	−0.370	−0.406	0.358	0.043	−0.420	−0.241	0.348	−0.200	0.395	0.335
vn 18	0.303	−0.041	0.604	−0.073	0.269	−0.067	−0.270	0.789	0.314	0.077	−0.558	0.136
ar 27	0.193	0.662	−0.050	0.179	0.304	−0.347	0.428	0.023	0.086	0.705	0.162	−0.024
br 27	0.379	−0.063	0.029	−0.165	0.378	−0.107	0.013	−0.263	0.385	−0.070	−0.017	0.172
co 27	0.294	−0.253	−0.199	0.589	0.223	0.603	0.250	0.078	0.323	−0.057	0.104	−0.666
mx 26	0.361	−0.053	−0.374	−0.373	0.360	0.016	−0.401	−0.237	0.357	−0.195	0.397	0.279
vn 27	0.330	−0.092	0.529	−0.033	0.342	0.065	−0.106	0.333	0.327	−0.013	−0.554	0.095
Panel B: Global Financial Crisis												
	Whole sample				Pre GFC sample				Post GFC sample			
	pc1	pc 2	pc3	pc4	pc1	pc 2	pc3	pc4	pc1	pc 2	pc3	pc4
Eigen Value	3.625	1.552	1.062	0.854	4.798	1.237	1.001	0.759	3.302	1.590	1.123	0.884
Cumulative R^2	0.363	0.518	0.624	0.709	0.480	0.604	0.704	0.780	0.330	0.489	0.602	0.690
Eigenvector loadings												
ar 17	0.024	0.697	0.121	−0.048	0.058	0.655	0.349	−0.625	0.015	0.695	−0.125	−0.019
br 20	0.392	−0.039	0.093	−0.132	0.386	−0.046	0.021	−0.013	0.382	−0.043	−0.118	−0.141
co 20	0.434	−0.035	0.104	−0.145	0.390	−0.028	−0.065	0.129	0.452	−0.034	−0.114	−0.094
mx 16	0.368	−0.017	0.243	0.123	0.328	−0.134	0.475	0.083	0.393	−0.003	−0.172	0.023
vn 18	0.275	0.070	−0.646	0.268	0.296	0.158	−0.446	−0.217	0.240	0.070	0.693	0.222
ar 27	0.009	0.703	0.047	−0.046	0.023	0.717	−0.059	0.673	0.004	0.701	−0.070	−0.035
br 27	0.440	−0.017	0.085	−0.140	0.401	−0.060	−0.057	0.028	0.450	−0.009	−0.137	−0.151
co 27	0.285	−0.081	0.210	−0.472	0.357	−0.014	−0.108	0.134	0.276	−0.088	−0.242	−0.265
mx 26	0.233	−0.005	0.384	0.792	0.308	−0.065	0.537	0.108	0.228	−0.003	−0.236	0.904
vn 27	0.342	0.077	−0.536	0.028	0.341	0.060	−0.377	−0.235	0.327	0.098	0.557	−0.096

This Table reports the Principal Component Analysis (PCA) of the Latin American sovereign bonds separated into two distinctive groups that represent shorter and longer maturity bonds. Panel reports the PCA for the sample involving the endogenous (Argentine default) while Panel B reports the PCA for the sample covering the exogenous (GFC) shocks. We report the four principle components (PC1 to PC4) for the whole sample and subsamples (pre and post) crisis covering these two periods with respect to eigenvalues, the percentage contribution of the first four principal components to the standardized variance and eigenvector loadings with respect to individual bonds. The specific bonds are coded with their respective countries and maturities and are shown in the first column: ar = Argentina; br = Brazil; co = Colombia; mx = Mexico; vn = Venezuela. Thus, the first bond listed, ar 06, is an Argentine sovereign bond with a maturity of 2006.

periods that are attributable to either the Argentine default sample, or the GFC sample. Each principal component explains the variance of the sovereign bond return series unexplained by the other components. As a result, these series are uncorrelated as each subsequent principal component only explains the remaining variance unexplained by the previous component(s). The eigenvalues and the proportion of total variance explained are reported in the first two rows followed by the respective individual eigenvector loadings of each sovereign bond.

Recall that the purpose of the PCA is to identify if there are common factors that shape the term structure during the various sample periods. In the spirit of Aiolfi, Catão and Timmermann (2011), we conjecture that a common global and Latin American level factor influences all bonds issued by the countries in the region with a one key level of separation being the perceived country or sovereign risk of the instrument. For example, the Mexican and the Colombian series should act as one group based on debt capacity and other credit considerations, while the Argentine, Brazilian and Venezuelan series should be a separate group based on the same criteria. The underlying elements that could drive the common factor would be inflation reflected in the U.S. term structure, the strength of the U.S. dollar vis a vis developing and emerging currencies and the relative value of alternate risky securities, such as securities included in the U.S. high yield index. Given the nature of this common factor, we expect all bonds to have the same sign with respect to the eigenvector loading.

Table 3
Cross-market volatility dynamics – shorter maturity group (Argentine crisis window).

	Whole sample		Pre-Argentine crisis		Post-Argentine crisis	
	LR1	LR2	LR1	LR2	LR1	LR2
2007 maturity basket						
ar – co	1.874	0.014	0.14	1.276	–	
ar – mx	2.156	0.714	**3.776**	**6.878***	–	
ar – vn	**7.494***	**0.61**	**6.764***	**0.258**	–	
co – mx	**3.93**	**52.2***	**4.801**	**25.835***	–	
co – vn	32.802*	11.92*	7.014*	8.722*	45.234*	11.298*
mx – vn	**47.866***	**0.584**	**31.918***	**2.478**	15.550*	10.8716*
2008 maturity basket						
ar – br	**5.728**	**11.258***	–		–	
ar – co	2.930	3.258	5.734	0.090	**13.696***	**4.516**
ar – mx	**4.984**	**8.256***	0.162	0.002	**9.918***	**5.160**
br – co	5.780	1.418	3.396	0.944	–	
br – mx	**3.362**	**7.114***	6.081*	8.033*	–	
co – mx	11.362*	36.426*	**9.136***	**4.475**	7.585*	13.511*
2009 maturity basket						
ar – br	5.256	4.774	5.326	2.260	0.266	0.756
ar – co	**9.316***	**0.040**	1.238	1.780	2.804	0.196
ar – mx	2.950	3.250	0.794	2.256	0.776	0.574
br – co	2.302	0.664	2.320	4.618	**28.308***	**1.092**
br – mx	**6.836***	**3.672**	–		**27.150***	**5.304**
co – mx	**0.062**	**69.728***	16.544*	39.944*	8.334*	8.016*

This table reports the cross-market volatility dynamics for the shorter maturity group consisting of 2007, 2008 and 2009 maturity baskets. The names reported in column 1 as Argentina [ar], Brazil [br], Colombia [co], Mexico [mx], Venezuela [vn] represent the sovereign bonds belonging to the five countries covered in this study. Columns 2, 3 and 4 report the likelihood ratio test results for the whole sample (March 1999 to September 2004), pre-Argentine crisis window (March 1999 to December 2001) and post-Argentine crisis window (December 2001 to September 2004). The sample period covers daily bond price series from March 1999 except for the 2009 maturity which starts only from October 1999. Pre and post crisis sub-sample widows for all three baskets carry the equal number of sub-sample observation covering the pre and-post Argentine crisis. The likelihood ratio tests (LR1 and LR2) reported in columns 2, 3 and 4 represent test statistic generated by comparing the log likelihood value of the restricted models by (imposing restriction 1 and restriction 2) with the unrestricted model. The LR test ratios have been marked in bold letters to highlight the existence of unidirectional volatility transmission channels. The 5% Chi-Square distribution critical value for with $df = 2$ is 5.991 for the nested testing on cross market dynamics. The sign "–" indicates convergence failures or unstable log likelihood values. Figures in bold indicate the existence of unidirectional volatility transmission.

Table 4
Cross-market volatility dynamics – longer maturity group (Argentine crisis window).

	Whole sample		Pre Argentine crisis		Post Argentine crisis	
	LR1	LR2	LR1	LR2	LR1	LR2
2020 maturity basket						
ar – br	**1.448**	**7.816***	**2.736**	**22.680***	**0.902**	**10.782***
ar – co	4.674	1.244	5.438	5.876	**11.458***	**4.848**
ar – mx	1.034	3.872	**7.100***	**5.242**	**1.970**	**6.752***
ar – vn	**24.598***	**2.638**	**26.970***	**1.702**	3.206	3.594
br – co	5.380	0.984	–		–	
br – mx	3.968	4.116	–		8.002*	7.806*
br – vn	**6.210***	**0.260**	–		5.788	0.976
co – mx	**5.366**	**34.320***	–		**3.589**	**53.636***
co – vn	2.464	4.704	1.292	3.724	**1.974**	**8.888***
mx – vn	4.158	0.100	–		4.729	0.217
2027 maturity basket						
ar – br	**4.194**	**14.238***	**12.158***	**3.330**	1.138	2.398
ar – co	0.940	5.098	0.086	1.858	**2.412**	**6.722***
ar – mx	**0.466**	**8.400***	2.220	1.858	1.808	1.838
ar – vn	**8.508***	**2.126**	**7.204***	**0.060**	2.998	2.078
br – co	**15.296***	**3.052**	–		**13.682***	**3.488**
br – mx	4.956	3.060	–		5.432	1.848
br – vn	3.968	0.968	**3.546**	**29.326***	1.384	5.386
co – mx	**5.674**	**6.984***	15.588*	18.766*	**3.634**	**8.648***
co – vn	**9.402***	**0.870**	**2.318**	**6.168***	**8.514***	**0.112**
mx – vn	4.534	0.42	–		1.422	1.548

This table reports the cross market volatility dynamics for the shorter maturity groups consisting of 2020 and 2027 maturity baskets. The names reported in column 1 as Argentina [ar], Brazil [br], Colombia [co], Mexico [mx], Venezuela [vn] represent the sovereign bonds belonging to the five countries covered in this study. Columns 2, 3 and 4 report the likelihood ratio test results for the whole sample31 March 1999 to 15 September 2004), the pre-Argentine crisis window (March 1999 to December 2001) and the post-Argentine crisis window (December 2001 to September 2004). The 2020 basket, however, starts from February 2000 due to the issue date restriction associated with the Colombian 2020 bond. The sample period covers daily bond price series from March 1999 to 15 September 2004. The likelihood ratio tests (LR1 and LR2) reported in columns 2, 3 and 4 represent test statistic generated by comparing the log likelihood value of the restricted models by (imposing restriction 1 and restriction 2) with the unrestricted model. The 5% Chi-Square distribution critical value for with $df = 2$ is 5.991 for the nested testing on cross market dynamics. The sign "–" indicates convergence failures or unstable log likelihood values. Figures in bold indicate the existence of unidirectional volatility transmission.

The countries in our sample have a high level of heterogeneity, while retaining some level of commonality as a distinct group within other emerging markets. As such, one could expect a separate common factor running across the highly risky countries and those that are stable and less risky (i.e. a market segmentation effect). Such behavior is also expected to be different in magnitude with respect to the shorter and longer maturity groups due to their different default probabilities. Naturally, the factor that better captures the default prospects is the shorter maturity group compared to the longer maturity group. These two factor loadings are also expected to move in opposite directions. During the pre-crisis period, the defaulting country along with the other riskier and vulnerable countries are expected to load higher, while the other countries that are not part of the group would have the opposite sign and would therefore tend to deviate from this group. A further common factor could be heavily loading on the idiosyncratic factor associated with a specific country that has a notable economic effect in the region. For example, an oil exporter like Venezuela would be very sensitive to a downward shift in the world oil price and this could then translate into higher levels of regional risk. Thus the oil price impacts on the health of the economy would then be captured by the stock market indicator (e.g. Le and Chang, 2015). However, Brazil which is dependent on ethanol for its energy needs would be expected to be immune from an increase in the world oil price. Thus one must always be mindful of the unique institutional and economic characteristics of the members within the Latin American region.

