Precautionary Liquidity Shocks, Excess Reserves and Business Cycles

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Precautionary Liquidity Shocks, Excess Reserves and Business Cycles[*]

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Abstract

This paper identifies a precautionary banking liquidity shock via a set of sign, zero and forecast variance restrictions imposed. The shock proxies the reluctance of the banking sector to "lend" to the real economy induced by an exogenous change in financial intermediaries' preference for "high" liquid assets. The identified shock has sizeable and state (volatility) dependent effects on the real economy. To understand the transmission of the shock, we develop a DSGE model of financial intermediation with credit and liquidity frictions. The precautionary liquidity shock is shown to work through two channels: it increases the level of reserves and the deposit rate. The former is a balance sheet effect, which reduces the loan-to-deposit ratio. The higher deposit rate affects the intertemporal decisions of households and the cost of borrowing to firms. The overall effect is a downward co-movement in output, consumption, investment and prices, which is amplified the higher are the long-run risk in the economy and the responsiveness of banks to potential risk.

JEL Classification Numbers: C10, C32, E30, E43; E51, G21

Keywords: SVAR; Sign and Zero Restrictions; DSGE; Precautionary Liquidity Shock; Excess Reserves; Deposit Rate; Risk, Financial Intermediation.

1 Introduction

The financial crisis of $2007 - 2008$ revealed our lack of understanding of the role played by financial intermediaries for the real economy and how they can propagate macroeconomic and financial shocks. There is sufficient evidence to suggest that during that period banks appeared more willing to accumulate reserves rather than lend. The large-scale quantitative easing, or the lack of confidence in the housing market, could not fully account for the persistent accumulation of excess reserves, or the increased spreads offered on safe liquid assets by banks during that period. This is also evident from the loan-to-deposit ratio that was falling for all loans, including Commercial & Industrial loans, for most of this period, (see Figures 1 and 2). Indeed, the fall in loans was not just confined in the mortgage credit market, that had just been shocked with the subprime mortgage crisis, but was also evident in the production sector, indicating the overall and sudden precautionary mood of lending banks during that period, that resulted in a dramatic fall of loans even in relation to deposits.

Figure 1: Commercial & Industrial Loans
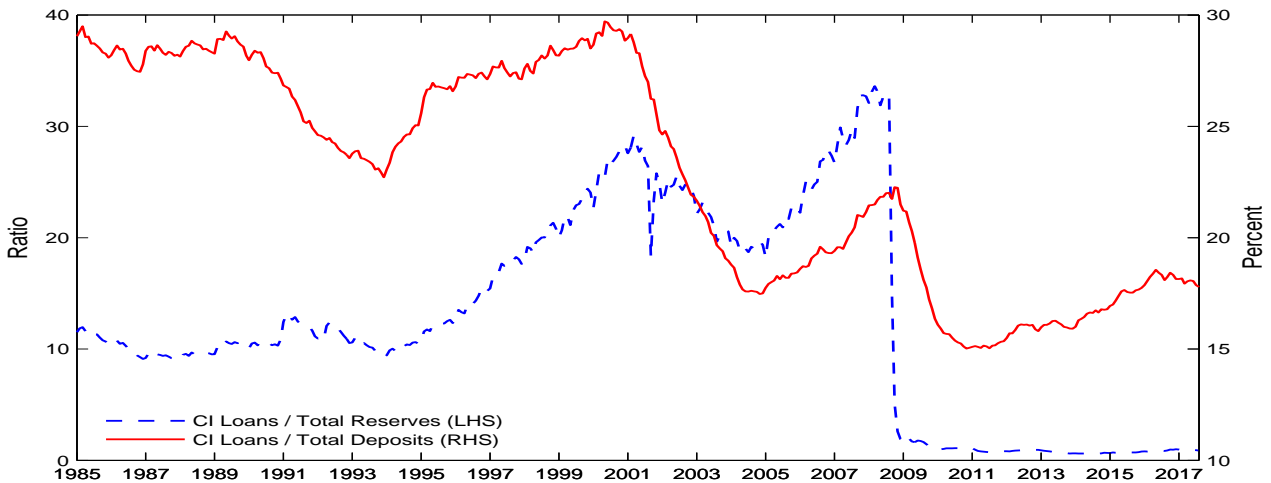
Figure 2: Total Loans
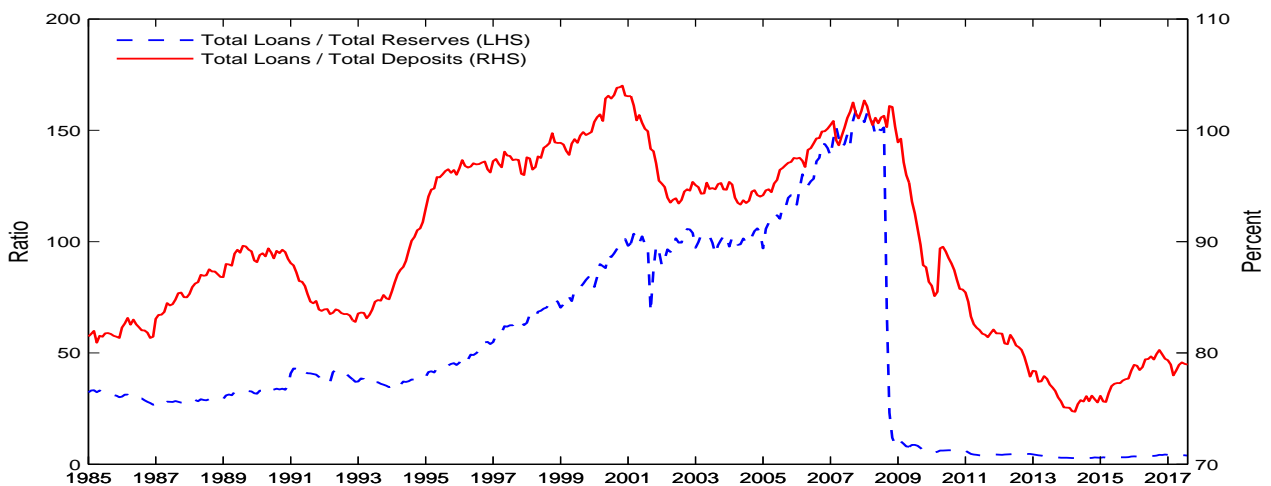
This paper contributes to this realm by trying to understand what happens to the economy when financial intermediaries suddenly become reluctant to make loans, as they become concerned about their liquidity position and start building up reserves so as to hedge against future liquidity shortages. The objectives of the paper are: i) to measure the adverse effect of financial intermediaries' precautionary liquidity actions on the real economy and ii) to understand how these actions are transmitted to the

economy. The first part of the paper is dedicated to assess the contribution of the banks' liquidity precautionary channel to the Great Recession and weak recovery in the US economy. This is the first study that provides exact estimates about the contribution of this channel. A big part of this task is the development of a novel identification scheme that allows to recover exogenous variations to bankers' preferences about liquidity (reserves and deposits, as opposed to loans). The action by financial intermediaries to hedge against future liquidity shortages is shown to reduce US GDP $2pps$ below its potential level, (relative to $2007Q4$) and, more importantly, this effect is active until the end of our sample ($2017Q4$). In other words, our analysis goes some way to explain the weak US economic recovery, despite the fact that most of FED's stimulus has not currently been withdrawn yet. Our empirical analysis goes a step further to show, via the use of a threshold VAR model, that the effects of the identified shock are state dependent. That is, the effects are both statistically and economically significant only when the level of the financial volatility, and thus uncertainty, in the economy is above a threshold. This is the first study, of this nature, that shows that credit supply shocks are state dependent.[1]

The paper is related to a number of strands of the macroeconomic literature, starting from the VAR literature that tries to identify credit supply shocks (Hristov et al. (2012), Barnett and Thomas (2014), Eickmeier and Ng (2015), Gambetti and Musso (2017), Mumtaz et al. (2018)). We make three distinct contributions to this literature:

1. Unlike all the studies in the literature, our credit supply shock is identified by imposing sign restriction only on banking type variables and no sign restriction is placed on real economic variables and inflation.

2. Along with real GDP, we include both real consumption and investment into our VAR (all three variables are left unrestricted). This allows to understand how the identified shock affects the two most important demand components and we illustrate that our credit supply co-moves all three variables.

3. We investigate the existence of nonlinear dynamics. Using a TVAR model we show that the effects of the shock are state dependent (i.e. they are significant only when financial volatility is above an estimated threshold).

