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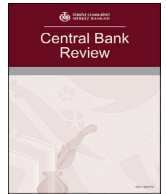
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Time varying determinants of bond flows to emerging markets[☆]



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ABSTRACT

This paper investigates the time varying nature of the determinants of bond flows with a focus on the global financial crisis period. We estimate a time varying regression model using Bayesian estimation methods, where the posterior distribution is approximated by Gibbs sampling algorithm. Our findings suggest that the interest rate differential is the most significant pull factor of portfolio bond flows, along with the inflation rate, while the growth rate does not play a significant role. Among the push factors, global liquidity is the most important driver of bond flows. It matters the most, when unconventional monetary easing policies were first announced; and its importance as a determinant of portfolio bond flows decreases over time, starting with the Eurozone crisis, and diminishes with the tapering talk. Global risk appetite and the risk perception towards the emerging countries also have relatively small and stable significant effects on bond flows.

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1. Introduction

Once the financial crisis hit the global economy in late 2008, capital flows to emerging market economies (EMEs) dropped sharply, as they witnessed huge outflows from both bond and equity markets. However, in the aftermath of the crisis, the expansionary policies pursued by advanced economies and ample global liquidity conditions once again drove investors towards riskier and higher yielding assets of emerging markets. Thus, because of their relatively stronger growth outlook and higher interest rates, coupled with rising risk appetite, EMEs witnessed a surge of capital flows in 2009 and 2010, mainly in the form of portfolio flows.

Given the past experience from the 1994 Mexican crisis and the 1997 Asian crisis (both of which were preceded by waves of

strong and volatile portfolio inflows often referred to as “hot money”), this latest wave of capital inflows to EMEs raised concerns over potential negative consequences on the recipient countries and once again highlighted the importance of designing appropriate policies, that are effective not only during surges but also during reversals, to ensure financial and macroeconomic stability. A good understanding of the determinants of these flows is surely a prerequisite for the design of such policies. Nonetheless, this task necessitates not only determining the factors that drive capital flows to EMEs, but also exploring how their impact on flows changes over time.

Ever since the seminal work of Calvo et al. (1993), determinants of capital flows are categorized under two main headings, namely, the pull factors and the push factors throughout the literature. The pull factors are associated with the country specific factors that attract capital flows. If pull factors are in effect to attract capital flows, then an appropriate design of policies in the recipient country would limit potential macro financial imbalances caused by these flows. On the other hand, push factors are associated with the external common conditions that drive flows. In such a case, the effectiveness of domestic macro policies to mitigate the potential adverse effects of the flows on the recipient country would be limited.

It is documented in the literature that the relative importance of the determinants of capital flows varies over time. However,

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there are not too many studies modelling the time varying nature of the determinants of capital flows. Fratzscher (2011) employs a factor model coupled with a dataset of high-frequency portfolio capital flows to 50 economies and shows that push factors were overall the main drivers of capital flows during the crisis, while pull factors were mainly dominant in explaining the dynamics of global capital flows in 2009 and 2010, particularly for the emerging economies. Lo Duca and Marco (2012) models the time varying nature of the drivers of portfolio equity flows by estimating a model with regression coefficients that endogenously vary over time, by means of a Kalman filter approach. The estimation results reveal that major changes in the importance of drivers of flows coincide with important market events/shocks, and that investors pay more attention to regional developments in emerging markets in periods when market tensions are elevated.

Looking at the literature on the spillover effects of Fed's unconventional monetary policies on capital flows to EMEs, both Fratzscher et al. (2013) and Chen et al. (2014) assert that the effect of Fed's asset purchase operations was more pronounced than conventional Fed policies. While the traditional signalling channel of monetary policy continued to play the leading role in transmitting shocks aiming to affect longer-term interest rates, larger spillovers stemmed from these unconventional policies in the post-crisis era.

This paper contributes to the literature on the determinants of capital flows by investigating the time varying nature of the determinants of bond flows, with specific attention to the global financial crisis period. The choice of bond flows as a dependent variable is for the following reasons: Firstly, while there are different measures of capital flows, we know that portfolio flows are the most affected form of capital flows during the crisis era. Second, emerging market portfolio flows can now be tracked from a new database that provides timely, high frequency data with portfolio choice breakdown for bond and equity markets. Third and more importantly, among the portfolio flows, we observe a structural change in bond flows through the examined period, while no alteration is evident in the course of equity flows. As to our knowledge, this is the first attempt to investigate the changes in the determinants of portfolio bond flows, with a focus on the global financial crisis era. For this purpose, we estimate a time varying regression model in a state space form, using Bayesian estimation methods, where the posterior distribution of the entire model is approximated by Gibbs sampling algorithm. It is documented in the literature that Bayesian estimation and Gibbs sampling algorithm works extremely well in estimations of state space models, especially in small samples where maximum likelihood can be computationally inefficient (Blake and Mumtaz, 2012).¹