Table 2 reports the PCA for the shorter and longer maturity groups covering the Argentine default sample in Panel A, while the GFC sample period is reported in Panel B. Columns 2, 3 and 4 report the results for the whole sample, pre-crisis sample and post-crisis sample respectively. For brevity, only the first four principal components and their eigenvector loadings are presented in Table 2. The first principal component for the shorter maturity group explains about 46% of the standardized variance, while the first component for the post crisis period explains about 42%. Similar variation is observed for the whole Argentina Crisis sample period that runs from April 1999 to September 2004. When it comes to the longer maturity group, the percentage of standardized variance explained by the first component is notably greater, with about 54% of the standardized variance explained by the first principal component for the longer maturity group during the pre-Argentine crisis period and 47% for the post Argentine crisis period. This figure is about 48% for the whole sample. The first four principal components, for the shorter maturity group, explain about 82% and 76% of the standardized variance for the pre and-post Argentine crisis period respectively, and similar numbers are observed for the longer maturity group.

On the other hand, a strikingly different pattern is observed for the pre and-post GFC periods. For example, the first principal component explains about 48% of the standardized variance for the pre-crisis period, while the first principal component for the post

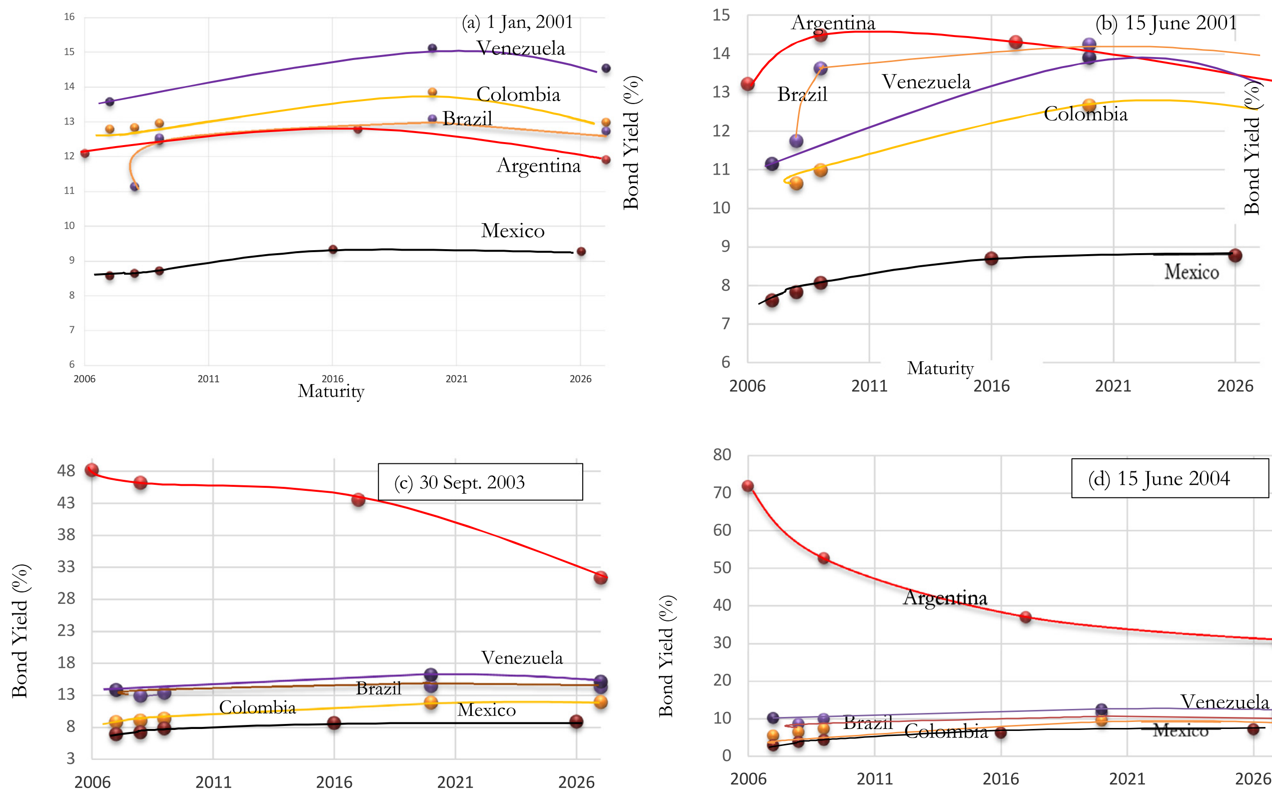

Fig. 2. Latin American sovereign bonds: regional term structure. The stratification of the term structure of sovereign yields of key countries in Latin America (Argentina, Brazil, Colombia, Mexico and Venezuela) is evident from the Figures below: (a) is about 12-months and (b) 6-months prior to the Argentine default of December 2001, while (c) and (d) are in September 2003 and June 2004. Mexican bonds effectively form the regional lowest risk-benchmark.

crisis period explains only about 33%. All four principal components explain about 78% of the standardized variance during the sample covering the pre-GFC period, while only 69% of the standardized variance is explained by the post-GFC period.

To facilitate analysis the eigenvector loadings with respect to the first three individual principal components covering the Argentine crisis, as well as the global financial crisis, are plotted in Fig. 3.[8] The first principal component (pc1) represented by the blue line in diagram (a) and (b), as expected, loads positively across all bonds in the shorter and longer maturity groups.[9] The post crisis period, however, discriminates against the Argentine bonds and shows evidence of a sharp decline in loading compared to the pre-crisis period. Thus, pc1 represents a common factor that is influenced by global markets and exerts a common influence across all bond maturities. This pattern is evident in pc1 during both the pre and-post Argentine crisis periods, with a pronounced discriminatory loading assigned to the Argentine bonds.

As discussed previously, the Mexican bond series represent the lowest risk and appears to represent the benchmark yield curve for the region. When the second principal component (pc2) is examined, it is clear that this is not a common factor that binds all the series as in the case of pc1. The Colombian series loads heavily during the pre-Argentine crisis, while the Argentine and Brazilian series receive sizable negative weights. It appears that Colombia is a country that falls in between the high credit risk group (Argentina, Brazil and Venezuela) and Mexico. The third principal component, pc3, appears to be the default factor and loads positively, in a significant manner, during the pre and post Argentine crisis, with a similar pattern prevailing across both groups. The fourth principal component (pc4) loads positively on Venezuela and Brazil, while assigning negative weights for the Mexican series in the shorter maturity group. However, this pattern changes with the longer maturity group, with significant positive weights being allocated to the Mexican series.

An examination of the GFC sample depicted in diagrams (c) and (d) of Fig. 3, confirms pc1 as the global/Latin American factor, although there appears to be discrimination towards Argentina being a defaulted country within the region. This finding would be consistent with sovereign default having a persistent and long lasting effect on sovereign yields. The second principal component, pc2, however, represents the default factor with significant positive weights being assigned to Argentina, as depicted in diagrams (c) and (d). The Venezuelan market also loads higher in pc3 during the post GFC, while all other series are loading negatively. Overall, these results are broadly consistent with Aiolfi et al. (2011), who identify a major common factor that is linked to the global and Latin American regional factors, which is likely to represent a transmission effect from the U.S. dollar and the U.S. term structure. In this sense the markets investigated are integrated to the extent that they share the impact from this common factor. The other less important factors appear to be driven more by idiosyncratic factors rather than a unique, or overall, Latin American risk factor.

5.3. Volatility transmission – the shorter maturity group

The shorter maturity group consists of three maturity baskets and comprises bonds issued by Argentina (ar), Brazil (br), Colombia (co), Mexico (mx) and Venezuela (vn). Table 3 reports the

[8] The fourth principal component has been excluded from the diagram to avoid cluttering.

[9] One notable feature is that Venezuela loads very low (0.034) and a similar pattern prevails during the post-Argentine crisis. However, this situation doesn't extend to the Venezuelan 2018 and 2027 series in the longer maturity group. We conjecture that this is mainly due to the smaller issue size of this particular bond and so this bond could suffer from an illiquidity related problem.

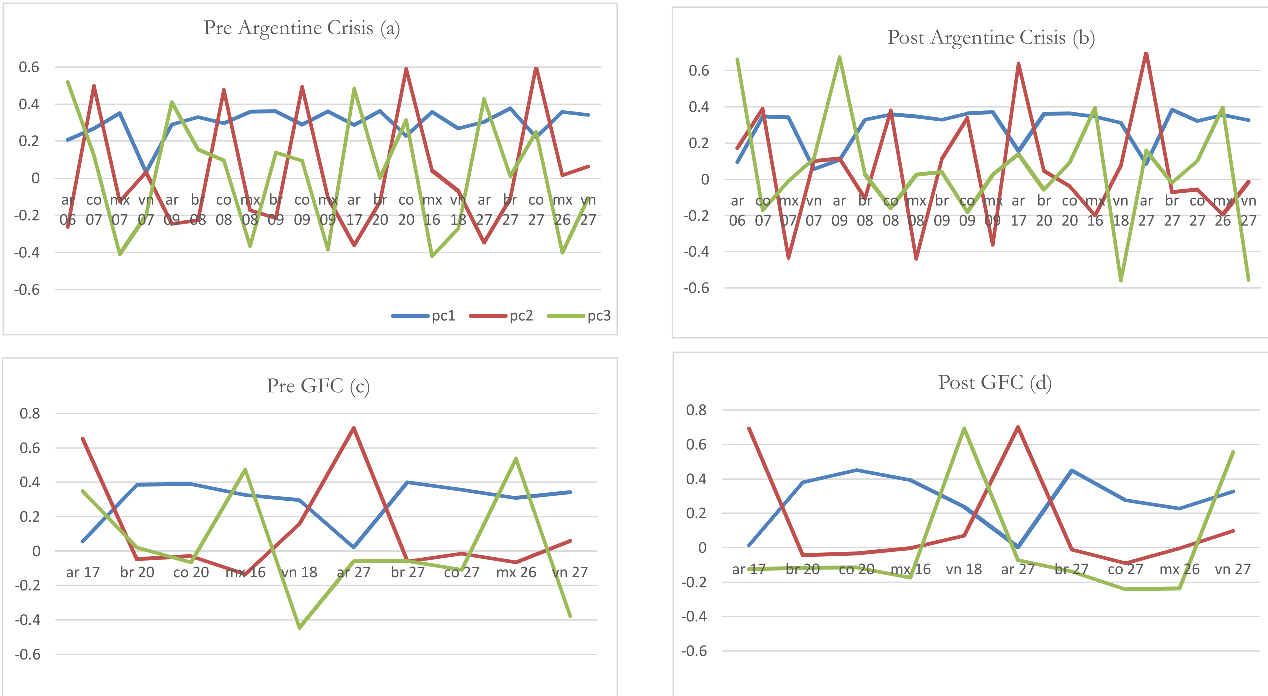

Fig. 3. Latin American Sovereign bonds: eigenvector loadings. This graph plots the eigenvector loadings with respect to individual bonds for the Argentine crisis (Fig. 2a and b) and the Global Financial Crisis (Fig. 2c and d). The first three principal components (pc1, pc2 and pc3) from the analysis are depicted in these diagrams. The diagrams 2a and b related to the Argentine crisis, cover 21 bonds belonging to all five baskets of bonds, while the bottom two diagrams (2c and d) bonds relate to the Global Financial Crisis period.

cross-market volatility dynamics covering the 2007, 2008 and 2009 maturity baskets of the five Latin American sovereign bond markets. Columns 2, 3 and 4 report the cross-market volatility dynamics for the whole sample and sub-samples representing the pre and-post Argentine crisis. A total of 12 sovereign bonds represent the shorter maturity group, rendering 18 different combinations across the three baskets in each window. Our main discussion is devoted to the unidirectional volatility dynamics and the identification of clear volatility transmission from one bond market to the other bond market. The likelihood ratio test across these three windows reveal 18 combinations of unidirectional transmission. To facilitate identification, in Table 3 the statistically significant unidirectional transmissions are identified in bold letters in Table 3. Of these 18 combinations that have unidirectional volatility dynamics, nine cases are associated with the whole sample period and the balance of nine is associated with the pre and – post Argentine crisis.