Our paper also contributes to the dynamic stochastic general equilibrium (DSGE) literature that studies how credit supply shocks are transmitted to the economy, (Gerali et al. (2010), Curdia and Woodford (2010), Gertler and Karadi (2011), Christiano et al. (2003) Christiano et al. (2014a), Cúrdia and Woodford (2016)). Unlike the bulk of this literature, we model excess reserves explicitly and focus on how the responses of a typical financial intermediary towards risk affects the optimal level of excess reserves and the price of safe liquid assets, the deposit rate in this model. Excess reserves are more liquid than loans and this allows banks to hedge against higher risks by moving away from loans and into more liquid assets: deposits and excess reserves. We introduce a closed economy DSGE model of financial intermediation with credit, liquidity and nominal frictions. As in Bernanke et al. (1999), the borrowers are risky entrepreneurs who place orders for fixed capital to capital producers and then rent their capital services to goods producing firms.[2] However, unlike this literature, the expected capital return to the entrepreneur is determined by the loan rate, which in this model has been derived

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[1]Gambetti and Musso (2017) on the other hand illustrate that credit supply shocks are time dependent and their importance increases post 2008.

[2]See also Christiano et al. (2003).

explicitly from a single maximization problem of the bank, along with its decisions about its optimal levels of excess reserves and the deposit rate.[3] The bank forms its decisions subject to its balance sheet, the endogenous risk of borrowers and a fixed bank capital requirement. This allows all key variables in the model, (excess reserves, the deposit rate, the loan and equity spreads and the entrepreneur's return), to be driven not only by credit demand conditions, but critically by the bank's behaviour. Within this framework, we examine the effect of a precautionary liquidity shock, that is, a shock to the way the bank perceives the cost of holding (precautionary) reserves above a given level of actual risk.

The precautionary liquidity shock is shown to work through two channels: it increases the level of excess reserves, while it simultaneously raises the return on the safe liquid asset, the deposit rate. The increased reserves induce a balance sheet effect, which is shown to reduce the loan-to-deposit and the loan-to-reserve ratios and discourage credit to firms in the real sector. The increased deposit rate affects the intertemporal choices of households and through this channel it reduces consumption. It also increases the loan rate, which reduces the entrepreneur's return spread, resulting also in a fall in investment. Both these effects are shown to result in a recession with a downward co-movement of all, output, consumption, investment and inflation. The fall in prices and the nominal interest rate, also imply an increased real deposit rate spread, that is, a deposit rate that is higher than the policy rate. This is an unusual feature that was, however, present during the 2008 crisis. The effects of the precautionary liquidity shock are shown to be amplified, the higher is the responsiveness of the bank to potential losses due to risk, and the higher is the actual risk in the economy.

This paper is also related, though perhaps indirectly, to the literature that tries to assess the effectiveness of unconventional policies (see Dell'Ariccia et al. (2018) for an excellent survey of this literature). Our empirical and theoretical findings complement this literature as we propose a mechanism, which has been absent from the literature, that counteracts with the set of unconventional policies adopted by monetary authorities to stimulate demand when the policy rate was reduced to its zero lower bound.

Finally, the empirical analysis take please in Section 2, the theoretical model and the simulations are discussed in Section 3, while Section 4 concludes.

2   Empirical Analysis

The main focus of this section is the discussion of the empirical results. It is important to emphasise again that no restriction is placed on the real economy variables for the identification of the banking sector precautionary shock. The shock is identified using a number of sign as well as quantity restrictions only on the banking sector variables. This is our way of formally assessing the importance of the shock from a policy maker's perspective. If a shock in the banking sector leaves the output gap and inflation unchanged, then the authorities have no scope to intervene, as consumption, investment and firms' pricing decisions are left unaffected. Our analysis below illustrates that the shock not only has a material effect on the real economy, but this effect is also state dependent. That is, the shock has significant implications in the economy only when the level of the volatility in the banking sector is above the estimated threshold. This is another important finding, that supports – ex-post – our

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[3]This framework is also different to Christiano et al. (2003), and Christiano et al. (2014b), where the loan rate and the rates offered on various deposits are estimated in two separate problems by the bank, with the deposit rates being derived through a bank management production technology that is a function of labour, capital services and excess reserves.

interpretation of the identified credit supply shock, as a disturbance related with bankers' preferences about liquidity during periods of high uncertainty.

2.1 Data

To make sure that the results are not driven by the selection of a particular model, we employ a quite large VAR model that consists of thirteen variables: i) Basu et al. (2006) TFP measure, ii) real GDP, iii) real consumption, iv) real investment, v) CPI inflation, vi) policy rate, vii) deposits rates, viii) deposits, ix) loans, x) interbank loans, xi), bank reserves, xii) credit spread (the BAA corporate minus the 10year government debt yield) and xiii) Jurado et al. (2015) financial uncertainty index. The data spans between 1974Q1 and 2017Q4.[4]

$$Y_t = C + B_1 Y_{t-1} + ... + B_k Y_{t-k} + V_t, \tag{1}$$

where $V_t \sim N(0, \Sigma_V)$. To capture the dynamics in the model we allow for four lags ($k = 4$), while we illustrate in the online appendix that the results are robust to different lag orders (see the discussion in Section 2.4). Similarly to Banbura et al. (2010), the model is estimated using Bayesian inference, however, we chose uninformative Normal-Wishart Minnesota type priors to limit the influence of the prior information to the results (see the discussion in the online appendix Section 2.1). Finally, the TFP, GDP, consumption, investment, deposits, loans, interbank loans, reserves series are all de-trended using the filter proposed by Hamilton (2018).

2.2 VAR Shock Identification

The identification scheme employed in this study is a modification of the scheme proposed by Mumtaz et al. (2018). The authors of the latter study illustrate, through a series of large scale Monte-Carlo simulation exercises, the procedure where the set of sign restrictions is augmented with forecast variance restrictions to successfully recover the credit supply shock, (as in Uhlig (2004); Angeletos et al. (2020)).[5]

Below we review the three (sign, zero and forecast variance) set of restrictions employed in this study individually. However, the main objective of the proposed identification procedure is to achieve the following objectives:

1. Differentiate the identified shock from a standard (old fashion) monetary policy shock (see, for example, the discussion in Christiano et al. (1998) and Del Negro and Otrok (2007)). This becomes an important objective as the sample includes the zero lower bound period and the use of FED's unconventional policies to stimulate demand

2. Differentiate the identified shock from other credit supply shocks in the literature (Eickmeier and Ng (2015), Mumtaz et al. (2018) and Cesa-Bianchi et al. (2018)) and proxy the reluctance of the banking sector to 'lend' due to precautionary reasons, (as discussed in the introduction).

Sign Restrictions: Table 1 summarises the sign restrictions imposed for four periods (a year). As it is expected, the credit supply shock causes the credit spread and loans to move in the opposite direction. However, additional characteristics are added to our credit supply shock, as it also increases

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[4]Section 1 in the online appendix offers more information about the data.

[5]The majority of schemes employed in the literature face significant difficulties in retrieving the true shock. An exception is the proxy SVAR scheme proposed by Mertens and Ravn (2013) and Mertens and Ravn (2014).

Table 1: Sign Restriction

Variables	TFP	GDP	Consumption	Investment	Inflation
Restrictions	?	?	?	?	?
Variables	Policy Rate	Deposit Rate	Deposits	Loans	
Restrictions	−	?	?	−	
Variables	Interbank Loans	Reserves	Credit Spread	Volatility	
Restrictions	−	+	+	+	

Notes: The sign restrictions are imposed for four periods.

reserves and volatility. These two features aim to capture banks' elevated concerns about their liquidity position and their precautionary actions to "stock" high value liquid assets (i.e. increase reserves and reduce loans). The decrease of the interbank loans is also consistent with banks' reluctance to "give away precious cash" even to other banks. Finally, the fall in the interest rate (from the second period onwards) ensures that any adverse effect on the real economy is not caused because of a higher policy rate.

Table 2: Zeros Restriction

Variables	TFP	GDP	Consumption	Investment	Inflation
Restrictions	**0**	**0**	**0**	**0**	**0**
Variables	Policy Rate	Deposit Rate	Deposits	Loans	
Restrictions	**0**	**n/a**	**n/a**	**n/a**	
Variables	Interbank Loans	Reserves	Credit Spread	Volatility	
Restrictions	**n/a**	**n/a**	**n/a**	**n/a**	

Notes: The zero restrictions are imposed only contemporaneously.