The determinants of bond flows to EMEs are investigated for the 2005–2013 period, using monthly data. Our findings suggest that relative importance of drivers of bond flows changes over time and important dates like Eurozone debt crisis or Fed's tapering signal can be traced through the coefficients. Among the pull factors, the interest rate differential is found to be the most significant driver of portfolio bond flows, along with the inflation rate, while the growth rate does not play a significant role. Global liquidity emerges to be the most important push factor of bond flows, with most volatile coefficient. It matters the most, when

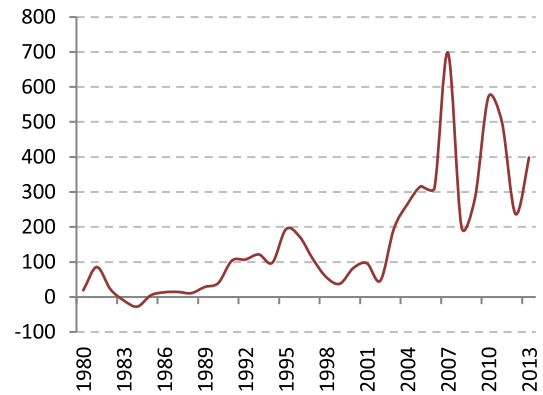


Fig. 1. Capital Flows To Emerging Markets (Net, private, billion US dollars).

unconventional monetary easing policies were first announced; and its importance as a determinant of portfolio bond flows decreases over time, starting with the Eurozone crisis, and diminishes with the tapering talk. Global risk appetite and the risk perception towards the emerging countries also have relatively small and stable significant effects on bond flows.

The paper is organized as follows: in Section 2 we provide a brief history of capital flows to EMEs; in Section 3 we introduce the model, the data and the methodology we use in the study; in Section 4 we present the main findings of the paper, and Section 5 concludes.

2. Capital flows from an historical perspective

Historically, emerging economies experienced three episodes of massive capital inflows (Fig. 1). The first episode started in 1990 and ended with the Asian crisis in 1997, which left many emerging economies with financial strains from a major capital flow downturn. In response, many EMEs have significantly improved their macroeconomic fundamentals, undergone structural reforms in the subsequent period and accordingly enhanced the composition of capital inflows through an improved debt structure, a larger share of flows in the form of foreign direct investment, and greater access to international debt markets (Suchanek and Vasishtha, 2010). As the global financial system went through a phase of greater integration, the EMEs improved on capital account openness and became more closely tied by increased trade and financial linkages with the rest of the world, which in turn increased fund flows; hence capital inflows to EMEs accelerated again in 2002. In this second wave of capital flows to EMEs, FDIs constituted around 80 per cent of total financial flows on average, portraying a healthier financial account composition (Fig. 2).

The third wave of capital flows to EMEs emerged in the aftermath of the 2008–2009 global financial crisis. When the crisis broke out in the third quarter of 2008, it not only drifted the world economies into prolonged recessions, but also caused emerging market capital flows to contract by an enormous proportion. In this period, EMEs witnessed sizeable net outflows from portfolio and other investments, while FDIs remained resilient. After the crisis, the expansionary monetary policies pursued by the advanced country central banks and the introduction of QE policies led to ample global liquidity conditions. The loss of confidence in advanced country assets in the post financial crisis period and the uncertainty about the speed of recovery in the developed world increased the interest on

¹ Chapter 3 of Blake and Mumtaz (2012) shortly discusses why classical approaches to state space modelling can be computationally inefficient and elaborates on the advantages of employing Gibbs sampling algorithm for state space models.