Volatility transmission within the shorter maturity group is dominated by Mexico and Argentina – the two countries that lie at the polar opposites in the credit quality spectrum within the group. These two countries are involved in 94% of the volatility transmission channels. A striking feature within the shorter maturity group is that 52% of the volatility transmission channels export volatility from Mexico, while only about 29% of the transmission channels receive volatility from Argentina. This is consistent with a clear pattern of credit-risk driven volatility sharing from the country with the highest credit quality in the region to its smaller and vulnerable neighbors. Note that importantly there is also a pattern of volatility sharing between markets within the high-risk category, which are economically weaker and therefore more vulnerable to exogenous shocks.

The dominance of Mexico is especially evident during the pre-Argentine crisis, with about 60% of the volatility transmission channels (3 out of 5) receive volatility from the Mexican market. In contrast only one channel receives volatility from Argentina. However, the situation changes during the post-crisis window with Mexico receiving volatility from Argentina and Brazil. The dominance of the Mexican sovereign bond market in Latin America is consistent with the reported volume surveys published by the Emerging Market Trade Association (EMTA).[10] This survey shows that Mexican bond market volume remained high during the sample period and accounted for about 30% of all emerging market trading volume.

The systematic transmission of volatility from the Mexican market to the markets of Argentina, Brazil, Colombia and Venezuela In the pre-crisis period is consistent with existing liquidity and segmentation based theories of term structure dynamics and credit spread pricing, where the transmission of shocks runs from a stable and higher quality market to those that are less credit-worthy via a specific adjustment of the credit-spread, as described in the structural model of Longstaff and Schwartz(1995). Thus, while the yields of bonds of other maturities may be driven by expectations and price-arbitrage, specific investor liquidity and maturity preferences will favor stronger relationships for some maturity baskets over others. In this sense the regional term structure of bond yields plotted in Fig. 2(a) are also consistent with this type of behavior.

As expected, there are some exceptions to this pattern that are driven by the idiosyncratic features of the region's economies. For example, in the 2009 maturity basket the volatility from the Brazilian market spills over to the Mexican market during the whole sample and post-Argentine crisis sample. The potential signal from this spillover is that despite Mexico being a more stable but smaller economy, the idiosyncratic risk associated with the significantly larger Brazilian economy does influence the volatility of the Mexican bond market. When the Brazilian long term debt rating by Standard & Poor's' was lowered to B+ in January 1999, this

[10] It is an organization dedicated the promotion and development of fair and efficient markets for emerging market investment products and provides information on aggregate annual trading volume with respect to individual countries from emerging markets. http://www.emta.org.

signaled an elevated level of regional risk with Brazil joining the ranks of its poorly performing neighbors such as Venezuela. However, the rating for Brazil did improve to BB- in January 2001 only to be downgraded again to B+ in July 2002 mainly due to concerns about debt sustainability.

While there is also a pattern of Argentine volatility being transmitted to the Venezuelan and the Colombian markets, there is also evidence of bidirectional volatility sharing between Colombia and Venezuela. These results potentially reflect investor concern with uncontained contagion and are clearly illustrated in Fig. 2, where the term structure has changed in response to both specific crisis events, as well as expectations about the likely impact on the region and on specific economies. Thus, despite the stronger economic performance of one country, its vulnerability to shocks emanating from the region is a priced risk premium. Simply stated, this is the effect of one "bad apple" affecting other specific countries with subsequent region wide effects. For example, the Argentine volatility matters to Colombia in all three baskets within the shorter maturity group, given that it does not enjoy the stability and the perceived credit status enjoyed by Mexico. However, Colombia falls in between the high-risk group (Argentina, Brazil and Venezuela) and Mexico, which remains the perceived regional benchmark. The optimal portfolio weights generated later, using the underlying variance-covariance structures for the in- and out-of-sample forecasts, clearly differentiate Colombia, Mexico and the other three countries, which form the high-risk group. In summary, the volatility transmission within the shorter maturity group is dominated by Mexico and more importantly these channels receive volatility from Mexico rather than from Argentina – indicating the importance of credit quality driven volatility transmission.

5.4. Volatility transmission – the longer maturity group

The longer maturity group consists of the 2020[11] and 2027 maturity baskets and includes the sovereign bond markets of Argentina (ar), Brazil (br), Colombia (co), Mexico (mx) and Venezuela (vn). There are 10 different combinations for each basket resulting in 20 possible transmission channels across the two baskets for each window as shown in column 1 of Table 4. Examining the unidirectional volatility transmission across both baskets of bonds in this group reveals that 26 pairs have unidirectional transmission of volatility from one market to the other. Of these 26 cases of spillover, 12 cases belong to the 2020 maturity basket and the rest of the 14 cases belong to the 2027 maturity basket.

There are about 18 volatility transmission channels out of the 26 channels that are dominated by Argentina and Mexico. Unlike the shorter maturity group, volatility transmission in the longer maturity group is dominated by Argentina with about 7 channels receiving volatility from Argentina. Four out of seven of these channels receive volatility from Argentina during the pre-Argentine crisis, while only one channel receives volatility from Argentina during the post-Argentine crisis. On the other hand, the Mexican volatility is exported only in one case (during the pre-Argentine crisis), while this increases to three channels during the post-Argentine crisis.

When we examine the 2020 maturity basket all five markets experience unidirectional spillover. Overall, Argentina and Brazil export volatility to Colombia and Venezuela. The Mexican market imports Argentine volatility during the pre-crisis window, although the direction of volatility reverses during the post-crisis period. According to the EMTA survey, the Brazilian issuance volume fell in 2001 to the lowest point since 1993 due to speculation over the spillover effects of the Argentine crisis. One key result is that Argentina consistently receives Brazilian volatility throughout the whole sample, as well as the sub-samples. The influence of Argentine volatility on Mexico did reverse during the post-crisis period with Colombia and Argentina receiving volatility from Mexico (i.e. volatility from a safe haven). Noticeably, Colombia also receives volatility from Venezuela, which is mostly disconnected from the other regional markets during the post-crisis period. It seems likely that Colombia is the recipient of volatility both from a stronger market like Mexico, as well as from a weaker and vulnerable market (Venezuela). In addition, it also receives volatility from the defaulted market (Argentina) during the post crisis period.

We now turn our attention to the 2027 maturity basket. Examining the 2027 maturity basket reveals significant interactions between the Latin American markets. There are 15 cases of unidirectional spillover occurring. During the pre-crisis period there is volatility spillover from Argentina to Brazil and Venezuela, indicating the political vulnerability of these two countries, which received rating downgrades during this period (to B+ and B respectively). The Venezuelan volatility also spills over to Brazil during the pre-crisis window. Similarly, the Venezuelan volatility also affected the Colombian market, although the latter was more economically stable as reflected by its relatively higher credit rating.

Mexico and Colombia, the two countries in the region with the best credit ratings and the lowest levels of sovereign risk, shared volatility in a bidirectional manner, although the direction of volatility is from the Mexican market to the Colombian market during the whole sample, as well as during the post-crisis period. What is evident from the shorter maturity group, and the longer maturity group, transmission patterns is that Colombia is susceptible to volatility transfers from a stable and economically stronger market like Mexico, as well as vulnerable markets like Brazil and Venezuela. Note that there was no noticeable relationship between Mexico and Brazil in the longer maturity series, except for the 2020 maturity basket where the two markets have some form of bi-directional volatility sharing. There is also no relationship between Mexico and Venezuela in the longer maturity series.

The pattern evident from all five markets suggests that the transmission channels are a function of specific grouping that link Mexico and Colombia as one cluster, and Venezuela, Brazil and Argentina as another cluster. Colombia has transmission channels with both of these two groups. Once again the term structure plots in Fig. 2 demonstrate the presence of these two groups: As depicted in the four diagrams it is clear that during the pre-crisis period all markets were moving together with a marked discrimination between Mexico and the other four markets in the region. By June 2001, Colombia had decoupled from the high credit risk group and moved closer to Mexico, while Brazil, Venezuela and Argentina moved closer together. The onset of the Argentine crisis separated the high credit risk group from the defaulting Argentina and moved them closer to Mexico.

One of the main findings from the Argentine crisis is that shorter maturity groups and longer maturity groups behave in fundamentally different ways in terms of volatility transmission. Shorter maturity bonds receive signals from the countries with low credit risk, while this is not necessarily the case with the longer maturity group, where volatility sharing dominates the high credit risk countries (Argentina, Brazil and Venezuela). The behavior of the longer maturity group is consistent with a segmented bond market, with limited interaction with lower credit risk markets during the pre-crisis period. In summary, the volatility transmission within the longer maturity group is dominated by the Argentine volatility. Noticeably, Argentine volatility is exported to the neighboring markets during the pre-Argentine crisis, while the

[11] Due to limitation on the availability of bonds with the exact maturity of 2020, the near maturity bonds (2016, 2017 and 2018 respectively belonging to Mexico, Argentina and Venezuela) are included with the Colombian 2020 and Brazilian 2020 bonds in this basket.

pattern reverses during the post Argentine crisis window as Argentinian bonds receive volatility from its neighbors.

5.5. Are the volatility dynamics affected by the global financial crisis?

So far the analysis has focused on the volatility dynamics of individual markets within the Latin American region using the 2001 Argentine default as the natural experiment to study the price effects of an endogenous shock. In this section we use the Global Financial Crisis (GFC) as an exogenous shock to see how the volatility dynamics evolved during the whole, pre and-post GFC period. It is well known that the GFC started with the U.S. sub-prime market, diffused to the global financial system, and then culminated in sovereign episodes in the European region that impacted both mature and emerging economies. It would be expected that countries sensitive to external borrowing to finance fiscal deficits – as is the case with Latin America – would be especially vulnerable during such an episode.

There is an extensive literature on the behavior of financial markets during this period. Grammatikos and Vermeulen (2012) show how the 2007 GFC contributed to European asset market dynamics and provides evidence of crisis transmission from the U.S. to the European Monetary Union countries. Eichengreen et al. (2012) show how key common factors become more important during the crisis period through their analysis of the prices of credit default swaps of 45 large financial institutions. Their evidence suggests that 62% of the variation explained by a common factor during normal times, increased to 77% during the crisis period. That is, these financial institutions became more susceptible to the common shock, thereby adding to the overall level of systemic risk in the financial system.

As outlined in the data section, the analysis covering the impact of GFC on Latin America utilizes only the longer maturity group of bonds as many of the bonds belonging to the shorter maturity group had either matured, or were nearing maturity. More specifically, we use the 2020 and 2027 baskets of bonds for this purpose. The sample period for this analysis begins on September 16, 2004 and ends on the September 14, 2012. In this case the pre and-post GFC sub samples cover equal sized windows. In line with the literature on dating the crisis, we use 15 September 2008 as the key crisis date as this was the time when Lehman Brothers filed for Chapter 11 bankruptcy protection. Examining the 2020 maturity basket in Table 5 reveals that the unidirectional flow of volatility was from the Mexican market to Brazil, Argentina and Colombia during the whole sample and pre-crisis sample. This pattern was also more evident during the pre-GFC crisis window. Reversal of this pattern is also evident in the pre-crisis window with respect to Venezuela and in the post-GFC window with respect to Brazil. However, this changes during the post-GFC crisis window with Mexico receiving volatility from the Brazilian market. Examining the results for the whole sample window for this maturity group reveals a dominance of bi-directional relationship revealing co-dependencies.