Zero Restrictions: Table 2 illustrates the zero restrictions used for the identification of the precautionary banking shock. A no response restriction is imposed on the TFP, GDP, consumption, investment, inflation and policy rate. The zero restrictions are imposed to satisfy the requirement that bankers' behaviour is not an endogenous response to:

1. an adverse shock that takes place in the real economy (GDP, consumption, investment and policy rate),

2. an adverse news shock about productivity (TFP).

In other words, it is an exogenous precautionary banking sector shock.

Forecast Variance Restrictions: The identified shock maximises its forecast variance contribution to both reserves and volatility measures. These restrictions attach both qualitative and quantitative characteristics to the shock and facilitate its interpretation as a precautionary banking shock. As explained earlier, the aim of this study is to "access" the contribution of banking sector's reluctance to "lend" to the real economy in those situations when there is an elevated desire by financial intermediaries to hold high liquidity assets. So the forecast variance restrictions ensure that the contribution of the identified disturbance to reserves and volatility is maximised. The rest of this section briefly explains the maximization problem that results from all these restrictions. The mapping between reduced and

structural errors is given by

$$\omega_t = A_0 v_t.$$

For any orthogonal matrix D ($DD' = I$, where I is the identity matrix) the above mapping can be written as

$$\omega_t = A_0 D v_t.$$

Meaning that

$$\Sigma_V = A_0 DD' A_0' = A_0 A_0'.$$

Using the companion form of the VAR(p) model, the impulse of variable j and the impulse of shock i in the period h can be expressed as

$$IRF_{i,j}(h) = J_j B^{h-1} A_0 D J_i', \tag{2}$$

where J_j and J_i are selection matrices of zeros and ones. In Uhlig (2004) the matrix D results from the following minimisation problem

$$D^* = \arg\min \frac{J_1' \left(\sum_{\tau=1}^{H} B^{h-1} A_0 D J_{[11,13]} J_{[11,13]}' D' A_0' \left(B^{h-1} \right)' \right) J_1}{J_1' \left(\sum_{\tau=1}^{H} B^{h-1} \Sigma \left(B^{h-1} \right)' \right) J_1}, \tag{3}$$

s.t.

$$DD' = I, \tag{4}$$
$$J_{Sign}' A_0 D \in \mathcal{I}_{Sign}, \tag{5}$$
$$J_0' A_0 D = \mathbf{0}, \tag{6}$$

where $\mathcal{I}_{Sign}$ denotes the set of the sign restrictions, $\mathcal{I}_0$ is the set of zero restrictions, $\mathbf{0}$ is a vector of zeros.

2.3 Empirical Results

This section discusses the benchmark results. As it is discussed in section 2.4, the results remain robust across different specifications

Impulse Responses: Figure 3 illustrates the effects of one standard deviation adverse precautionary banking sector shock that increases the deposit spread – defined as the difference between the deposit and policy rate – by around $5bps$. The shock has quite sizeable economic effects, where GDP falls by more than 0.3% relative to its trend and it takes almost three year to recover. Interestingly, the shock moves consumption and investment towards the same direction. Consumption and investment decrease by around 0.3% and 1.25%, respectively, despite the fall in the policy interest. The reluctance of the bank to lend to the real economy is reflected via the higher external finance cost ($12bps$) that explains the collapse in investment. The higher uncertainty in the economy and the increase in the deposit rate, induces households to act in a precautionary manner and reduce their consumption to acquire

higher savings. Banks aiming to attract households deposit and they, therefore, only partially pass the reduction in the policy rate to the deposit rate. This results in an increase deposits and, together with fewer loans, reserves rise by roughly 80% relative to their trend.

Figure 3: Benchmark Model: Impulse Responses Functions
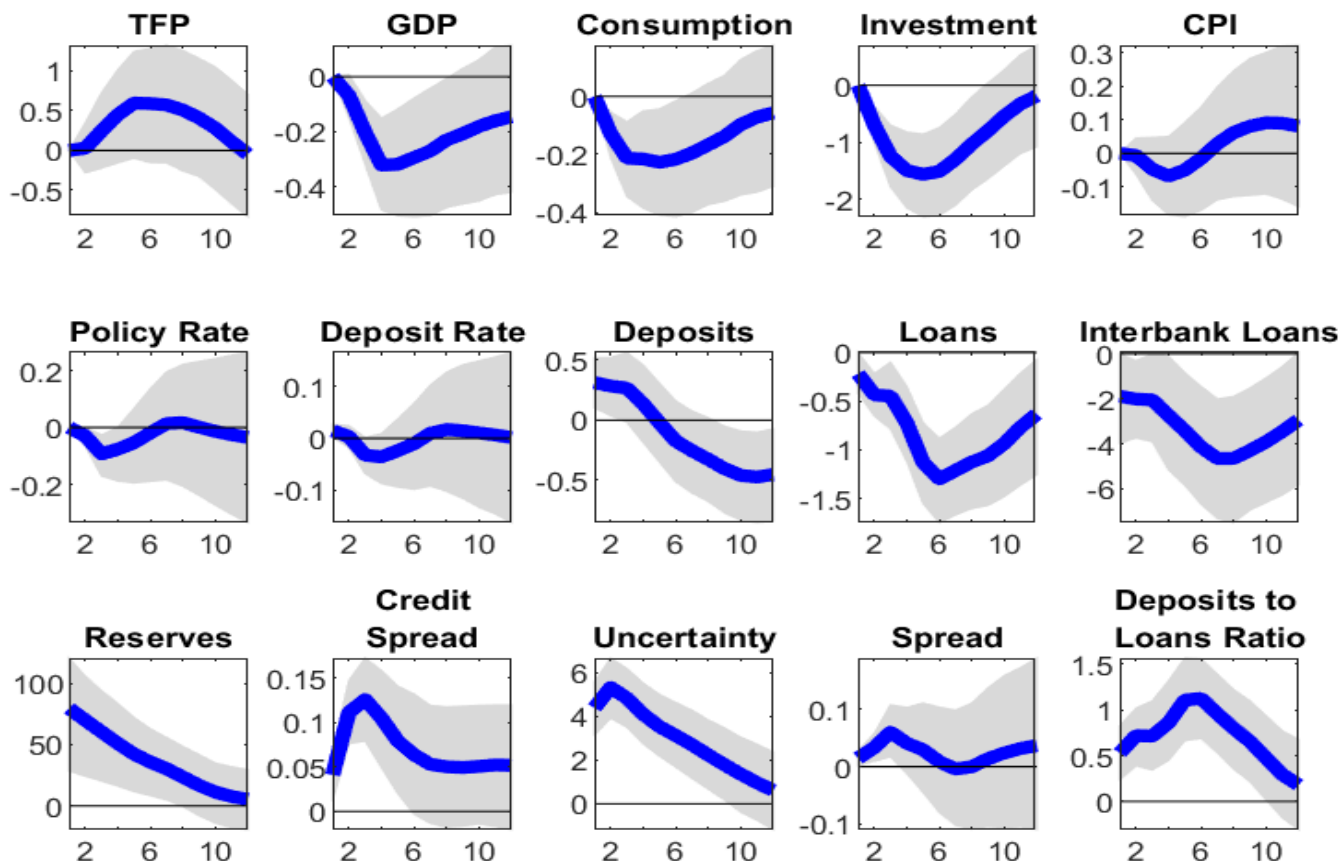
Notes: Solid line: posterior mean response. Shaded area: 16th-84th posterior percentile bands. Spread is defined as the difference between the deposit and policy rate.

Forecast Variance Decomposition   Figure 4 displays the forecast variance contribution of the identified shock. Clearly, the shock cannot be considered as the "driver" of the US business cycle and, given its characteristics, it would have been "unrealistic" for readers to have formed priors for a much larger contribution than what it is revealed by the posterior estimates. This is because the sample does not contain any other episode similar to the Great Recession, where liquidity became extremely scarce. The Asian financial crisis and the collapse of the dot-com bubble are the only other episodes that put the banking sector under pressure and, consequently, caused financial intermediaries to form strong precautionary liquidity motives, but again these cannot be compared with the 2008 financial crisis.