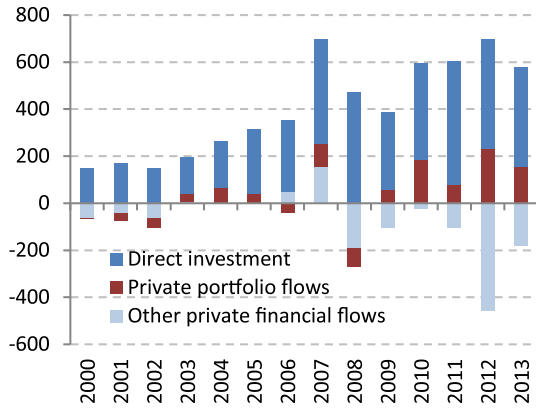
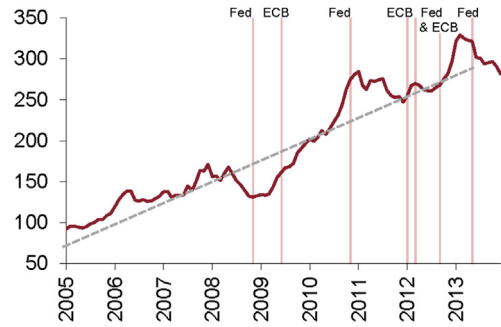
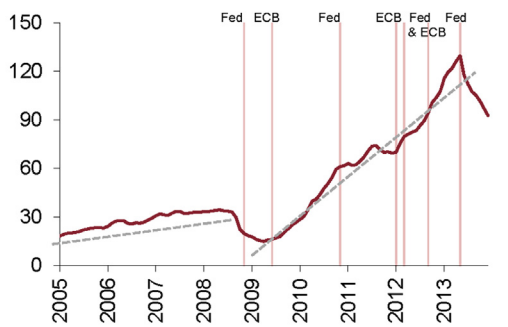


Fig. 2. Breakdown of Private Financial Flows To EMEs (Net, billion US dollars).



* Adjusted for exchange rates and prices. Vertical lines show the dates of QE and long term asset purchase programs of Fed and ECB, respectively. Source:EPFR.

Fig. 4. Equity Flows to EMEs* (Stock, billion USD).



* Adjusted for exchange rates and prices. Vertical lines show the dates of QE and long term asset purchase programs of Fed and ECB, respectively. Source:EPFR.

Fig. 3. Bond Flows to EMEs* (Stock, billion USD).

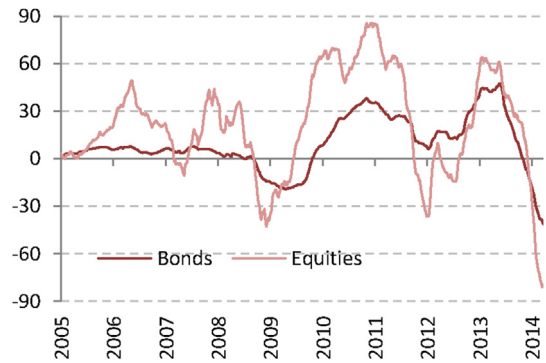


Fig. 5. The Evolution of Portfolio Flows to EMEs (52 week cumulative, billion US dollars).

emerging country assets.² Owing to better growth prospects than their advanced counterparts and higher yielding assets, along with rising risk appetite, EMEs attracted a third wave of capital inflows. During this third wave, the share of portfolio inflows in overall capital flows considerably increased. More precisely, the rising interest rate differential between advanced and emerging countries, as well as the preference of short-term assets due to increasing uncertainty, have led international investors to become more inclined towards emerging market bond funds compared to equity funds, thereby leading to a structural break in the former (Fig. 3, Fig. 4). According to Barlas and Kaya (2013), the fact that emerging markets had enough room to decrease interest rates to foster domestic economic activity in the face of worsening global growth outlook and expectations that monetary policies could further be eased, have contributed to the increase in the return prospects on investments on EME bonds. Moreover, the loss of confidence in advanced country bonds which were once known as safe-haven assets and the relatively underinvestment in emerging country bonds in the pre-crisis period were the other factors that led to stronger capital flows to EMEs bond funds during this period.

² Despite highly stimulatory monetary policies, the recovery in advanced countries remained sluggish due to deleveraging of both the household, the banking and the private sector balance sheets, with collapses in consumption rates and hardly operative credit channels, especially in the Eurozone.

In addition to strength, portfolio flows in the post-crisis period were also characterized by being markedly more volatile. Higher frequency data on portfolio flows reveals the extent to which the volatility of different asset classes has risen since 2009 (Fig. 5). One apparent reason for the increasing volatility is that portfolio investments steadily became more sensitive to shifting conditions in the global financial conditions and the global business cycle, rather than country specific factors (IMF, 2014).

3. The model, data and methodology

3.1. Time varying parameter model and the data

In order to find out whether the determinants of bond flows to emerging markets have witnessed a structural change following the global financial crisis, we estimate the following time varying parameter equation for bond flows:

$$BF_t = \alpha_t Ph_t + \beta_t Pl_t + \varepsilon_t. \tag{1}$$

where BF_t is bond flows at time t . The determinants of capital flows are categorized as push and pull factors, which is represented by Ph_t and Pl_t , respectively. Throughout the literature, global liquidity and investors' risk appetite are considered as important push factors of capital flows. On the other hand, pull factors of capital flows mostly cover the country specific variables, such as the economic growth rate, the interest rate and the inflation rate.