Observing the results presented for the 2027 maturity basket, the following pattern is evident: Brazilian volatility spills over to Argentina, Colombia and Venezuela mostly during the pre-GFC window. Similarly, Venezuelan volatility spills over to Brazil, Colombia and even Mexico during the post-GFC window. Overall, this shows there is a heterogeneous spillover pattern in the 2020 and 2027 baskets during the GFC analysis. One plausible explanation could be that the 2020 basket during the post crisis period was no longer behaving as a long term maturity basket since the average maturity was now closer to a medium term maturity than a longer term maturity basket and so the dynamics of the Argentine default period no longer applied.

Table 5
Cross-market volatility dynamics (Global financial crisis window).

	Whole sample		Pre-GFC		Post-GFC	
	LR1	LR2	LR1	LR2	LR1	LR2
2020 maturity basket						
ar – br	–		–		–	
ar – co	–		–		–	
ar – mx	–		**2.374**	**37.254***	0.464	1.282
ar – vn	36.932*	541.000*	1.504	1.228	–	
br – co	29.252*	13.566*	21.691*	14.885*	**2.760**	**12.708***
br – mx	**5.934**	**23.898***	–		**7.319***	**2.104**
br – vn	–		28.983*	12.359*	–	
co – mx	6.348*	25.228*	**3.981**	**10.662***	34.665*	15.092*
co – vn	8.942*	25.112*	8.658*	9.297*	37.458*	16.660*
mx – vn	7.402*	38.468*	**4.083**	**16.892***	35.124*	10.336*
2027 maturity basket						
ar – br	**5.116**	**484.520***	924.118*	908.242*	–	
ar – co	–		**7.364***	**0.936**	2.718	-5.016
ar – mx	112.956*	220.040*	23.506*	33.474*	–	
ar – vn	16.440*	539.880*	10.560*	9.008*	–	
br – co	23.780*	13.362*	**23.722***	**3.766**	**6.700***	**0.840**
br – mx	20.636*	11.274*	12.935*	14.371*	0.960	4.356
br – vn	16.874*	36.108*	**16.384***	**3.950**	**2.800**	**34.176***
co – mx	**19.496***	**1.784**	–		2.184	5.980
co – vn	7.260*	30.106*	**3.850**	**6.856***	**1.812**	**14.966***
mx – vn	6.210*	26.562*	**18.088***	**1.264**	**3.414**	**7.476***

This table reports the cross market volatility dynamics for the longer maturity groups consisting of 2020 and 2027 maturity baskets. The names reported in column 1 as Argentina [ar], Brazil [br], Colombia [co], Mexico [mx], Venezuela [vn] represent the sovereign bonds belonging to the five countries covered in this study. Columns 2, 3 and 4 report the likelihood ratio test results for the whole sample (from September 2004 to September 2012), the pre-GFC window (September 2004 to September 2008) and the post-GFC window (September 2008 to September 2012). The sample period covers daily bond price series from September 2004 to September 2012. The likelihood ratio tests (LR1 and LR2) reported in columns 2, 3 and 4 represent test statistic generated by comparing the log likelihood value of the restricted models by (imposing restriction 1 and restriction 2) with the unrestricted model. The 5% Chi-Square distribution critical value for with $df = 2$ is 5.991 for the nested testing on cross market dynamics. The sign "–" indicates convergence failures or unstable log likelihood values. Figures in bold indicate the existence of unidirectional volatility transmission.

5.6. Tri-variate BEKK modeling

In addition to the previously described bivariate modeling a tri-variate BEKK framework was also investigated to establish the three-way relationships revealed by the previously described transmission channels. For brevity these results are not reported as separate tables and the results are available upon request. However, a summary of these findings provides further insights into (a) the nature of unexpected shocks captured by the squared residuals of Mexico, Argentina and Venezuela; (b) the cross-values of residuals with respect to: $\varepsilon_{1,t}\varepsilon_{2,t}$, $\varepsilon_{1,t}\varepsilon_{3,t}$ and $\varepsilon_{2,t}\varepsilon_{3,t}$; (c) idiosyncratic volatility generated by the own market and indirectly by the volatility transferred from other markets. In the first combination examined, the underlying volatility structure is the Mexico–Argentina–Venezuela group within the 2007 basket during the pre-Argentine crisis. Argentina receives volatility from Mexico and in the same way Venezuela receives volatility from Mexico in the 2007 basket during the pre-Argentine crisis. Mexico is the market that links Argentina and Venezuela. Similarly, the combination of Argentina–Brazil–Mexico in the 2009 basket and Argentina–Colombia–Venezuela in the 2027 basket was also tested. All of these combinations confirm statistically significant direct effects from the individual volatility as well as indirect effects involving the cross-market terms. For brevity these results are not reported as separate tables and the results are available upon request.

5.7. Economic significance analysis

To provide additional insights into the economic implications of volatility transmission, we consider the issues faced by investors when allocating assets within a regional sovereign bond portfolio. The procedure we adopt minimizes the risk of two bonds with unidirectional spilling of volatility from one bond market to the other bond market. The main question addressed is whether utilizing the time-varying covariance matrix, to derive optimal portfolio weights for two risky assets in a cross-market setting, provides tangible economic benefits to investors.

We identify those pairs of markets, within a specific maturity basket with unidirectional transmission, to demonstrate the economic significance of this strategy. First, we target those combinations of markets that experience unidirectional volatility during the whole sample and subsamples surrounding the Argentine crisis. We limit our analysis only to the Argentine crisis as an illustration of the importance of the volatility dynamics for portfolio management. The rationale for this strategy is to understand how the dynamics relating to portfolio outcomes evolve with those assets that receive volatility, and those that export volatility, given that there is a lagged impact on the asset that exports volatility.

Given that the correlation coefficient between most of the financial assets fall in the range of $-1 < \rho_{12} > 1$, the optimal portfolio weight for a portfolio with two risky assets can be derived by taking the partial derivative of the portfolio variance with respect to the weight on the first risky asset. The resulting optimal portfolio is the risk minimizing portfolio weight as represented by Kroner and Ng (1998) and is captured by Eq. (15) subject to a short-sale constraint. One minus the weight on the first asset is the optimal weight with respect to the second asset. Kroner and Ng (1998) note the relevance to portfolio managers of the optimal portfolio holding represented by Eq. (15), which has the benefit of overcoming the task of forecasting expected returns. Risk-minimizing optimal portfolio weights are then generated on a daily basis assuming a mean-variance utility function. We further relax this assumption to accommodate more risk tolerance in Eq. (16) by allowing limited short selling.

Using the variance-covariance metrics from Engle and Kroner (1995) the optimal portfolio holding of the first bond at time t based on Kroner and Ng (1998) is captured by ω_t. Assuming a mean-variance utility function, the optimal portfolio weights for an investor whose utility function is constrained by short-selling may then be determined. With the short-sale constraint, the portfolio weight with respect to the first bond is represented by ω_t^*, while the optimal weight of the second bond is $1-\omega_t^*$. These relationships are expressed as:

$$\omega_t = \frac{h_{22,t}-h_{12,t}}{h_{11,t}-2h_{12,t}+h_{22,t}} \quad \text{and} \quad \omega_t^* \begin{cases} 0, & \text{if } \omega_t < 0 \\ \omega_t, & \text{if } 0 \le \omega_t \le 1 \\ 1, & \text{if } \omega_t > 1 \end{cases} \tag{15}$$

where ω_t refers to the risk minimizing optimal weight at time t with respect to the first bond in the pair of bonds; ω_t^* is the constrained weight which is restricted to be between 0 and 1; $h_{22,\,t}$ is the conditional volatility of the second bond in the pair at time t; $h_{11,\,t}$ is the is the conditional volatility of the first bond second bond in the pair at time t; $h_{12,\,t}$ is the conditional covariance between the pair of bonds.

Although we allow limited short-selling, the benefit arising from such a risky undertaking has limited benefits in a sovereign setting based on the results derived in Tables 6 and 7. The results from this analysis show that trading strategies that utilize the short-selling of excessively volatile sovereign bonds have limited benefits for investors.

This assumption may be further relaxed to accommodate more risk tolerance by allowing limited short-selling of 30%. This amount represents the widely practiced short-selling strategy termed 130–30, where the poorly performing bond is shorted by 30%, with the leveraged amount (130%) directed towards a better performing bond. Relaxing the short-sale constraint, allows the weight to range between −0.3 and 1.3, producing the optimal weight of ω_t^{**} for the first bond, and $1-\omega_t^{**}$ for the second bond.

The optimal portfolio weights by considering the behavior of the portfolio frontiers when limited short-selling is permitted and with a short selling cap to 30% is represented:

$$\omega_t = \frac{h_{22,t}-h_{12,t}}{h_{11,t}-2h_{12,t}+h_{22,t}} \quad \text{and} \quad \omega_t^{**} \begin{cases} -0.3, & \text{if } \omega_t < -0.30 \\ \omega_t, & \text{if } -0.3 \le \omega_t \le 1.3 \\ 1.3, & \text{if } \omega_t > 1.3 \end{cases} \tag{16}$$

where ω_t^{**} is the weight allowing for limited short-selling of the poorly performing bond by allowing the weight of the portfolio to range between −0.3 and 1 at time t and $1-\omega_t^{**}$.

The in-sample results are reported in columns 2 and 3 of Panel A in Table 6 for the shorter maturity, and columns 2 and 3 of Panel A in Table 7. The out-of-sample results are reported in Panel B of both Tables. To illustrate the trading strategy, consider two examples of the pairs reported in Table 6. The first combines (a) a defaulting country (Argentina) and a perceived safe heaven (Mexico) (the 2007 maturity basket ar-mx pair); and (b) a defaulting country (Argentina) and Venezuela, a riskier country with sovereign vulnerability (the 2007 maturity basket ar-vn pair.). For the Argentine–Mexican pair an average daily weight of 20.2% with respect to Argentina and 79.8% with respect to Mexico is identified. On the other hand, the Argentina–Venezuela pair during the same window shows an optimal allocation of 49.1% and 50.9%. These ratios change if short selling is permitted: the Argentina–Mexico pair is now 18.7% and 81.3%, while the Argentina–Mexico pair is 48.6% and 51.4%.

In the first instance, the economic meaning of these weights suggests it is optimal to hold 20.2 cents of a one-dollar portfolio in the Argentinian bond while 79.8 cents should be allocated to Mexico, but only when the Argentinian bond is paired with Mexico. However, when the Argentinian bond is paired with the Venezuelan bond the optimal portfolio weight increases to 49.1 cents with respect to the same Argentinian bond. Thus, when the Argentinian bond is paired with a less riskier market (Mexico) and a more riskier market (Venezuela), it is optimal to invest less in the Argentine bond than in the Argentine–Mexican pair while, a greater percentage can be allocated to Argentina when it is paired with Venezuela in the Argentina–Venezuela pair. In this case the own market volatility with respect to the pair of markets, and the covariance between the two markets, drive the percentage to be allocated to individual assets as captured by Eq. (15).