Historical Decomposition   It is important that the reader does not draw any conclusion about the "economic importance" of the shock from its forecast variance share. This information could be inferred by studying the contribution of the shock during important historical periods. We therefore use the empirical model to measure the contribution of the shock to the real economy post 2008Q1. The motivation of why we focus our attention on this period comes from the work of Gambetti and

Figure 4: Benchmark Model: Forecast Variance Contributions
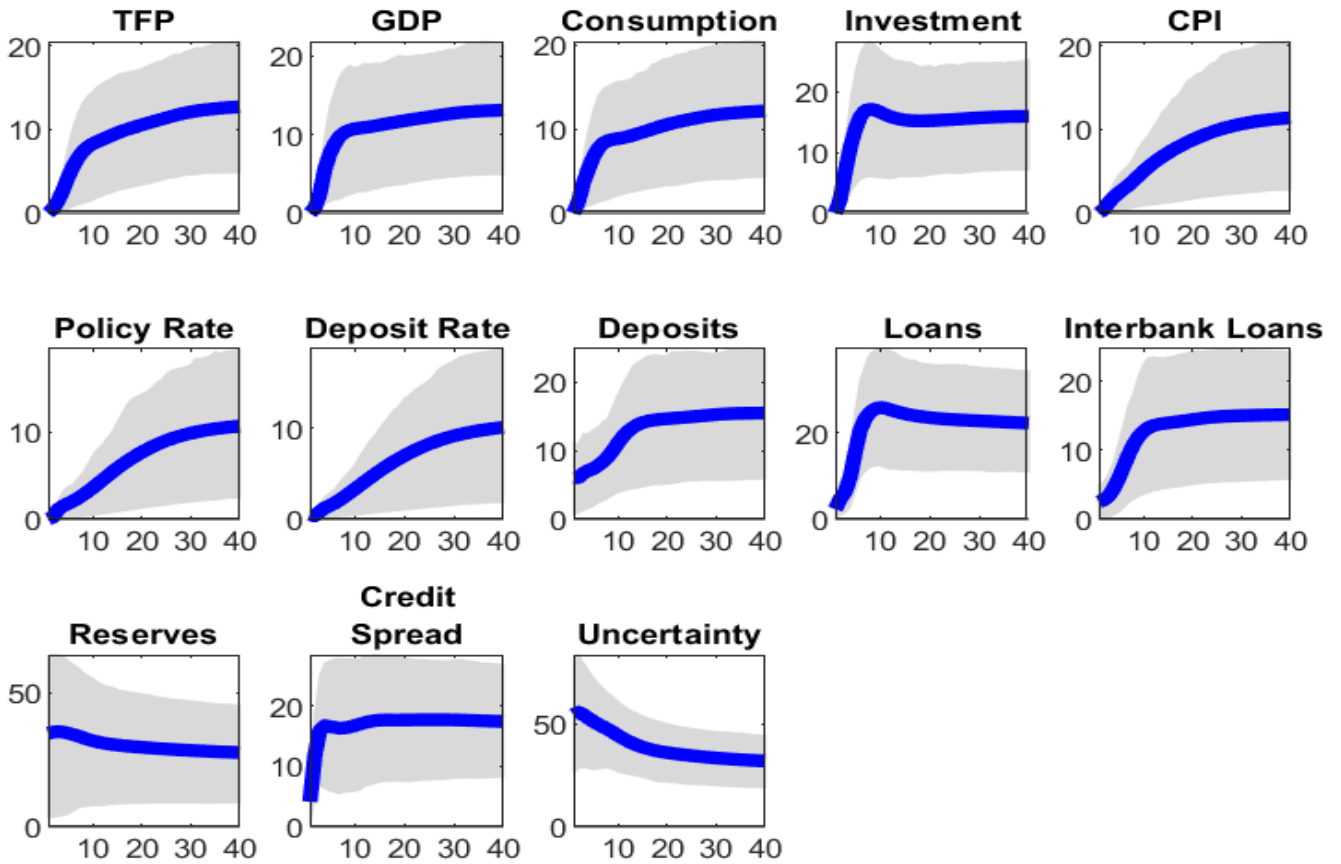
**Notes:** Solid line: posterior mean response. Shaded area: 16th-84th posterior percentile bands.

Musso (2017), who use a time-varying VAR model and show the effects of credit supply shocks become larger (relative to the past) during this period.

Figure 5 illustrates the contribution of the shock to GDP, consumption and investment relative to its contribution in 2007Q4. The shock explains 2% (on average) of the decrease of the US output, 1.5% of the consumption fall, while for the investment this estimate increases to 6% relative to their pre-crisis trends. These estimates are far from negligible and illustrate that the banking sector's precautionary actions contributed significantly to the unprecedented recession and to the very weak recovery of the US economy.

2.4   Robustness Analysis

In the online appendix we illustrate that the results are robust: i) to different lag orders (Figures 1 and 2), (ii) to "looser" and "tighter" priors (Figures 3 and 4), iii) when the number of periods used for the sign restrictions is reduced to one (Figure 5), iv) when the consumption and investment series are removed from the empirical model (Figure 6), and, v) when the data has been detrended using Hodrick-Prescott filter (Figure 7).

Figure 5: Benchmark Model: Post 2008Q1 Precautionary Banking Shock Contributions
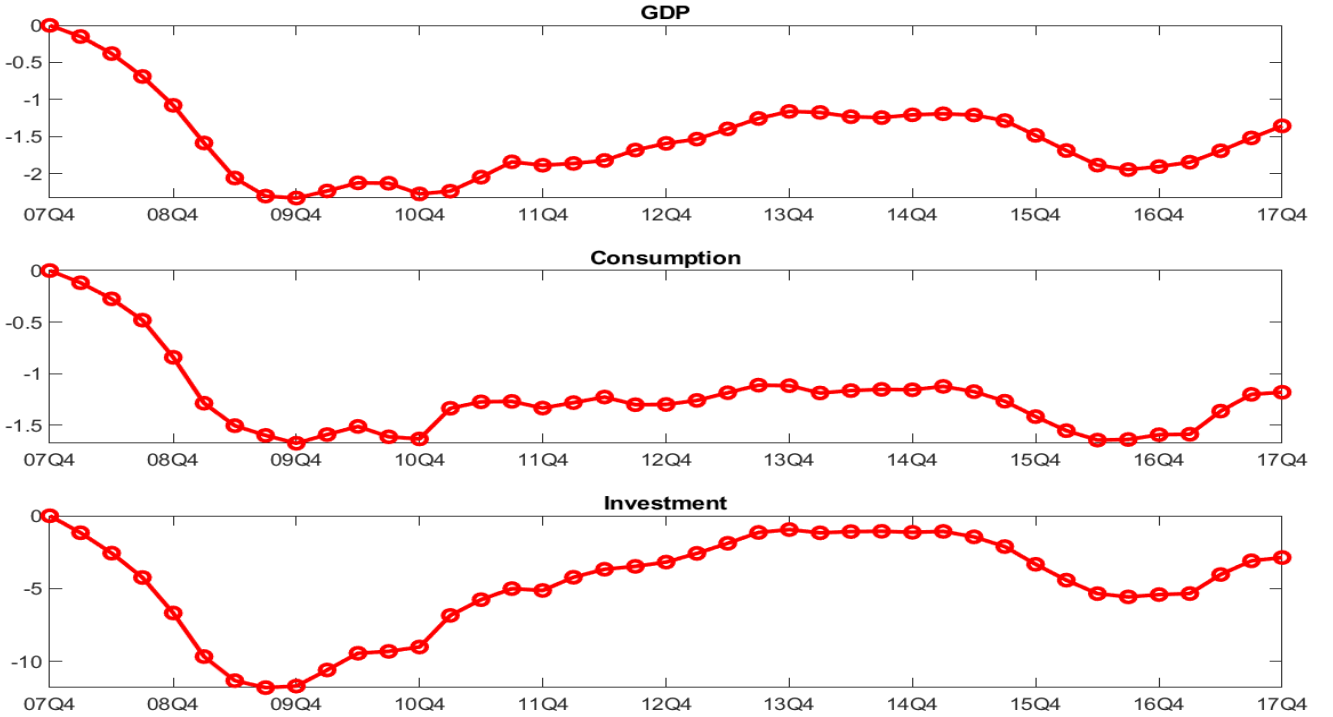
Notes: The posterior mean contribution of the Precautionary Banking Shock relative to 2007Q4.

2.5 Non-linear Analysis

The impulse response function analysis (Figure 3) and the historical decomposition (Figure 5) analysis in Section 2.3 imply that the identified shock induces sizeable effects on the economic activity, however, the forecast variance analysis (Figure 4) on the other hand suggests that the shocks explain very little of the variability of the GDP overall. In this section, we "dig deeper" into this issue and try to identify what causes this discrepancy. We believe that this divergence hints to potential non-linearities and therefore, in this section, we use a Threshold VAR (TVAR) model to assess whether the banking sector's responses to a precautionary liquidity shock are state dependent. In other words, we investigate whether these adverse effects take place only when certain economic conditions are present. It is perhaps important at this point to stress that the type of the non-linearity considered here is different from the one employed by Gambetti and Musso (2017), who allow economic dynamics to evolve across time.