The concept of global liquidity and how it is to be measured have recently become hotly debated policy topics (BIS, 2011, ECB, 2011). While the term “global liquidity” continues to be used in a variety of ways, the common element in all definitions is a reference to the ease of financing. To our common knowledge, in the aftermath of the recent global financial crisis, the QE policies of advanced economies have been one of the main sources of excess global liquidity. In this study, we stick to a rather traditional definition of global liquidity and measure the global liquidity by the sum of the total assets of the Federal Reserve Bank (Fed) and the European Central Bank’s (ECB) balance sheets (measured in US dollars), which were the two central banks that resorted to QE most heavily.³ This is firstly because we are more interested in the effect of advanced country monetary policies on capital flows and secondly because cross border flows are to some extent integrated in the private component of global liquidity definition. This variable is used in logarithms.

As for the other push factors, we use the monthly difference of the VIX index in order to track the changes in the global risk appetite, while the Emerging Markets Bond Index (EMBI) in levels serves as a measure to capture the risk perception towards the emerging markets.

On the other hand, pull factors of capital flows mostly cover the country specific variables. In this study, we capture the country specific variables by the annual growth rate of industrial production, the CPI based annual inflation rate and the policy rate differential between the emerging markets and the US. All of the pull factors are GDP weighted aggregations for 23 emerging economies, selected to represent a wide range of countries from different geographies of emerging Asia, Europe, Latin America and Middle East and Africa.⁴

The dataset consists of monthly data from 2005:M1 to 2013:M12. Bond flows data is compiled from Emerging Portfolio Fund Research (EPFR) database and is adjusted for price and exchange rates. It is an aggregated measure of portfolio bond flows to all emerging markets. The most important advantage of using this database is that it provides high frequency and timely data dating back from 2005. Thus, it is not only a better alternative to IMF’s Balance of Payments Statistics and Institute of International Finance’s (IIF) quarterly EMEs capital flows reports that are published with considerable time lags and with lower frequency; but also to IIF’s Portfolio Flows Tracker, which provides more timely monthly data, but only starting from 2010. The EPFR database contains daily, weekly and monthly flows by more than 8000 bond funds; and is being widely used by credible organizations such as the IMF and the ECB. It provides a fairly representative sample in capturing the market capitalization in bonds for most countries.⁵ Lo Duca and Marco (2012), Miao and Pant (2012) and Fratzscher (2011) are some of the other studies that

have lately used this database to analyse capital flows. Graphical representations of variables used in the analysis are provided in Appendix 1.

3.2. State space representation of the model

The above time varying parameter equation (1) can be put in the following state-space form:

$$Y_t = \theta_t X_t + \varepsilon_t, \quad \varepsilon_t \sim \mathcal{N}(0, R) \quad (2)$$

$$\theta_t = \theta_{t-1} + v_t, \quad v_t \sim \mathcal{N}(0, Q) \quad (3)$$

where $\theta_t = \{\alpha_t, \beta_t\}$.

In equation (2), Y_t represents an observable dependent variable, which corresponds to bond flows to emerging economies; BF_t in the model. X_t is the vector of explanatory variables that capture the push and pull factors; Ph_t and Pl_t in the model. θ_t is the vector of corresponding coefficients and, as shown in equation (3), it evolves as an AR(1) with a unit root coefficient.

3.3. Estimation

The time-varying parameter model above is estimated via Bayesian methods using Kalman filtering and the posterior distribution of the entire model is approximated by Gibbs sampling algorithm. Bayesian methods can obtain joint posterior distributions of parameters and unobserved states which are mixtures (multiplications) of the prior information and the “current information” that is, the data. However, in many cases, these joint distributions are difficult or impossible to characterize analytically, but distributions of parameters and unobserved states conditional on each other are easier to characterize or simulate. Hence, the posterior distribution of the entire model is approximated by Gibbs sampling algorithm, which iteratively draws parameters and unobserved states conditional on each other, from joint distributions. In our model, the unobserved states are the time-varying coefficients (θ_t) and the parameters are the variance of the time varying (observation) equation (R) and the variance of the innovations in coefficients (Q).

In order to have posterior results for the state space form, we run the Gibbs sampler for 12,000 replications, with 10,000 burn-in replications discarded and 2000 replications retained. All priors and initial values to initiate the Gibbs sampling algorithm are set using pre-sample data information from 2004:M3 to 2005:M10. First, we estimate OLS regressions for the pre-sample data and use the point estimate of coefficients as the prior mean for θ_0 and its asymptotic variance \bar{P} as the prior variance. Second, we use an inverse-Wishart distribution as the prior for Q with degree of freedom $T_0=20$ and prior $Q_0 = T_0 * \bar{P} * 3.5e^{-03}$. Third, the prior for the variance of the time varying regression equation is inverse gamma with the scale parameter equal to 0.1. Appendix 2 provides, in detail, the steps of the Gibbs sampling algorithm.