Prior to further discussion of the results of the economic significance analysis presented in Tables 6 and 7, it is pertinent to examine the role of conditional variances and the correlated link between the pair of bonds covered in the analysis. The time-varying covariance matrix captures the dynamics between the pairs of assets and contributes to the optimal allocation of weight within the portfolio. Fig. 4 plots the links between time-varying correlations of weighted bond-pairs (top line in each figure). These correlations are generated as the ratio of the covariance and the square root of the product of the conditional variances. Only those pairs that have clear unidirectional volatility transmission are considered. For brevity we only report the whole sample window results surrounding the Argentine crisis to explicate this link.

The unidirectional transmission of volatility from one market to the other market influences the volatility of the market that receives or imports volatility, from the market that exports volatility. In this context, Eq. (15) captures the impact of volatility

Table 6
In-sample and out-of-sample economic significance analysis (shorter maturity group).

	Panel A: In-sample optimal portfolio weights				Panel B: Out-of-sample optimal portfolio weights			
	No shorting allowed		Shorting Allowed		No shorting allowed		Shorting Allowed	
	ω	$(1-\omega)$	ω	$(1-\omega)$	ω	$(1-\omega)$	ω	$(1-\omega)$
Whole sample								
2007 maturity basket								
ar – vn	0.284	0.716	0.279	0.721	0.007	0.993	0.007	0.993
co – mx	0.159	0.841	0.141	0.859	0.127	0.873	0.127	0.873
mx – vn	0.913	0.087	0.921	0.079	1.000	0.000	1.019	−0.019
2008 maturity basket								
ar – br	0.281	0.719	0.263	0.737	0.002	0.998	0.003	0.997
ar – mx	0.037	0.963	0.017	0.983	0.000	1.000	−0.0002	1.0002
br – mx	0.050	0.950	−0.002	1.002	0.000	1.000	−0.018	1.018
co – mx	0.217	0.783	0.194	0.806	0.015	0.985	0.015	0.985
2009 maturity basket								
ar – co	0.175	0.825	0.166	0.834	0.080	0.920	0.080	0.920
br – mx	0.062	0.938	0.001	0.999	0.0003	0.9997	−0.0003	1.0003
co – mx	0.190	0.810	0.167	0.833	0.089	0.911	0.089	0.911
Pre-Argentine crisis								
2007 maturity basket								
ar – mx	0.202	0.798	0.187	0.813	0.372	0.628	0.372	0.628
ar – vn	0.491	0.509	0.486	0.514	0.784	0.216	0.784	0.216
co – mx	0.167	0.833	0.157	0.843	0.125	0.875	0.125	0.875
mx – vn	0.882	0.118	0.890	0.110	0.820	0.180	0.820	0.180
2008 maturity basket								
co – mx	0.267	0.733	0.254	0.746	0.019	0.981	0.019	0.981
Post-Argentine crisis								
2008 maturity basket								
ar – co	0.047	0.953	0.042	0.958	0.353	0.647	0.353	0.647
ar – mx	0.011	0.989	0.006	0.994	0.005	0.995	0.005	0.995
2009 maturity basket								
br – co	0.099	0.901	0.067	0.933	0.396	0.604	0.396	0.604
br – mx	0.182	0.818	0.159	0.841	0.0186	0.981	0.0186	0.981

This table reports the economic significance of our results reported in Tables 3 covering the shorter maturity group for the Argentine crisis. We have only chosen the unidirectional volatility transmission pairs for the purpose of this analysis and report the in-sample optimal portfolio weights for the whole, pre-and-post Argentine crisis in Panel A while Panel B reports the out-of-sample optimal portfolio weights for the pairs in column 1 with Argentina [ar], Brazil [br], Colombia [co], Mexico [mx], Venezuela [vn] representing the sovereign bonds belonging to these countries. Columns 2 and 3 (Panel A) report the optimal portfolio weights with no short-selling provision while columns 4 and 5 (Panel A) report the optimal portfolio weights for a strategy which allows for limited short-selling (130–30). Similarly, Panel B of the table reports the out-of-sample optimal portfolio weights in columns 6 and 7 (Panel B) for the no short selling case while columns 8 and 9 (Panel B) report the optimal portfolio weights with short selling allowed. The reported portfolio weights are the average of daily weights generated for the pairs. ω reports the weight associated with the first market in the pair, while $(1-\omega)$ captures the weight associated with the second market in the pair.

transmission from one market to the other in the form of the underlying conditional volatility of the individual markets, together with the covariance between the pairs of bond markets by collectively determining the optimal allocation of weights to the risk minimizing portfolio.

Given that the objective function of Eq. (15) is to minimize risk, the natural choice leads to less weighting for the asset with higher relative volatility, while the asset with lower relative volatility will receive a higher weighting subject to the magnitude of the underlying correlation relationship between the two assets. The magnitude of the weight allocation will also be influenced by the interrelationship between the pairs of bonds as depicted in Fig. 4. The credit quality driven allocation of weight is evident when the volatility spillover between high credit quality bonds and low credit quality bonds is examined. When the volatility spills over from high quality bond markets like Mexico to low quality markets (like Argentina, Brazil and Venezuela), the optimal portfolio allocation of weight skews significantly towards Mexico. This results in the higher weighting allocated to Mexico, evident in both Tables 6 and 7. This pattern is stronger for shorter maturity bonds when compared to the longer maturity bonds. This is likely due to the significant differences in volatility experienced by these bond-baskets. As shown in Fig. 4, when volatility spills over between low credit-quality markets the portfolio allocation is influenced by the relative individual volatility and the underlying correlation between the bond markets. Overall, the nature of volatility experienced by individual markets and the resultant allocation of optimal portfolio weights with respect to the pairs of markets tend to depend on the underlying correlation between the markets as well as the nature of transmission and the sensitivity of a given maturity basket to credit quality related shocks.

The results are reported in Panel A of Tables 6 and 7 for the shorter maturity group and longer maturity group respectively. Examining the results provides some interesting additional insights. First, when volatility is exported from a stronger and more stable (less volatile) bond market to a weaker bond (more volatile) market, greater weighting is allocated to the stronger market compared to the weaker market. While on the other hand, if volatility is received by a stronger market with a higher credit rating, from a weaker neighbour with a lower rating, then the greater weighting is allocated to the stable market. Recall that since shorter and longer maturities of sovereign bonds also have different levels of volatility, the optimal portfolio decisions of investors will be shaped by the interaction of potentially differing maturity and risk optimization preferences. Specific maturity preferences by investors (e.g. favoring a longer maturity Argentine bond to a shorter) will therefore affect the covariance structure that underlies the weighting allocated to a specific bond.

Volatility transmission patterns presented respectively in Tables 3 and 4 for the shorter maturity and longer maturity groups, reveal strikingly dissimilar behavior with respect to the directions of spillover, as well as implications to risk management measured in terms of optimal portfolio weights (i.e. changes in weighting implies a rebalancing of the portfolio, which could involve either buying more of one bond while selling the other). In order to provide a perspective on the economic significance of this behavior,

Table 7
In-sample and out-of-sample economic significance analysis (longer maturity group).

	Panel A: In-sample optimal portfolio weights				Panel B: Out-of-sample optimal portfolio weights			
	No shorting allowed		Shorting Allowed		No shorting allowed		Shorting Allowed	
	ω	$(1-\omega)$	ω	$(1-\omega)$	ω	$(1-\omega)$	ω	$(1-\omega)$
Whole sample								
2020 maturity basket								
ar – br	0.294	0.706	0.264	0.736	0.027	0.973	0.027	0.973
ar – vn	0.121	0.879	0.108	0.892	0.048	0.952	0.048	0.952
br – vn	0.202	0.798	0.181	0.819	0.664	0.336	0.664	0.336
co – mx	0.282	0.718	0.263	0.737	0.105	0.895	0.105	0.895
2027 maturity basket								
ar – br	0.342	0.658	0.324	0.676	0.003	0.997	0.003	0.997
ar – mx	0.100	0.900	0.079	0.921	0.001	0.999	0.001	0.999
ar – vn	0.234	0.766	0.225	0.775	0.002	0.998	0.002	0.998
br – co	0.275	0.725	0.268	0.732	0.531	0.469	0.531	0.469
co – mx	0.257	0.743	0.248	0.752	0.216	0.784	0.216	0.784
co – vn	0.494	0.506	0.494	0.506	0.439	0.561	0.439	0.561
Pre-Argentine crisis								
2020 maturity basket								
ar – br	0.089	0.911	0.025	0.975	0.178	0.822	0.178	0.822
ar – mx	0.049	0.951	0.012	0.988	0.000	1.000	−0.101	1.101
ar –vn	0.084	0.916	0.057	0.943	0.230	0.770	0.230	0.770
2027 maturity basket								
ar – br	0.284	0.716	0.257	0.743	0.375	0.625	0.375	0.625
ar – vn	0.270	0.730	0.253	0.747	0.676	0.324	0.676	0.324
br – vn	0.310	0.690	0.305	0.695	0.685	0.315	0.685	0.315
co – vn	0.386	0.614	0.385	0.615	0.439	0.561	0.439	0.561
Post-Argentine crisis								
2020 maturity basket								
ar – br	0.432	0.568	0.438	0.562	0.566	0.434	0.566	0.434
ar – co	0.087	0.913	0.082	0.918	0.398	0.602	0.398	0.602
ar – mx	0.044	0.956	0.040	0.960	0.140	0.860	0.140	0.860
co – mx	0.231	0.769	0.204	0.796	0.147	0.853	0.147	0.853
co – vn	0.586	0.414	0.589	0.411	0.754	0.246	0.754	0.246
2027 maturity basket								
ar – co	0.155	0.845	0.151	0.849	0.068	0.932	0.068	0.932
br – co	0.139	0.861	0.120	0.880	0.062	0.938	0.062	0.938
co – mx	0.228	0.772	0.206	0.794	0.394	0.606	0.394	0.606
co – vn	0.583	0.417	0.583	0.417	0.936	0.064	0.936	0.064

This table reports the economic significance of our results reported in Tables 4 covering the longer maturity group for the Argentine crisis. We have only chosen the unidirectional volatility transmission pairs for the purpose of this analysis and report the in-sample optimal portfolio weights for the whole, pre and post Argentine crisis in Panel A while Panel B reports the out-of-sample optimal portfolio weights for the pairs in column 1. Columns 2 and 3 (Panel A) report the optimal portfolio weights with no short-selling provision while columns 4 and 5 (Panel A) report the optimal portfolio weights for a strategy which allows for limited short-selling (130–30). Similarly, Panel B of the table reports the out-of-sample optimal portfolio weights in columns 6 and 7 for the no short-selling case while columns 8 and 9 report the optimal portfolio weights with limited short-selling allowed (130–30). The reported portfolio weights are the average of daily weights generated for the pairs. ω reports the weight associated with the first market in the pair, while $(1-\omega)$ captures the weight associated with the second market in the pair.

we consider the behavior of the yield curves as well as the ratings associated with individual countries in this analysis. Accordingly, we classify Mexico as the low-risk country with benchmark status, while Argentina, Brazil and Venezuela are classed as high-risk countries. Colombia on the other hand falls in between these two groups and is therefore classed as medium risk despite the civil war during the Argentine crisis.

5.7.1. Out-of-sample forecast and the diagonal BEKK model

This section is concerned with how in-sample optimization of portfolio outcomes, using the underlying volatility structures of the initial 50% data, and then applying these parameters to conduct the out-of-sample forecasts. We do this separately for the whole sample, pre and-post Argentine crisis windows. It is important to employ the full BEKK model to identify the volatility transmission across the markets investigated. However, despite its usefulness for modeling cross-market volatility spillover, the full BEKK does have problems with the interpretation of key parameters, in addition to the difficulties faced when tracing their effects on future variance and covariance (see, among others, Tse, 2000; Bekaert and Wu, 2000; Bauwens, Laurent and Rombouts, 2006). The diagonal BEKK model, while maintaining positive definiteness of the conditional covariance, remains a relatively simple specification that is free from the above problems, since the off-diagonal terms are set to zero. Further, the diagonal BEK is empirically effective for hedging purposes.[12] Therefore, we use the diagonal BEKK of Engle and Kroner (1995) to forecast the variance and co-variance matrices using the first 50% of the sample for each of the pairs reported in Column 1 of Tables 6 and 7, and then roll the window on a daily basis. Using the forecasted conditional variance and covariance series, the out-of-sample optimal portfolio weights are generated using Eqs. (15) and (16).