The TVAR model used here is based on the original study by **?**, which allows the VAR parameters to vary across an aggregate state of the economy. The switching mechanism is based on the value of one of the endogenous variables being above or below a threshold, and unlike Markov-switching models, the parameter change is endogenous to the dynamics of the VAR process. The reduced-form model can be expressed as follows:

$$Y_t = \xi_t \left\{ C_1 + \sum_{k=1}^{K} B_{k,1} Y_{t-k} + \Sigma_{V,1}^{1/2} V_t \right\} + (1 - \xi_t) \left\{ C_2 + \sum_{k=1}^{K} B_{k,2} Y_{t-k} + \Sigma_{V,2}^{1/2} V_t \right\}. \tag{7}$$

Switches across regimes are governed by the indicator variable, $\xi_t \in \{0, 1\}$, that is equal to 1 if the variable that proxies the economic conditions of interest in period $t - 1$, $\tilde{y}_{t-1}$, is below the threshold

y^*, otherwise it is equal to zero:

$$\xi_t = 1 \quad \text{if} \quad y_{t-1} < y^*, \quad \text{otherwise} \quad \xi_t = 0. \tag{8}$$

Similarly to Castelnuovo and Pellegrino (2018), the threshold variable that dictates the regime switching process in our study is the financial volatility. In other words, we investigate whether the effects of the precautionary liquidity shock to the economy are larger, smaller, or the same when the degree of the financial volatility exceeds a certain threshold. The estimation of the model is discussed in the online appendix (Section 3), while the identification process is the one described in Section 2.2 in the online appendix.

The results are striking, the identified shock has no effect on the real economy when volatility is below the estimated threshold (Figure 6), but the impact of the shock turns significant when financial volatility is elevated (Figure 7). Interestingly, the comparison between the estimates where state dependence is taken into account (Figure 7) with those ignored (Figure 3) reveals that the former effects are substantially larger. In other words, the shock that increases the credit spread by $12bps$ in the third period lowers GDP by almost 60% more (i.e. 0.5%) when the non-linearities are not overlooked, than in the case where dynamic are considered to be homogenous across volatility regimes.

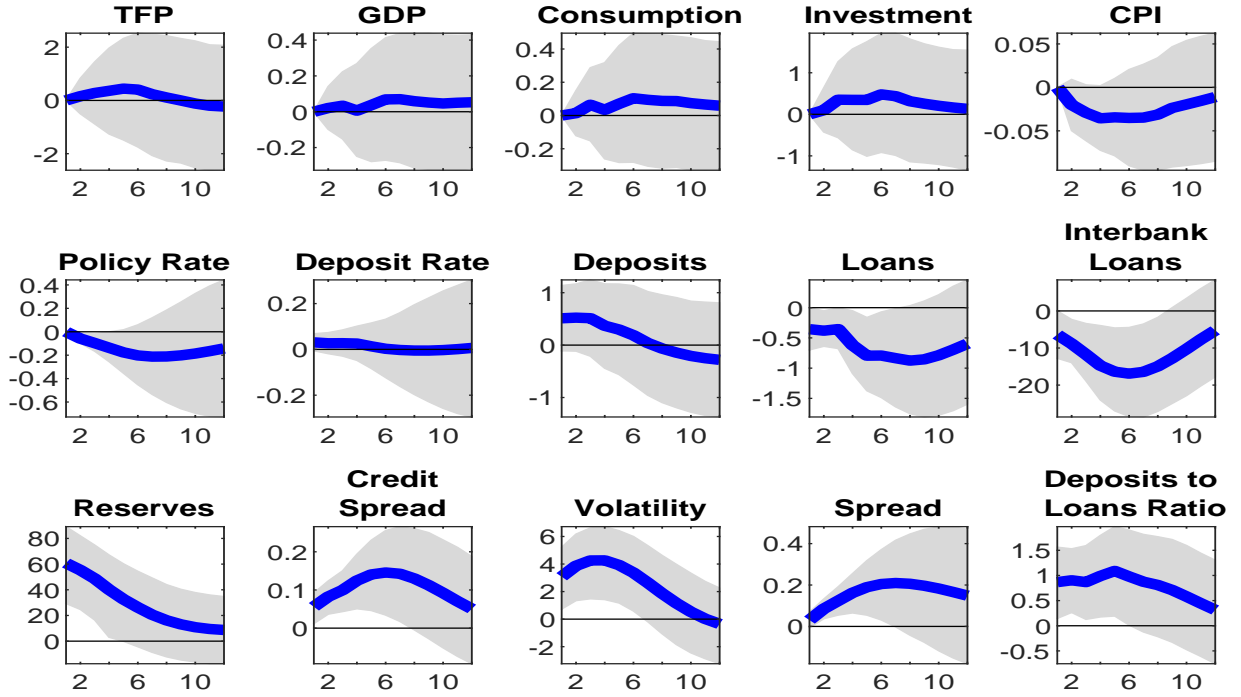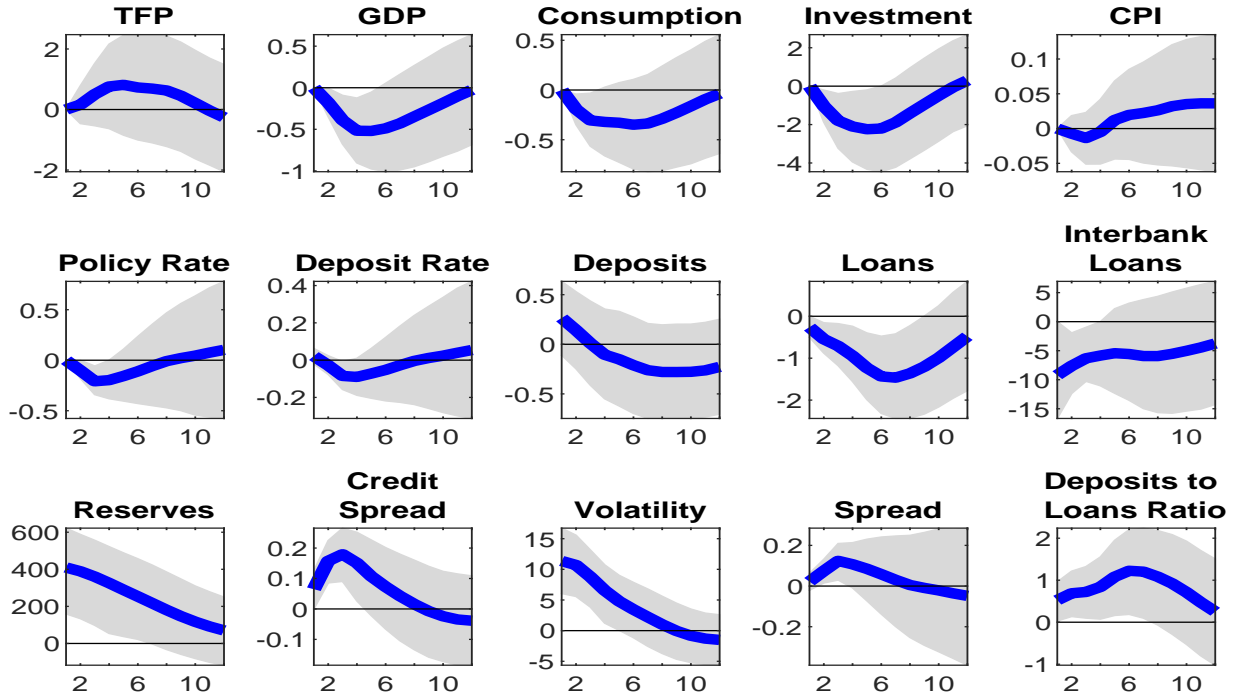Figure 6: Low Volatility Regime

Figure 7: High Volatility Regime

Notes: Solid line: posterior mean response. Shaded area: 16th-84th posterior percentile bands. Spread is defined as the difference between the deposit and policy rate. The shock has been normalised to increase the credit spread by 12*bps* in the third period so the responses become comparable with those displayed in Figure 3.

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3   The DSGE Model

In this section we develop a dynamic stochastic general equilibrium (DSGE) model, as described in the introduction, to understand the transmission of a precautionary liquidity shock.