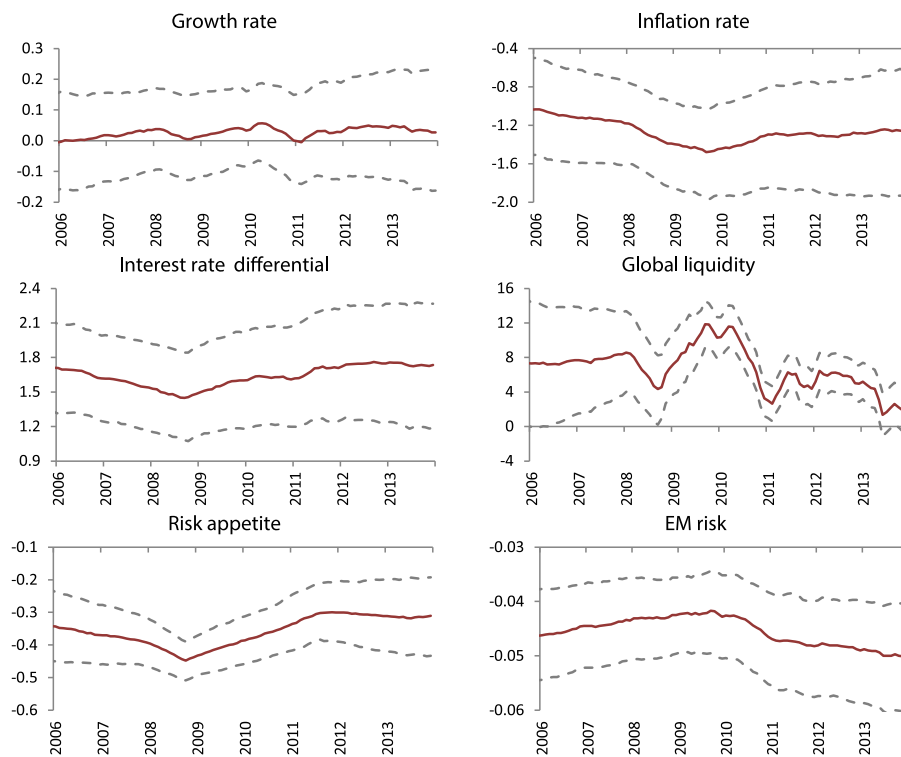
4. Results

Fig. 6 displays the obtained time varying coefficients from the model. The fluctuations in θ s, though small in some cases, provide evidence for the appropriateness of estimating a time varying regression model to explain the portfolio bond flows to emerging economies. The changes in the relative importance of the

³ The Bank of England and the Bank of Japan also introduced similar quantitative easing programs during the period under investigation, the international spillover effects of which are less pronounced.

⁴ Countries included in the analysis are: Brazil, Mexico, Colombia, Peru, Chile, Venezuela, China, Indonesia, Malaysia, Philippines, Thailand, South Korea, India, Taiwan, Russia, Turkey, Poland, Hungary, Kazakhstan, South Africa, Israel, Lebanon and Egypt. As of 2012, these countries constitute the 95 percent of bond flows to emerging economies.

⁵ Although there is not an official figure regarding the representative power of the database on a global scale, Fratzscher (2011) argues that its coverage ratio of assets varies between 5 and 20 per cent for the countries. For instance, for Turkey, we see that the coverage of bond holdings in Turkey of foreign residents is around 10.8 per cent between 2005 and 2008; and its coverage ratio increased to 17.9 per cent in the aftermath of the global financial crisis.



Note: The figures report the time varying coefficients (solid line) for each of the explanatory variables included in the model described in section 3.1 and the confidence bands for the time varying coefficients (dotted lines). We displayed the 68 per cent confidence interval bands in the figure, as it is the common practice in Bayesian analysis. The estimates with 90 per cent bands produce similar results and are available from the authors upon request.

Fig. 6. Time varying coefficients of the determinants of portfolio bond flows.

determinants of portfolio flows both on the onset of the global financial crisis and in its aftermath can clearly be detected through the estimated θ s. Moreover, the estimation results clearly mark some important dates of events or shocks (such as the Eurozone debt crisis or the Fed's tapering signal) that have occurred during the period under review, depicted through the turning points in time varying coefficients.