Tables 6 and 7 also provide further information on the cross-market dynamics when limited short-selling is permitted both for the in-sample and out-of-sample analyses. Although we have presented the optimal portfolio weights for the whole sample window, given the possibilities of a structural break following the December 2001 default, our discussion on the economic significance analysis is confined to the pre and-post Argentine crisis windows. There are five different baskets of securities differentiated by terms to maturity and grouped into shorter maturity and longer maturity groups.

[12] Chang, McAleer and Tansuchat (2011) find diagonal BEKK as the best model for hedging effectiveness for optimal hedge ratio in terms of reducing the variance of the portfolio.

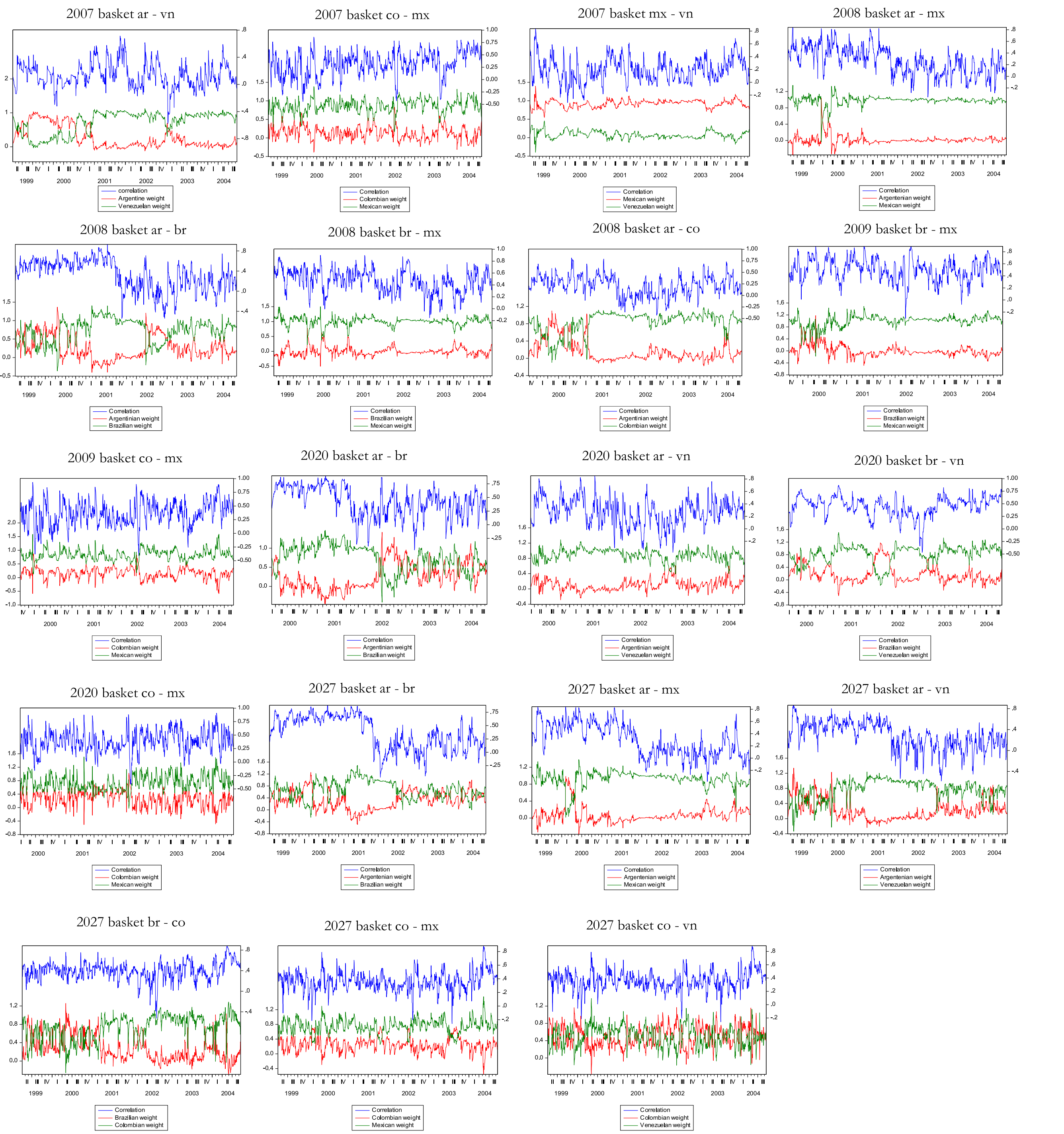

Fig. 4. Latin American sovereign bonds: conditional correlation and pairwise portfolio loadings. The figures below capture the role of the correlated links and direction of transmission influencing the optimal portfolio weights generated for the whole sample widow covering the Argentine crisis. The optimal portfolio weights depicted below were generated using the conditional variances and covariance within the full BEKK model for the pairs involved using $\omega_t = \frac{h_{22,t} - h_{12,t}}{h_{11,t} - 2h_{12,t} + h_{22,t}}$. Shorter maturity groups consisting of 2007, 2008 and 2009 and longer maturity baskets consisting of 2020 and 2027 baskets are presented below for the whole sample. The abbreviation represented in the title for the pairs of bonds as Argentina [ar], Brazil [br], Colombia [co], Mexico [mx], Venezuela [vn] represent the sovereign bonds belonging to the five countries covered in this study.

5.7.2. In-sample and out-of-sample optimal portfolio weights (shorter maturity group)

An examination of the pre-Argentine default spillover dynamics for the shorter maturity group, shows evidence of spillover from a low-risk country with a benchmark status within the region (Mexico) to high-risk countries (Argentina and Venezuela) in the 2007 basket. The average in-sample optimal portfolio weights generated in the absence of short-selling suggest that investors should have a smaller holding of the Venezuelan bond (12%) compared to the Argentine bond (20%). When short selling is allowed, Argentina and Venezuela assume negative weights, with the optimal portfolio weights on average reduced to 19% and 9% respectively. The out-of- sample portfolio weights, however, allocates 37% for Argentina and 63% for Mexico. Thus there is a slight increase in the weight for Venezuela (18%). When spillover occurs between countries with low-risk the direction of spillover has a bearing on the optimal portfolio weight. For example, Colombia receives a 17% average portfolio weight when it receives volatility from Mexico (2007 maturity basket). However, this percentage increases to 27% when Colombia exports volatility to Mexico (2008 maturity basket). Short-selling does occur with respect to the Colombian bonds in both cases.

The out-of-sample analysis suggests only a 2% allocation towards Colombia and 98% to Mexico for the 2008 maturity basket, and 13% towards Colombia for the 2007 basket. The transmission pattern with respect to shorter and longer maturity groups, and the optimal portfolio weights arising from the joint volatility dynamics, reflects the heterogeneity of international sovereign bonds. The interaction between bonds belonging to high risk countries highlight the spillover effects between Argentina, Brazil and Venezuela, within the shorter maturity group, during the pre-Argentine crisis window. The Argentine volatility spills over to the Venezuelan market in the 2007 maturity basket, resulting in 49% of the optimal portfolio allocation being directed towards Argentina and 51% towards Venezuela. However, the out-of-sample portfolio weights, suggest only a 22% weight allocation to Venezuela and 78% to Argentina. This is reflective of the low volatility experienced by Argentina until March 2000, together with the excessive volatility experienced by Venezuela during the same period. These combined effects shift both markets to a low correlation phase resulting in more weighing being allocated towards Argentina. The out-of-sample forecast conditions on the first 50% of the sample cover the low volatility phase for the Argentinian bond. As a result the forecast allocates more weighting towards Argentina.

The post-Argentine default period for the shorter maturity group is characterized by spillover from high-risk to low-risk countries with a high discrimination against low risk countries with respect to portfolio weights. For example, in the 2008 maturity basket, both Mexico and Colombia receive volatility from Argentina, but Argentina is highly discriminated with 1% weight going toward Argentina while 99% is allocated to Mexico. The out-of-sample allocation for this pair turns out to be slightly more discriminatory and allocates only 0.05% to Argentina and 99.95% to Mexico.

Similarly, for the Colombia and Argentina combination within the same basket, Argentina receives a 5% optimal portfolio weight while 95% is allocated to Colombia, with evidence of short-selling of Argentine bonds within this basket. However, the out-of-sample analysis suggests a 35% weighting on the Argentine bond with 65% going towards the Colombian bond. This also reveals a lack of discrimination with respect to these two combinations, likely due to the high-level of volatility in the Colombian forecast. The 2009 basket, with respect to Brazilian volatility spilling over to low-risk Colombia and Mexico, displays a consistent minimal weight of 0.07% to Brazil and 99.93% towards Mexico. On the other hand, nearly 10% is allocated to Brazil when it comes to the pair of Brazil– Colombia. The out-of-sample exercise reveals a consistent pattern when it comes to the benchmark bonds of Mexico, while this discriminatory power is weaker with respect to the Brazil–Colombia combination. The Brazilian market then receives about 40% weighting, which is 30% more than the in-sample allocation with respect to the Brazil–Colombia pair.

5.7.3. In-sample and out-of-sample optimal portfolio weights (longer maturity group)

The pre-Argentine default window in the longer maturity group is characterized by a dominant spillover within the high-risk group with some evidence of spillover from high-risk countries to low-risk countries. In the latter case, the Argentine volatility in the 2020 basket spills over to Mexico, while the Venezuelan volatility in the 2027 basket spills over to Colombia.

Examining the in-sample optimal portfolio weights indicate that there is a high level of discriminatory power with respect to Mexico as the risk-free benchmark within the region, while this is not so with Colombia. Argentina receives only 5% with 95% being allocated to Mexico for the in-sample analysis in the 2020 basket. The out-of-sample analysis, however, further discriminates against Argentina and allocates 100% to Mexico. The discriminatory behavior in the out-of-sample analysis for this pair is further evident when short-selling is allowed. This analysis suggests 10% short-selling with respect to the Argentine 2017 bond. The direction of volatility from the high-risk category Venezuelan 2027 bond to the low risk Colombian 2027 bond reveals that the in-sample allocation of portfolio weight discriminates against Colombia and allocates 61% in favor of the high-risk Venezuelan bond, while only 39% is allocated to the Colombian bond. The reason could be attributed to the excessive volatility experienced by the Colombian 2027 bond in the lead up to the Argentine crisis. This situation contrasts to the shorter maturity group. In-sample portfolio allocation is also corroborated by the out-of-sample allocation, with the optimal portfolio weight allocation for Colombia being 43.9% and 56.1% for Venezuela.

Next, we focus on the pattern of optimal portfolio weight allocation in the category where transmission is within the high-risk segment of the bond markets. In this instance, transmission during the pre-Argentine crisis window occurs when Argentina, Brazil and Venezuela both export and import volatility to one another in the 2020 and 2027 baskets. In this segment of the market, high-risk countries in the region display volatility dependencies. For example Argentina exports volatility to Venezuela and imports volatility from Brazil in the 2020 basket. What is interesting is that when this occurs Argentina receives 9% and 8% optimal portfolio weights in the 2020 baskets when paired with Brazil and Venezuela respectively. There is also some evidence of short-selling with respect to Argentina as there is a reduction in weight (to 6.4% for Brazil and 2.7% for Venezuela) when limited short-selling is allowed for these pairs. The out-of-sample portfolio weights for these pairs indicate significantly higher allocations when compared to the in-sample allocation weighting being assigned to Argentina.