3.1   Households

A large family of homogenous households maximize their expected lifetime utility,

$$U_t = \mathbb{E}_t \sum_{s=0}^{\infty} \beta^s \left\{ \log[c_{t+s}] \ - v\frac{n_{t+s}^{1+\eta}}{1+\eta} \right\}, \tag{9}$$

subject to their real budget constraint,

$$c_t + d_t + e_t = w_t n_t + \frac{R_t^d d_{t-1}}{\pi_t} + \frac{(1 - \Phi_t[\omega_t^*])(R_t^e - \xi^e)e_{t-1}}{\pi_t} + V_t, \tag{10}$$

where $\mathbb{E}_t$ is the expectations operator, $\beta \in (0,1)$ is the discount factor, n_t is average labour hours, $v, \eta > 0$, and $\pi_t \equiv \frac{p_t}{p_{t-1}}$ is the inflation rate. Households decide on their levels of bank deposits, d_t, and bank equity (capital), e_t, and spend their remaining income on a consumption basket, c_t. Their income consists of real wages w_t and gross interest payments on deposits, R_t^d and bank equity R_t^e, net of a fixed transaction cost, ξ^e. Bank equity returns are paid only if the bank does not default in period t, where $\Phi_t[\omega_t^*]$ is the probability of default of the borrower in the real sector (derived below).[6] At the end of each period, households also receive aggregate real profits from firms, capital producers entrepreneurs and banks, $V_t = \sum \Pi_t^S$, $S \in \{F, K, E, B\}$. The first order conditions are,

$$c_t = \mathbb{E}_t \left\{ \frac{\pi_{t+1}}{\beta R_{t+1}^d} c_{t+1} \right\}, \tag{11}$$

$$w_t = v n_t^{\eta} c_t, \tag{12}$$

$$R_{t+1}^e = \frac{R_{t+1}^d + \xi^e}{1 - \Phi_{t+1}[\omega_t^*]}. \tag{13}$$

Equation (13) is the arbitrage-free condition between the return on bank equity and the risk-free deposit rate, which determines the intertemporal choices of consumers and sets the benchmark rate for the equity rate.

3.2   Capital Goods Producers

Capital is produced by a competitive producer, who buys existing installed capital, $x_t = (1 - \delta)k_{t-1}$, (where, $0 < \delta < 1$ is the depreciation rate), and new investment, i_t, to produce new installed capital for the next period,

$$x_{t+1} = x_t + \left(1 - S\left[\frac{i_t}{i_{t-1}} \right] \right) i_t,$$

where $S[\cdot]$ is an investment-adjustment cost function, with $S[1] = 0$, $S'[1] = 0$ and $S''[\cdot] > 0$, as in Christiano et al. (2003). The new installed capital is then sold to the entrepreneur at $q_t x_{t+1} = q_t k_t$, where q_t is the relative price of capital, with a steady state value, $q = 1$. The capital producer maximizes

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[6]For simplicity the bank defaults with the same probability as its borrower.

real profits,

$$\max_{\{i_t\}_{t=0}^\infty} \mathbb{E}_t \sum_{s=0}^\infty \beta^s \frac{\lambda_{t+s}}{\lambda_t} \{\Pi_{t+s}^K\},$$

where real period profits are[7]

$$\Pi_t^K = q_t x_{t+1} - q_t x_t - i_t = q_t \left(1 - S\left[\frac{i_t}{i_{t-1}}\right]\right) i_t - i_t.$$

From the first order condition of this problem we can write,

$$q_t = \frac{1 - \beta \mathbb{E}_t \frac{\lambda_{t+s}}{\lambda_t} q_{t+1} S'\left[\frac{i_{t+1}}{i_t}\right] \left(\frac{i_{t+1}}{i_t}\right)^2}{1 - S\left[\frac{i_t}{i_{t-1}}\right] - S'\left[\frac{i_t}{i_{t-1}}\right] \left(\frac{i_t}{i_{t-1}}\right)^2},$$

where the evolution of capital is,

$$k_t = (1 - \delta)k_{t-1} + \left(1 - S\left(\frac{i_t}{i_{t-1}}\right)\right) i_t.$$

3.3 Entrepreneurs

At the end of each period entrepreneurs sell their existing installed capital, $(1 - \delta)k_{t-1}$, to capital producers and borrow loans from the bank to buy new capital. Entrepreneurs can borrow a fraction, $0 < \vartheta < 1$, of their value of existing capital, $q_t k_t$,[8]

$$l_t \leqslant \vartheta q_t k_t. \tag{14}$$

The loan is repaid in the beginning of the next period when the return on capital R_{t+1}^k is revealed. The return on capital is subject to an idiosyncratic risk, ω_t, that makes the loan repayment uncertain. For simplicity, ω_t is uniformly distributed over the interval $(\underline{\omega}, \overline{\omega})$, with a constant variance and a unity mean.[9] In a good state the entrepreneur repays the full borrowing cost, $R_{t+1}^l l_t$, where R_t^l is the gross loan rate set by the bank, whereas in a bad state the entrepreneur repays the bank a fraction χ of the total value of their capital, $\chi \omega_{t+1} R_{t+1}^k q_t k_t$.[10] The break even condition of the entrepreneur is,

$$R_{t+1}^l l_t = \chi \omega_{t+1} R_{t+1}^k q_t k_t, \tag{15}$$

from which we derive the cut-off value,

$$\omega_{t+1}^* = \left(\frac{R_{t+1}^k}{R_{t+1}^l} \frac{\chi q_t k_t}{l_t}\right)^{-1}, \tag{16}$$

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[7] Since profits from entrepreneurs and capital producers accrue to the household, capital producers use the household's discount preferences.

[8] This credit constraint is necessary to pin down the level of borrowing, since for simplicity, we do not consider net worth. We also, implicitly, assume that there is always an equal amount of entrepreneurs replacing non-surviving entrepreneurs at the end of each period.

[9] The assumption of the idiosyncratic shock ω_t following a uniform distribution is only to facilitate a tractable probability of default, with no loss in generality.

[10] For the role of χ, in a different model setup with no capital, see Agénor et al. (2014).

which is shown to be inversely related to the spread between the return on capital and the loan rate, and the fraction of seizable collateral, $\chi q_t k_t$, to total loans l_t. Given the above information, the average expected payment that the entrepreneur makes to the bank is, $\int_{\omega_{t+1}^*}^{\overline{\omega}} R_{t+1}^l l_t f(\omega_{t+1}) d\omega_{t+1} + \int_{\underline{\omega}}^{\omega_{t+1}^*} \chi \omega_{t+1} R_{t+1}^k q_t k_t f(\omega_{t+1}) d\omega_{t+1}$.[11] The entrepreneur's problem is to choose the levels of capital and loans that maximize the average expected income, $\max_{\{k_t, l_t\}} \mathbb{E}_t\{\Pi_t^E\}$,

$$\max_{\{k_t,l_t\}} \mathbb{E}_t \left\{ \begin{array}{c} \int_{\omega_{t+1}^*}^{\overline{\omega}} \left\{\omega_{t+1} R_{t+1}^k q_t k_t - R_{t+1}^l l_t\right\} f(\omega_{t+1}) d\omega_{t+1} \\ + \int_{\underline{\omega}}^{\omega_{t+1}^*} \left(\omega_{t+1} R_{t+1}^k q_t k_t - \chi \omega_{t+1} R_{t+1}^k q_t k_t\right) f(\omega_{t+1}) d\omega_{t+1} \end{array} \right\},$$

subject to the loan constraint (14) and taking as given the loan rate set by the bank (derived below). Using the distribution properties of ω_t and from (15), the condition, $R_{t+1}^l l_t = \chi \omega_{t+1}^* R_{t+1}^k q_t k_t$, we can write,[12]

$$\max_{\{k_t,l_t\}_{t=0}^{\infty}} \mathbb{E}_t \left\{ R_{t+1}^k q_t k_t - R_{t+1}^l l_t - \int_{\underline{\omega}}^{\omega_{t+1}^*} (\omega_{t+1} - \omega_{t+1}^*) f(\omega_t) d\omega_t \chi R_{t+1}^k q_t k_t + \lambda_t^l(\vartheta q_t k_t - l_t) \right\} \quad (17)$$

where the term, $\int_{\underline{\omega}}^{\omega_t^*} (\omega_{t+1} - \omega_{t+1}^*) f(\omega_t) d\omega_t \chi R_t^k q_t k_t$, is the fraction of the entrepreneur's income lost in times of default, (that is when, $\omega_{t+1} < \omega_{t+1}^*$). From the first order conditions,

$$\lambda_t^l \vartheta q_t + q_t \mathbb{E}_t R_{t+1}^k (1 + \frac{\chi(\overline{\omega} - \underline{\omega})}{2} \Phi_{t+1}^2[\omega_{t+1}^*]) = 0, \quad (18)$$

$$\lambda_t^l = -R_{t+1}^l. \quad (19)$$

where λ_t^l is the Lagrangian multiplier to the credit constraint. Combining these we derive,

$$\mathbb{E}_t \left(\frac{R_{t+1}^k}{R_{t+1}^l}\right) = \mathbb{E}_t \left\{ \frac{\vartheta}{\left(1 - \frac{\chi(\overline{\omega} - \underline{\omega})}{2} \Phi_{t+1}^2[\omega_{t+1}^*]\right)} \right\}, \quad (20)$$

where $\Phi_{t+1}[\omega_{t+1}^*]$, is the probability of credit default,

$$\Phi_t[\omega_t^*] = \int_{\underline{\omega}}^{\omega_t^*} f(\omega_t) d\omega_t = \frac{\omega_t^* - \underline{\omega}}{\overline{\omega} - \underline{\omega}},$$