The growth rate does not seem to play a significant role in affecting portfolio bond flows during the examined period. The estimated coefficient for growth carries a positive sign, which is in line with the theory, but its confidence bands comprise the x-axis most of the time, implying statistical insignificance. While this would be a surprising finding if we had been examining data starting from the 1990s, for the period under investigation one can argue that the impact of growth rate on capital flows has gradually diminished due to increasing globalization and greater financial integration. During the 1990s, while emerging markets were going through a phase of financial liberalization, international investors were in search of high yielding investment opportunities. The growth potential of emerging markets was one of the main factors that nourished investor appetite at the time: the stronger the growth outlook was, the more likely the higher expected returns were. Once investors started to head funds to emerging markets with sound fundamentals, emerging markets gained greater access to international debt markets. As Suchanek and Vasishtha (2010) suggest, markets for domestic fixed-income securities in these countries, which were relatively underdeveloped until the late

1990s, later became a major source of financing and until 2007 benign global financial conditions allowed them to assure longer-term funding and to improve their debt structures. The establishment of strong financial linkages may have lessened the effect of growth rate as a determinant of bond flows in this context.⁶

The inflation rate has a significant negative effect on portfolio bond flows. High inflation rates not only worsen macro fundamentals in emerging markets, but also – if PPP holds – may decrease the real return of international investors from investments in local currency, discouraging portfolio flows. The effect of inflation rate on bond flows is found to be large and stable until late 2008 and gets even larger after the global financial crisis, until the breakout of the Eurozone debt crisis in early 2010. The results show that its effect slowly decreases until 2011, and remains at a stable level thereafter, as there is some relief from the debt crisis in the Euro area following the introduction of temporary crisis resolution mechanisms (such as the European Financial Stability Facility).

The interest rate differential is the most significant pull factor of portfolio bond flows during the examined period, which is in line with our expectations. Although we observe a decline in the coefficient prior to the global financial crisis, it gradually turns

⁶ Two other possible explanations may also apply here: first, growth may be an important factor in the long run, and second, its effects may be more pronounced if the model was run using equity flows or FDIs.

back to its pre-crisis levels in the aftermath of the crisis, as the interest rate sensitivity lost during the crisis regains momentum. The coefficient reaches to a steady level after 2011 with the partial cooling down of the Euro area crisis. Yet, we can interpret that the effect of the interest rate differential on bond flows has been strong and stable as suggested in the literature. Thus, our findings confirm that, in an environment of deteriorating global economic outlook, increased uncertainty and ample liquidity conditions; relatively higher yields of fixed-income low maturity emerging market assets have significantly contributed to the surge in capital flows to emerging market bond funds in the post-crisis period.

Among the push factors, global liquidity emerges as the determinant with most volatile coefficient. While global liquidity has played a solid and stable role in determination of portfolio bond flows before the global financial crisis, we can see a moderate rise in its coefficient between 2007 and late 2008. Our results indicate that the effect of global liquidity declines considerably during the global crisis period, due to panic, plummeted confidence and increased uncertainty. However, with the introduction of QE programs by major advanced country central banks, the effect of global liquidity on bond flows becomes more significant and the magnitude of its coefficient reaches far beyond its pre-crisis levels. This finding validates that the surge in capital flows to EMEs in the aftermath of the global crisis was the spillover effect of the abundant global liquidity, resulting from the unconventional expansionary policies of the advanced world. The breakout of the Eurozone debt crisis in early 2010 lessens the importance of global liquidity conditions sharply. Given the high uncertainty and low investor confidence of the times in which the probability of double-dip recessions were discussed, the coefficient falls to a level even lower than the trough of the global financial crisis. Afterwards, the effectiveness of global liquidity conditions of portfolio bond flows fluctuates, marking some dates like the Eurozone banking crisis in 2011 on the way, up until 2013. In May 2013, we observe another sharp drop in the coefficient, corresponding to the “tapering talk”, which signalled the possibility of the Fed to taper its large-scale asset purchases and to gradually end its quantitative easing program, which in turn triggered a massive capital outflow from EMEs. However, we should mention that after this date, the effect of global liquidity on portfolio bond flows becomes insignificant. In short, our findings suggest that global liquidity mattered the most, when QE was first announced, and its importance as a determinant of portfolio bond flows seems to decrease over time, starting with the Eurozone crisis, and diminishing with the tapering talk.

As for the risk appetite, the change in the VIX index has a significant and negative effect on bond flows. Both the significance and the magnitude of changes in the investors' risk perception reach to a peak during the crisis period, making it the most important driver of bond flows between 2008 and 2009. The magnitude of its coefficient slowly decreases until 2012, coinciding with the ECB's second long term refinancing operations. Following this date, the effect of changes in the risk appetite on bond flows lands at a level lower than its pre-crisis levels and remains relatively steady thereafter, while a muted effect of the tapering talk can still be traced in the coefficient.