Noticeably, the allocation of optimal portfolio weights within the longer maturity group is heterogeneous. The in-sample portfolio allocation for the 2027 basket is also strikingly different. The Argentine 2027 bond exports volatility to Brazil and Venezuela, while Brazil, on the other hand, receives volatility from Venezuela. Irrespective of the direction of volatility, Argentina receives 28% and 27% with respect to its pairing with Brazil and Venezuela. This allocation is significantly different from the allocation Argentina received within the 2020 basket. The out-of-sample portfolio weights show a greater discriminatory power with respect to the Argentina–Venezuela pairing. For the out-of-sample optimal portfolio allocation, Argentina receives a 61% weighting with respect to its pairing with Venezuela, while only 37% weighting with respect to its pairing with Brazil. This suggests that while there is a level of heterogeneity present across baskets differentiated by maturity, there is also a lack of ability to discriminate against a defaulting country in the pre-Argentine crisis. The Brazil and Venezuela pairing has Brazil receiving about 31% weight for the in-sample analysis. However, the out of sample analysis allocates 69% to Brazil and discriminates against Venezuela.

Finally, we focus on the post-Argentine default widow for the longer maturity group. This window is characterized by a significant level of interaction between different risk groups in terms of transmission: Argentina and Venezuela belong to the high-risk group and receive volatility from Mexico and Colombia covering both baskets. Similarly, there is also interaction between low-risk countries (Mexico and Colombia) covering both 2020 and 2027 baskets. There is also volatility transmission from high-risk countries (Argentina, Brazil and Venezuela) to Colombia covering the 2020 and 2027 baskets. Then, there is interaction between high-risk countries with volatility spillovers from the Brazilian market to the defaulted Argentine market.

For the optimal portfolio weight allocation, Argentina receives the lowest weight of 4% when interacting with the regional benchmark- Mexico in the 2020 basket. However, a greater percentage is allocated to Argentina (16%) when it receives volatility from Colombia in the 2027 basket. The third combination for Colombia–Venezuela has a 42% allocation to Venezuela. The out-of-sample exercise reveals greater allocation of weights towards risker countries compared to the in-sample allocations. During the post crisis period, the interaction between markets in the low risk segment results in an allocation of a greater weight (23%) to Colombia in the 2020 and 2027, when it receives volatility from Mexico. The out-of-sample allocation for Colombia amounts to 15% for the 2020 basket and 40% for the 2027 basket. The other combinations covering transmission from high-risk to low-risk countries as well as transmission between high-risk countries produce similar weight allocations. Finally, although the portfolio weights seem to produce marginal effects when we allow for limited short selling, the effect seems to have limited economic consequences. What these results suggest is that even if short selling is permitted in the risky Latin American market, the beneficial effect from a portfolio management perspective is minimal.

5.8. Robustness test on cross market dynamics–is volatility transmission an artefact of illiquidity?

In order to test the robustness of our results on volatility transmission, additional robustness have been undertaken to confirm the results reported in Tables 3, 4 and 5 respectively covering the shorter maturity and longer maturity group and the GFC sample. When market makers provide two way quotations in the bond market, the bid–ask spread includes liquidity related costs due to asymmetric information and inventory carrying costs. If the volatility transmission results reported in Tables 3–, 4 and 5 are driven by illiquidity then accounting for such costs should change the results significantly.

We test this effect by absorbing 50% of the bid–ask spread in the pricing of these series and then again estimating the tests using the mid quote i.e. $[(bid\ price + ask\ price)/2]$ for each bond in our sample. The mid quote in effect captures 50% of the buyer's remorse, thereby facilitating a robustness check on liquidity related effects. These new estimations are then undertaken for the previous volatility transmission tests with the new results reported respectively in Panels A, B and C of Table 8. The shorter maturity and the longer maturity group covering the Argentine endogenous crisis are reported in Panels A and B, while the robustness results covering the exogenous GFC episode are presented in Panel C. Both the unrestricted and restricted models are estimated and the log likelihood ratios computed.

5.8.1. Robustness test on shorter and longer maturity groups

First, we examine the robustness of our results reported for the shorter maturity group by testing whether our results are driven by liquidity related factors. These results are reported in Table 8. Columns 2, 3 and 4 of this Table report the volatility transmission results for the whole sample, pre-Argentine crisis and post Argentine crisis windows respectively. Interestingly, there are 22 combinations that have unidirectional volatility transmission when we use the mid quote compared to the bid quote. These findings support liquidity driven factors, to some extent, affecting both the direction of volatility transmission as well as providing a caveat on the significance of some of the specific results. Despite these caveats the broad trends remain. Importantly, the results are not only consistent with the findings for unidirectional and bidirectional transmission, but are also consistent with the absence of transaction channels present in the original results reported in Table 3.

Next, we repeat the estimations and test the robustness of the longer maturity group results using the mid quote. These test results are reported in Panel B of Table 8. Columns 2, 3 and 4 report the volatility transmission results respectively for the whole sample and the subsample periods covering pre-Argentine crisis and post Argentine crisis windows. In the 2020 baskets there were 12 cases of unidirectional transmission based on the original results reported in Table 3. The robustness results reported in Panel B for the 2020 basket confirm the direction and the nature of volatility dynamics between the markets of Colombia–Venezuela, Argentina–Venezuela, Argentina–Colombia.

However, the earlier findings relating to the Argentine link with the Brazilian market, and the Mexican market, are not clear due to convergence problems experienced with the unrestricted model. Except for the Argentine link with the Brazilian and Mexican markets, the robustness of all other volatility interactions are confirmed for the 2020 basket. Thus the robustness test results for the 2027 basket results confirm the interactions between the markets of Argentina, Brazil, Mexico, Colombia and Venezuela with respect

Table 8
Robustness tests on illiquidity.

	Whole sample		Pre-Argentine crisis		Post-Argentine crisis	
	LR1	LR2	LR1	LR2	LR1	LR2
Panel A: Shorter maturity group (Argentine crisis window)						
2007 maturity basket						
ar – co	5.394	0.016	0.146	1.42	**26.634***	**3.964**
ar – mx	3.73	0.584	**2.326**	**6.982***	6.81*	–21.43
ar – vn	**7.352***	**0.700**	**6.992***	**0.282**	–8.874	–8.566
co – mx	**2.532**	**48.512***	**4.9036**	**26.215***	**3.4182**	**7.7576***
co – vn	28.528*	12.714**	7.12*	8.684*	41.628*	12.91*
mx – vn	**46.504***	**2.442**	**29.992***	**2.068**	25.980*	24.641*
2008 maturity basket						
ar – br	**5.808**	**10.986***	–		5.764	1.768
ar – co	3.620	3.042	5.746	0.096	**11.698***	**5.634**
ar – mx	**3.908**	**7.086***	0.130	0.024	**10.964***	**3.324**
br – co	5.760	1.532	3.382	0.972	–	
br – mx	**3.752**	**6.670***	**5.780**	**8.159***	–	
co – mx	**4.032**	**33.176***	**7.638***	**2.034**	8.668*	20.386*
2009 maturity basket						
ar – br	**6.862***	**4.688**	5.860	4.552	0.120	0.550
ar – co	**10.382****	**0.018**	1.324	2.082	1.136	1.514
ar – mx	2.066	3.340	1.284	2.210	0.874	0.886
br – co	1.814	0.866	2.496	4.796	**30.468***	**0.362**
br – mx	**7.328***	**3.908**	–		**23.764***	**1.898**
co – mx	**0.830**	**69.448***	22.693*	39.102*	11.907*	9.106*
Panel B: Longer maturity group (Argentine crisis window)						
2020 maturity basket						
ar – br	0.640	5.924	–		7.094*	10.724*
ar – co	5.100	1.100	5.16	5.554	**25.426***	**1.812**
ar – mx	0.790	3.806	5.444	3.834	–	
ar – vn	**24.416***	**2.020**	**26.88***	**1.892**	1.792	0.870
br – co	2.440	0.868	**7.91***	**0.964**	–	
br – mx	3.896	2.930	3.0348	0.0526	10.582*	7.530*
br – vn	**6.018***	**0.414**	9.0452*	6.5292*	**14.670***	**1.082**
co – mx	**5.644**	**30.054***	–		**4.899**	**33.761***
co – vn	3.704	5.048	3.7826	3.838	**16.914***	**5.700**
me – vn	4.848	0.066	–		5.363	0.167
2027 maturity basket						
ar – br	**3.986**	**14.258***	**4.712**	**19.246***	1.040	1.700
ar – co	0.888	5.560	0.104	1.410	**2.282**	**7.852***
ar – mx	**0.432**	**8.282***	2.280	2.634	1.632	2.024
ar – vn	**9.722***	**2.268**	**8.090***	**0.090**	3.320	2.322
br – co	**22.196***	**3.812**	–		**18.242***	**3.574**
br – mx	4.786	3.358	–		4.570	2.616
br – vn	3.798	1.418	**0.486**	**22.426***	0.494	4.816
co – mx	6.570*	10.428*	14.958*	21.894*	**4.732**	**6.966***
co – vn	5.958	1.200	**2.160**	**6.002***	5.160	0.252
mx – vn	4.182	0.554	0.698	3.958	1.258	0.946

(continued on next page)

Table 8
Continued.

Panel C: Global financial crisis window (GFC)						
	Whole sample		Pre -GFC		Post -GFC	
2020 maturity basket						
ar – br	–		–		–	
ar – co	32.654*	529.562*	–		–	
ar – mx	–		–		–	
ar – vn	–		1.372	0.902	–	
br – co	60.196*	39.534*	26.677*	20.994*	0.237	1.0642
br – mx	**5.450**	**20.312***	–		**11.663***	**2.5534**
br – vn	7.384*	20.192*	29.9606*	9.4626*	15.142*	12.484*
co – mx	**5.312**	**23.096***	–		37.168*	19.384*
co – vn	9.622*	25.870*	13.367*	10.852*	38.66*	11.39*
mx – vn	8.616*	36.808*	8.8238*	21.4178*	**36.75***	**3.622**
2027 maturity basket						
ar – br	–		**17.838***	**1.902**	–	
ar – co	72.834*	689.022*	10.966**	26.478*	–	
ar – mx	–		**5.138**	**19.234***	–	
ar – vn	–		10.04**	9.32**	–	
br – co	20.714*	14.774*	–		5.716	1.118
br – mx	15.350*	9.262*	11.7324**	18.3848*	**0.322**	**56.62***
br – vn	15.964*	44.288*	**14.586***	**4.768**	**5.216**	**38.334***
co – mx	**12.178***	**2.890**	–		5.496	5.088
co – vn	6.350*	28.162*	**5.98**	**6.346***	**0.578**	**7.302***
mx – vn	9.462**	34.998*	**18.500***	**2.524**	**0.956**	**68.926***

This table reports the robustness test verifying the role of illiquidity contributing to volatility transmission reported in Tables 3–5. We cover both the shorter maturity group (Panel A) and the longer maturity group (Panel B) with respect to the Argentine crisis window. We report the report the robustness test on the results reported in Table 5 in Panel C. with respect to the Global financial crisis window. The names reported in column 1 as Argentina [ar], Brazil [br], Colombia [co], Mexico [mx], Venezuela [vn] represent the sovereign bonds belonging to the five countries covered in this study. Columns 2, 3 and 4 report the likelihood ratio test results for the whole sample, pre-Argentine crisis and post-Argentine crisis window (Panels A and B) while Panel C reports the results pertaining to the Global Financial Crisis. The likelihood ratio tests (LR1 and LR2) reported in columns 2, 3 and 4 represent test statistic generated by comparing the log likelihood value of the restricted models by (imposing restriction 1 and restriction 2) with the unrestricted model. The 5% Chi-Square distribution critical value for with $df = 2$ is 5.991 for the nested testing on cross market dynamics. The sign "–" indicates convergence failures or unstable log likelihood values. Figures in bold indicate the existence of unidirectional volatility transmission.

to the direction and the nature of volatility interactions, with the exception being the Argentina–Brazil link during the pre-Argentine crisis. The reversal of volatility transmission between Columbia and Venezuela during the post crisis is also not confirmed by the robustness test.