From (20), it is shown that the expected return *spread* of the entrepreneur, R_{t+1}^k/R_{t+1}^l, increases the higher is the risk, $\Phi_{t+1}[\omega_{t+1}^*]$, and the leverage ratio, ϑ, and it decreases the higher is the cost of borrowing, determined by the loan rate set by the bank. The entrepreneur receives a rental price of capital r_{t+1}^k from firms and also receives $q_{t+1}(1 - \delta)$ from selling the undepreciated capital at the end of each period. Hence, the average (per nominal unit $p_t q_t$) real return to capital at the end of each period is,

$$R_{t+1}^k = \frac{p_{t+1}(r_{t+1}^k + q_{t+1}(1 - \delta))}{p_t q_t}. \quad (21)$$

---

[11]where $f(\omega_{t+1})$ is the probability density function of the uniform distribution.

[12]Here we use the assumption, $\left\{\int_{\omega_t^*}^{\overline{\omega}} \omega_{t+1} f(\omega_t) d\omega_t + \int_{\underline{\omega}}^{\omega_t^*} \omega_{t+1} f(\omega_t) d\omega_t\right\} = \mathbb{E}_t\{\omega_{t+1}\} = 1$

3.4 The Financial Intermediary

The financial intermediary (bank) supplies loans to the entrepreneur at the end of each period and settles interest payments at the beginning of the next period. It raises loan funds from household deposits d_t at the gross return R^d_{t+1}, and bank equity e_t at the gross return R^e_{t+1}, and it can also borrow from the central bank, l^{cb}_{t+1}, at the interbank rate, R_{t+1}. The Bank's maximization problem is,

$$
\begin{aligned}
\Pi^B_t &= \widetilde{r}_t d_t R_{t+1} + \int_{\omega^*_{t+1}}^{\overline{\omega}} R^l_{t+1} l_t f(\omega_{t+1}) d\omega_{t+1} + \int_{\underline{\omega}}^{\omega^*_{t+1}} \omega_{t+1} \chi R^k_{t+1} q_t k_t f(\omega_{t+1}) d\omega_{t+1} \\
&\quad -\xi^l l_t - (R^d_{t+1} + \xi^d) d_t - R^e_{t+1} e_t - R_{t+1} l^{cb}_t - \frac{\varrho}{2} d_t (\widetilde{r}_t - b\widetilde{r}_{t-1})^2 \\
&\quad -\frac{\psi}{2} d_t \left(\widetilde{r}_t - \varphi(1+\theta_t) \int_{\underline{\omega}}^{\omega^*_t} f(\omega_t) d\omega_t \right)^2 ,
\end{aligned}
\tag{22}
$$

where, $\widetilde{r}_t$ is the fraction of deposits the bank holds as total reserves and receives R_{t+1}.[13] The rest of its deposits, $(1-\widetilde{r}_t)d_t$, together with bank equity, e_t, and loans from the central bank l^{cb}_t are made available as loans, l_t, to the entrepreneur, (see also 23). From the loan markets, the bank receives $\int_{\omega^*_{t+1}}^{\overline{\omega}} R^l_{t+1} l_t f(\omega_{t+1}) d\omega_{t+1}$ in a good state, or the stochastic collateral, $\int_{\underline{\omega}}^{\omega^*_{t+1}} \chi \omega_{t+1} R^k_{t+1} q_t k_t f(\omega_{t+1}) d\omega_{t+1}$, in a bad state. ξ^l and ξ^d capture all other fixed loan and deposit related costs, respectively. To ensure that the dynamics of reserves are well-behaved, we assume two quadratic costs related to the accumulation of reserves, the last two terms in (22). The first term captures the cost of adjusting the fraction of reserves away from the previous average in the banking system, $\widetilde{r}_{t-1}$, where b, regulates the persistence in reserves. The second term captures the cost that the bank faces when it keeps reserves, above the potential level of required liquidity, that is, above the fraction of deposits that are expected to be lost if loans default in a bad state, $\int_{\underline{\omega}}^{\omega^*_{t+1}} f(\omega_{t+1}) d\omega_{t+1}$; where φ determines how sensitive this cost is to the level of potential risk. Importantly, we allow this cost to be scaled by a stochastic shock, θ_t, which captures our precautionary liquidity shock. This is not a risk shock, but a shock to how the bank perceives the cost of holding reserves and hence liquidity, for any given level of potential risk. A higher θ_t, implies that a higher fraction of deposits can be potentially lost in a bad state, which implies that the bank perceives a higher benefit (lower cost) in holding reserves for precautionary reasons. We assume that $\log \theta_t = \rho_\theta \log \theta_{t-1} + \epsilon^\theta_t$, where ϵ^θ_t, is an i.i.d. normal random variable with zero mean and a standard deviation of σ^θ.

The bank maximizes (22), subject to,

$$
l_t \leq (1-\widetilde{r}_t)d_t + e_t + l^{cb}_t,
\tag{23}
$$

$$
e_t = \gamma l_t.
\tag{24}
$$

Equation (23) is the bank's balance sheet constraint, whereas (24) is a bank capital-to-loan requirement ratio, that is fixed to γ and is satisfied at all times in this model.[14] The bank's optimization problem can be explained in two stages.[15] In the first stage the bank chooses it optimal levels of reserves and the desired level of borrowing from the central bank and sets the deposit rate. Having selected these, in the second stage the bank sets the loan rate so as to break even. From the above problem the bank

---

[13]We assume that the interest on reserves is equal to the interest rate. For simplicity we also assume that total reserves include some fixed required reserves, which are not modelled explicitly here, so that all reserves are excess reserves.

[14]Since raising funds through equity is more costly for the bank ($R^e_t > R_t$), bank equity is issued merely to satisfy the fixed regulatory bank capital requirements in this model. Hence we assume that, $e_t/l_t = \gamma$

[15]The full optimization problem of the bank is described in detail in the online appendix Section 4.

calculates the deposit rate,

$$R_{t+1}^d = R_{t+1} - \frac{\varrho}{2}(\tilde{r}_t - b\tilde{r}_{t-1})^2 - \frac{\psi}{2}(\tilde{r}_t - \varphi(1+\theta_t)\Phi_t)^2 - \xi^d, \tag{25}$$

and the fraction of deposits it desires to holds as (excess) reserves is,

$$\tilde{r}_t = \frac{b\varrho}{\varrho+\psi}\tilde{r}_{t-1} + \frac{\psi\varphi(1+\theta_t)\Phi_t}{\varrho+\psi} + \frac{\chi R_{t+1}^k(\overline{\omega}-\underline{\omega})\Phi_{t+1}^2}{2\vartheta(\varrho+\psi)(1-\gamma)}, \tag{26}$$

where in deriving its optimal level of reserves, we assume that the bank also takes into account the value of the fraction of the loans that can be lost in a bad state as a result of its decision, captured by the last term in (26). Having derived its optimal levels of reserves and the deposit rate the bank calculates the break-even loan rate,

$$\begin{aligned}R_{t+1}^l &= \frac{1-\gamma}{1-\tilde{r}_t}(R_{t+1}^d + \xi^d - \tilde{r}_t R_{t+1}) + R_{t+1}^e\gamma + \frac{\chi R_{t+1}^k}{\vartheta}\frac{(\overline{\omega}-\underline{\omega})\Phi_{t+1}^2}{2}\\ &+\frac{\varrho}{2}\frac{1-\gamma}{1-\tilde{r}_t}(\tilde{r}_t - b\tilde{r}_{t-1})^2 + \frac{\psi}{2}\frac{1-\gamma}{1-\tilde{r}_t}(\tilde{r}_t - \varphi(1+\theta_t)\Phi_t)^2 + \xi^l.\end{aligned} \tag{27}$$

An interesting effect here is that a precautionary liquidity shock, θ_t, can overturn what the bank normally perceives as a cost of accumulating reserves to a desired effect of precautionary liquidity. From (26), this is shown to increase the level of reserves, while from (25), the bank is shown to be willing to provide a higher deposit rate, indicating its desire to increase its holdings of safe liquid assets (deposits and reserves). These effects are larger, the more responsive is the bank to potential risk (φ), in assessing the cost of holding precautionary reserves, and the higher is the actual level of risk, (Φ_t). These effects are also larger the smaller is the degree of reserve persistence exhibited by the bank, b and ϱ. The direct effect of the precautionary liquidity shock appears to reduce the loan rate, as it reduces risk exposure to loans, however its full effect on the loan rate depends also on the the deposit rate and the level of reserves. These effects are simulated in section 3.8.1.