The importance of risk perception towards emerging countries as a determinant of bond flows is found to be fairly stable for the whole period under investigation. It has a small but highly significant negative coefficient, which slowly gets looser until 2010, and rises at a gentle pace afterwards.

5. Conclusion

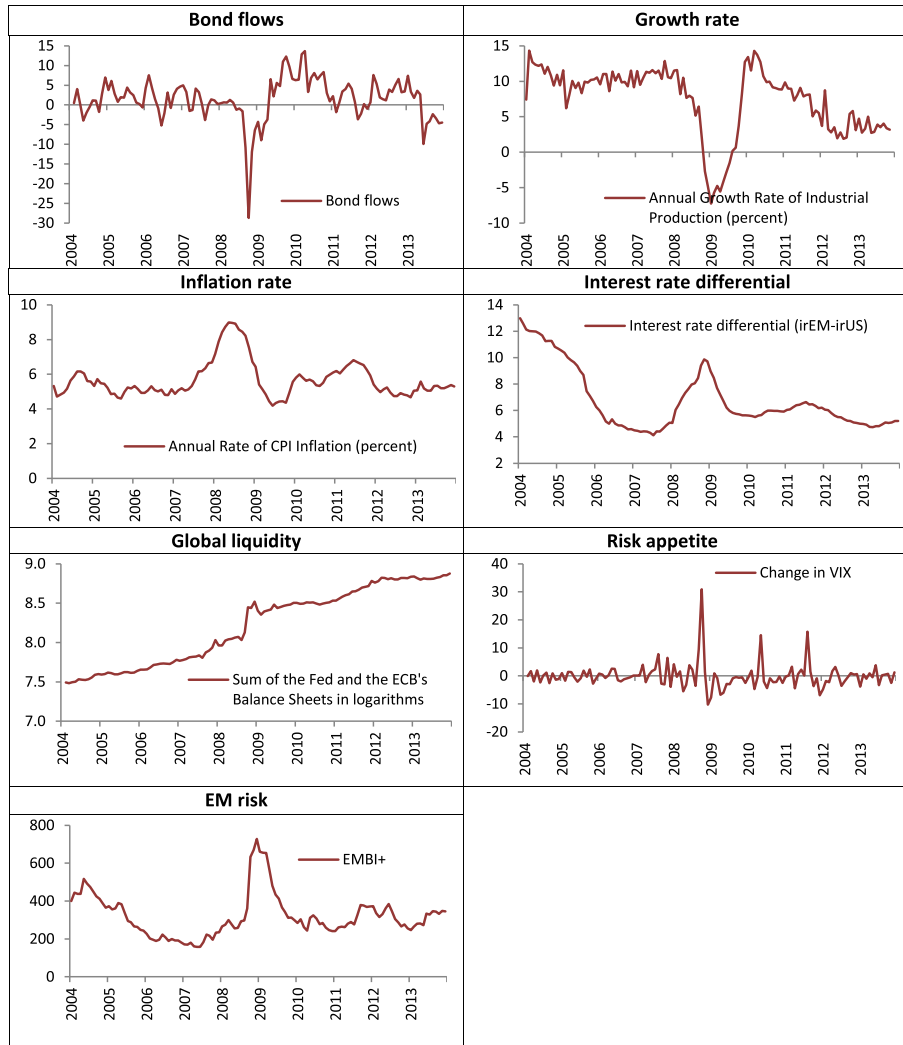
Looking at the importance of the determinants of bond flows to EMEs in a time-varying framework, we find that among the push factors, global liquidity displays the most volatile coefficient, clearly marking several important events, during and after the global financial crisis period. With the onset of the QE programs, the coefficient reaches far beyond its pre-crisis levels in magnitude and its significance as a determinant of bond flows increases. This is in line with our expectations and with the more recent research carried out on the evidence of the spillover effects of the unconventional expansionary policies on capital flows to EMEs in the aftermath of the global financial crisis. While the global liquidity mattered the most when QE programs were first put into effect; it seems to diminish thereafter. With the breakout of the Eurozone crisis, as the uncertainty regarding the global economy increased drastically, the importance of global liquidity as a determinant of portfolio bond flows starts to decrease over time. It diminishes even more with the tapering talk, which was the first signal of a gradual ending of the abundant global liquidity era.