5.8.2. Robustness test on GFC sample

An examination of the test results reported in Panel C of Table 8 on the robustness of the GFC results (reported in Table 5) demonstrate a high level of consistency with respect to the 2027 maturity basket. Many of the unidirectional results reported in the 2020 basket now show bi-directional volatility interaction. In addition, two of the unidirectional results for the pre-Argentine window could not be verified as there were convergence failures. As reported in Table 8, there are 21 bi-directional volatility interactions and 14 unidirectional transmissions evident in the robustness test. Nine of these unidirectional transmissions match the results reported in Table 5, while five new transmission channels are present when using the mid quote as the basis for estimation.

Examining the 2020 maturity basket in Panel C of Table 8 confirms the unidirectional dominance of Mexican market volatility to Brazil and Colombia, but the Mexican influence on Argentine market could not be verified due to convergence failures. This pattern is more evident in the whole sample analysis but could not be verified due to convergence failure during the pre-GFC window as shown in Panel C of Table 8. The robustness test also confirms the bidirectional spillover Brazil, Colombia and Venezuela. The unidirectional spillover between Mexico and Venezuela experiences a change in direction during the post-GFC window with Mexican volatility spilling over to Venezuela (bidirectional spillover turning unidirectional) Brazilian volatility spilling to Mexico is confirmed during the post-GFC window. Observing the robustness results for the 2027 maturity basket, confirms the evidence of the Brazilian volatility spilling to Venezuela. However, this result could not be repeated with respect to Colombia during the pre-GFC window, due to convergence failure. The evidence of Venezuelan volatility spilling to Brazil, Colombia and even Mexico during the post-GFC window is confirmed by the robustness test. Overall, the robustness test confirms the main story on the volatility dynamics relating to the endogenous crisis.

5.9. Robustness test on the timing of the default date

The purpose of this robustness test is to determine the appropriateness of using the official default date of December 23, 2001 as the basis for the default by Argentina. Recall that there is evidence of increasing default risk in the period prior to actual default due to the deterioration in both sovereign risk and debt service as evidenced in Fig. 1a and b. Thus, as a robustness check we test the implications of utilizing an earlier date by setting the start date of the pre-Argentine crisis to June 15, 2001. This date was when Argentina voluntarily restructured its debt by exchanging short bonds with the issuance of higher yielding long bonds. The following day, the various rating agencies revised down Argentina's credit rating.

Appendix A reports the sub-sample results for this robustness test for the whole sample and the pre and-post Argentine crisis with equal windows assuming the breakpoint corresponding with the Argentine default was the earlier date of June 15, 2001. Note that the earlier date places limitations on the number of observations covered for the analysis for the pre and-post Argentine windows across all baskets (a reduction of 270 observations for the 2007, 2008 and 2027 baskets and results in a decline from 713 observations to 578 observations for each of the pre and post crisis windows). The reduction in observations also has greater effect on the 2009 and 2020 baskets as these baskets start only from 18 October 1999 and 23 February 2000 respectively – a decline in the sample size from 1140 observation for the 2009 basket to 871 observations for the whole sample; a decline in sample size from 956 observations to 686 observations for the whole sample.

Recall that the earlier results demonstrate that volatility transmission with respect to the shorter maturity group is dominated by transmission from Mexico. This is consistent with credit quality driven volatility transmission, although the volatility flow was not necessarily one way from the Mexican market to the other markets despite the nature of information sharing between all the bond markets in the presence of crisis. As the sample of analysis is moved further from the effect of the Argentine default, the credit effect should dominate other idiosyncratic factors. The longer maturity basket, however, was dominated by the Argentine volatility as per the original results reported in Table 4. Noticeably, Argentine volatility is exported to the neighboring markets during the pre-Argentine crisis while the pattern reverses during the post Argentine crisis window. The bidirectional transmission for the 2020 basket appears to be a function of the reduced sample size as windows of equal length need to be maintained to retain consistency. The smaller sample size also resulted in some convergence failures. As reported in Narayan and Narayan (2007), the behaviour of volatility changes in different window sizes tends to have parallels in sovereign bonds in some pairs of markets.

Overall, while the transmission channels to some degree are sensitive to estimation problems associated with the 2020 basket, the main pattern of transmission channels sending credit quality implied shocks and idiosyncratic shocks, confirms the earlier findings from the pre-crisis window with respect to shorter and longer maturity groups. However, the results for the post crisis window differ due to the inclusion of the impact of later shocks (e.g. the actual default in December 2001 s).

6. Conclusions

The nature of the cross-market linkages between Latin American sovereign bonds issued in international markets that are bundled into groups based on maturity are investigated in this study. Our approach allows for identification of the direction and linkages between these various groups of bonds, which also differ based on credit quality. The sample includes only U.S. dollar denominated sovereign bonds, which do not include a foreign exchange risk premium in the bond prices. The analysis uncovers significant time-varying transmission channels that exist across these markets in relation to the different maturity clusters. These transmission channels change in response to crisis and whether the shock originates within the region (an endogenous shock), or outside (an exogenous shock). The default by Argentina in December 2001 is considered an endogenous shock, while the GFC is considered an exogenous shock.

Shorter maturity groups and longer maturity groups behave in fundamentally different ways in terms of volatility transmission. In addition, from a portfolio management perspective we show that the optimal asset allocation weight for pairs of bonds, arising from the underlying volatility structures, differs during the pre and – post default windows. During the pre-default episode, shorter maturity bonds tend to receive signals from the countries with high credit quality. This is not the case with the longer maturity group, where volatility sharing is dominant between high credit risk countries (Argentina, Brazil and Venezuela). The behavior of the longer maturity group is consistent with a segmented market where there is little interaction with lower credit risk markets during the pre-crisis period. The formation of volatility transmission channels and the direction of volatility sharing in Latin America appear driven by default episodes in individual markets, with the subsequent transmission of such vulnerabilities to surrounding regional markets.

Our findings add to the existing understanding of the second-order linkages between sovereign bond issues, and provide further evidence on the more general volatility sharing of international bonds. We show that there is a common factor driving the dynamics across the markets in the Latin American region with the Brazilian market separating itself from the other markets. The exogenous analysis covering the GFC, reveals a general pattern of spillover from high-risk countries to low and medium risk countries, in addition to bidirectional dependencies. Our economic significance analysis, using in and out-of-sample forecasts, highlights the importance of identifying and devising portfolio strategies based upon the complex interactions between the second moments of sovereign bonds when held in portfolios. Our results also survive a number of robustness tests accounting for liquidity and the exact dating of the Argentine default. The presence of these transmission channels also provides insights into the nature of the intra-regional vulnerabilities embedded in the prices of emerging market international bonds.

Appendix A. Robustness test on dating the Argentine crisis point

This table reports the robustness test on the volatility dynamics for the shorter and longer maturity groups consisting of 2007, 2008, 2009, 2020 and 2027 baskets reported in Table 3 and 4 with respect to the dating of the Argentine crisis. The names reported in column 1 as Argentina [ar], Brazil [br], Colombia [co], Mexico [mx], Venezuela [vn] represent the sovereign bonds belonging to the five countries covered in this study. Columns 2, 3 and 4 report the likelihood ratio test results for the pre-Argentine crisis, post-Argentine crisis windows and the whole sample with the dating of the crisis being shifted from the official date of 23 December 2001 to 15 June 2001 as the first sign of Argentine default was visible with the announcement of a voluntary debt restructuring by exchanging short bonds with the issuance of long bonds carrying higher coupon rate. The likelihood ratio (LR1) tests in columns 2,3 and 4 represent test statistic generated by imposing restrictions on the cross market terms for the pre and-post Argentine crisis windows as a robustness test on dating the crisis point reported in Tables 3 and 4. LR test ratios have been marked in bold letters to highlight the existence of unidirectional volatility transmission channels. The 5% Chi-Square distribution critical value for with $df = 2$ is 5.991 for the nested testing on cross market dynamics. The sign "–" indicates convergence failures and unstable log likelihood values. Figures in bold indicate existence of unidirectional volatility transmission.

	Pre-Argentine crisis		Post-Argentine crisis		Whole sample	
	LR1	LR2	LR1	LR2	LR1	LR2
2007 maturity basket						
ar – co	**0.944**	**6.328***	0.228	0.458	0.716	0.122
ar – mx	**5.343**	**9.622***	2.146	3.11	0.516	2.252
ar – vn	1.942	3.686	4.636	0.042	**10.520***	**4.102**
co – mx	**0.587**	**12.195***	–		**4.1244**	**34.660***
co – vn	–		24.218*	9.006*	**4.7844**	**10.896***
mx – vn	–		20.310*	25.446*	**31.890***	**0.424**
2008 maturity basket						
ar – br	2.968	0.388	0.040	1.050	4.762	4.736
ar – co	**7.826***	**4.670**	0.488	1.820	–	
ar – mx	3.686	4.007	9.546**	11.324*	**5.042**	**8.736***
br – co	5.606	5.212	–		0.420	4.344
br – mx	–		–		3.978	4.616
co – mx	**8.006***	**1.257**	6.055	12.773*	29.574*	17.260*
2009 maturity basket						
ar – br	**4.757**	**47.321***	3.128	1.454	**11.834***	**5.25**
ar – co	0.293	3.524	5.380	2.266	**8.092***	**4.042**
ar – mx	–		–		0.820	0.236
br – co	7.701*	22.960*	**28.082***	**1.248**	0.482	1.334
br – mx	**1.405**	**11.987***	**–**		12.276*	12.276*
co – mx	**7.439***	**4.133**	**9.080***	**1.331**	–	
2020 maturity basket						
ar - br	92.293*	40.609*	0.304	1.116	**13.784***	**0.774**
ar - co	3.847	1.933	2.278	3.76	**2.412**	**6.592***
ar - mx	2.430	1.723	5.660	2.72	0.656	1.324
ar - vn	2.373	1.172	**10.470***	**5.604**	**1.448**	**22.074***
br - co	**7.948***	**2.059**			**3.130**	**25.212***
br - mx	–		68.026*	9.351*	**6.990***	**3.334**
br - vn	**4.385**	**7.870***	13.966*	12.025*	1.474	3.360
co - mx	–		–		**3.822**	**6.024***
co - vn	15.355*	31.106*	–		27.126*	6.294*
mx - vn	0.755	2.796	–		0.820	1.112
2027 maturity basket						
ar - br	4.368	3.43	0.106	0.472	1.888	2.194
ar - co	0.93	3.586	0.256	0.786	0.666	0.332
ar - mx	**6.136***	**0.574**	0.448	1.088	0.182	0.112
ar - vn	**6.036***	**3.842**	5.078	2.036	**0.758**	**12.388***
br - co	13.668*	8.376*	**24.394***	**0.710**	**0.66**	**11.99***
br - mx	–		**9.596***	**3.772**	0.762	5.782
br - vn	**0.836**	**21.018***	1.656	2.326	3.334	1.988
co - mx	14.172*	15.508*	0.866	0.28	**11.114***	**0.66**
co - vn	**5.736**	**8.360***	13.536*	16.362*	10.272*	12.672*
mx - vn	–		0.078	0.558	0.06	3.718

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