Designing an appropriate monetary policy to cope with strong and volatile capital flows to ensure financial and macroeconomic stability is a hard-enough task for emerging country central banks. Policy making in an environment, in which the parameters are beyond control, is even harder. The spillover effects of advanced country monetary policies, not only gave rise to the abundant global liquidity to emerge as a critical driver of bond flows during the examined period, but also gave rise to introduction of new macro-prudential policy tools in countries such as Brazil and Turkey, to counter the adverse effects of increasing capital inflows in the post-Lehman period. Even the IMF changed its long defended argument against capital controls and gave green light to measures for managing capital flows at the time. On the other hand, the capital flow reversal in emerging markets triggered by the Fed's tapering signal in May 2013 implies that global liquidity continues to play the major part in determination of capital flows to emerging markets; along with the expected interest rate rise in the US which will alter the interest rate differential. Hence, the tapering talk also marks the start of another challenging period for emerging country central banks.

All in all, the effectiveness of the capital management measures taken by the emerging country central banks in the aftermath of the global financial crisis should be evaluated taking into account the strength of the exogenous factors. In other words, given the strong impact of external determinants on capital flows, the efficacy of domestic responses could only be limited, and hence their success could be to a certain extent. As [Eichengreen and Gupta \(2014\)](#) underlines, better domestic fundamentals may not always provide the insulation in recipient countries.

Appendix 1

Graphical representations of variables used in the analysis



Appendix 2

Gibbs sampling algorithm of bayesian estimation for a time varying parameter model

This appendix elaborates on the Gibbs sampling algorithm, which is utilized to obtain the posterior distribution of the time varying parameter model. All codes are written in Matlab. The steps of the algorithm are outlined below:

Step 1. Initialization.

Set priors for mean and variance of θ_0 . Set priors for R and Q : R_0 and Q_0 .

Step 2. Sample θ conditional on R and Q using the Carter and Kohn algorithm.

The model is a linear and Gaussian state space model. Assuming that the prior distribution for θ_0 , represented as $p(\theta_0)$, is Gaussian;

the conditional posterior distribution of $p(\theta_t|y_t,R,Q)$ is also Gaussian. A forward recursion using the Kalman filter provides expressions for posterior means and the covariance matrix.

$$p\left(\frac{\theta_t}{y_t}, R, Q\right) = N\left(\theta_t, P_t\right),$$

$$P_{t/t-1} = P_{t-1/t-1} + Q,$$

$$K_t = P_{t/t-1}X_t\left(X_t'P_{t/t-1}X_t + R\right)^{-1},$$

$$\theta_{t/t} = \theta_{t/t-1} + K_t\left(y_t - X_t'\theta_{t/t-1}\right),$$

$$P_{t/t} = P_{t/t-1} - K_tX_t'P_{t/t-1},$$

Starting from $\theta_{T/T}$ and $P_{T/T}$, we can run the Kalman filter backward to characterize posterior distributions of $p(\theta^T/y^T, R, Q)$.

$$p(\theta_t/\theta_{t+1}, y^T, R, Q) = N(\theta_{t/t+1}, P_{t/t+1}),$$

$$\theta_{t/t+1} = \theta_{t/t} + P_{t/t}(P_{t/t} + Q)^{-1}(\theta_{t+1} - \theta_{t/t}),$$

$$P_{t/t+1} = P_{t/t} - P_{t/t}(P_{t/t} + Q)^{-1}P_{t/t}.$$

We can generate a random trajectory for T using the backward recursion starting with a draw of θ^T from $\mathcal{N}(\theta_{T/T}, P_{T/T})$ as suggested by Carter and Kohn (1994).

Step 3. Sample Q from the inverse Wishart distribution.

Conditional on a realization for θ^T , innovations in coefficients, v_t , are observable. Assuming the inverse-Wishart for Q with prior Q_0 and degree of freedom T_0 , the posterior is also inverse-Wishart.

$$p(Q/y^T, \theta^T) = IW(Q_1^{-1}, T_1),$$

$$Q_1 = Q_0 + \sum_{t=1}^T v_t v_t', \quad T_1 = T_0 + T.$$

Step 4. Sample R from the inverse Gamma distribution.

Conditional on a realization for θ^T , residuals of the time-varying regression are observable. Assuming the inverse-Gamma for R with prior R_0 and degree of freedom T_0 , the posterior is also inverse-Gamma.

$$p(R/y^T, \theta^T) = IG(T_1/2, 1/(2R_1)),$$

$$1/R_1 = (1/R_0 + \sum_{t=1}^T \varepsilon_t \varepsilon_t')/2, \quad T_1 = (T_0 + T)/2.$$

Step 5. Posterior Inference.

Go back to step 1 and generate new draws of θ^T , R , and Q . Repeat this M_0+M_1 times and discard the initial M_0 draws. Use the remaining M_1 draws for posterior inference.

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