3.5 Final Goods Firm

The competitive final good firm assembles all intermediate goods, y_t, $j \in (0,1)$, to produce a final output, y_t, which then sells at the price p_t. This is produced using a CES technology with Dixit-Stiglitz (1977) preferences, $y_t = (\int_0^1 y_{j,t}^{\frac{\lambda_p-1}{\lambda_p}} dj)^{\frac{\lambda_p}{\lambda_p-1}}$ where $\lambda_p > 1$. The demand for each intermediate good j is, $y_{j,t} = y_t \left(\frac{p_{j,t}}{p_t}\right)^{-\lambda_p}$, where $p_{j,t}$, is the price set by intermediate firm j and $p_t = \left(\int_0^1 p_{j,t}^{1-\lambda_p} dj\right)^{\frac{1}{1-\lambda_p}}$ is the corresponding average price index.

3.6 Intermediate Goods Firms

Each firm j produces a differentiated intermediate good by hiring capital from entrepreneurs $k_{j,t}$, and labour hours from households, $n_{j,t}$. Its production technology is,

$$y_{j,t} = A_t k_{j,t}^\alpha n_{j,t}^{1-\alpha} \qquad 0 < \alpha < 1, \tag{28}$$

where A_t is an aggregate supply shock, where $\log A_t = \rho_A \log A_{t-1} + \epsilon_t^A$, and ϵ_t^A is an i.i.d. shock, with standard deviation σ^A and mean $A = 1$. From the firm's cost minimization problem, real marginal

cost is,

$$mc_t = \frac{(r_t^k)^\alpha w_t^{(1-\alpha)}}{\alpha^\alpha (1-\alpha)^{(1-\alpha)} A_t}, \tag{29}$$

and the capital to labour ratio is determined by the relative price of input factors, $k_{j,t}/n_{j,t} = \alpha w_t/(1-\alpha)r_t^k$. Price setting is based on Calvo-type price contracts, where ζ_p firms keep their prices fixed, while the rest $(1-\zeta_p)$ of firms adjust prices optimally. Each firm j maximizes, $\max_{p_{j,t+s}} \mathbb{E}_t \sum_{s=0}^\infty \zeta_p^s \beta^s \lambda_{t+s} \{\Pi_{j,t+s}^F\}$, subject to, $\Pi_{j,t}^F = \frac{P_{j,t}}{P_t} y_{j,t} - mc_t y_{j,t}$, which results in the standard new Keynesian Phillips curve,

$$\widehat{\pi}_t = \beta \mathbb{E}_t \widehat{\pi}_{t+1} + \frac{(1-\zeta_p)(1-\zeta_p\beta)}{\zeta_p} \widehat{mc}_t. \tag{30}$$

3.7 Monetary Policy and Aggregate Equilibrium

The interest rate, R_t, is set according to a conventional Taylor rule,

$$R_t = R^{(1-\rho_R)} R_{t-1}^{\rho_R} \left[\left(\frac{\pi_t}{\pi}\right)^{\phi_\pi} \left(\frac{y_t}{y}\right)^{\phi_y} \right]^{(1-\rho_R)}, \tag{31}$$

where, $\rho_R \in (0,1)$ and $\phi_\pi, \phi_y > 0$.

At the aggregate equilibrium, with no government intervention, aggregate demand is determined by aggregate consumption and investment, $y_t = c_t + i_t$. Equations, (14), (23) and (24) are binding and the loans demanded by entrepreneurs equal the loans supplied by banks, $l_t = \vartheta q_t k_t = (1-\widetilde{r}_t)d_t + e_t + l_t^{cb}$, and deposits are determined endogenously. We finally assume that at the aggregate equilibrium there is no borrowing from the central bank, $l_t^{cb} = 0$. The model is log-linearized around its non-stochastic zero inflation steady state. The steady state and the full log-linearized system are described in Section 4 in the online appendix.

3.8 Calibration

Table 3 presents the baseline parameter values of the model. In solving for the steady values, we calibrate the model to the following target values that are based on US data for the period 1985Q1 to 2017Q4. The average total reserves to deposits ratio is, $\widetilde{r} \approx 6.99\%$. The effective federal funds rate is, 3.63%, (or a net quarterly rate of 0.009). The average interest rate to deposit rate spread, over the sample period is calibrated to, $R - R^D = 1.60\%$, (annually) which also implies $\beta = 0.9949$. The loan spread is calibrated to $R^L - R = 3.91\%$, and the equity spread to, $R^E - R = 7.65\%$. We also set $\vartheta = 0.27$, that implies a loan to output ratio of approximately $l/y = 2$. The bank capital ratio is fixed at $\gamma = 11\%$, which approximates the average bank capital to loan ratio as set by the Basel Accords. The baseline parameter values also imply that at the steady state the rental rate of capital is, $r^k = 0.043$, as in Christiano et al. (2003).[16] The probability of default is set to, $\Phi = 3\%$ (annually) and the fraction of collateral received by the bank to $\chi = 97\%$.[17] The parameters that we solve for in the calibration are, $w,\ y,\ d,l,\ v,\ \xi^l, \xi^d, \xi^e,\ \overline{\omega}$ and $\underline{\omega}$; the lower and upper ranges of the idiosyncratic

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[16]The values of α, η, δ, λ_p, ζ_p, q, A, r^k and $S''[1]$, follow Christiano et al. (2003), and Christiano et al. (2014b). Christiano et al. (2003), has also a small government sector but here we distribute this share to investment.

[17]For the value of $\chi = 0.97$ see also Agénor et al. (2014).

Parameter	Value	Description
β	0.9949	Discount factor
α	0.40	Discount factor
η	1.00	Frisch elasticity of labour supply
δ	0.02	Capital depreciation rate
λ_p	6.00	Price elasticity of demand
ζ_p	0.50	Price stickiness
q	1.00	Steady state price of investment
A	1.00	Productivity mean
χ	0.97	Proportion of capital value seized at default
γ	0.11	Bank capital required ratio
S''	7.69	Curvature of investment-adjustment cost
ϱ	3.0	Reserve Adjustment cost parameter
ϑ	0.27	Collateral constraint ratio
ϕ_π	1.50	Interest rate responsiveness to inflation
ϕ_y	0.50	Interest rate responsiveness to output
ρ_R	0.90	Interest rate smoothing parameter

shock must also satisfy that their mean is unity, $Mean(\omega) = (\overline{\omega} + \underline{\omega})/2 = 1$. Finally, we employ the following aggregate shares, $n = 0.33$, $c/y = 0.80$, and $i/y = 0.20$.

3.8.1 Impulse Response Functions: A Precautionary Liquidity Shock

Figures 8 and 9 illustrate the effects of a large precautionary liquidity shock, $\widehat{\theta}_t$, with $\sigma^\theta = 10$ and $\rho_\theta = 0.90$. As shown in section, 3.4, the effects of such a shock are amplified the larger are, (i) the responsiveness of the bank to potential risk in assessing the cost of holding precautionary reserves, (φ), (ii) the higher is the actual potential risk in the economy (Φ), and (iii) the lower is the persistence exhibited in reserves, determined largely by the parameter b, which here we set to $b = 0.40$. In Figure 8 the red line shows the case where $\varphi = 10$, whereas the blue line considers a higher responsiveness of the bank to potential risk, with $\varphi = 15$. The precautionary liquidity shock increases the level of reserves but also the deposit rate. The increased reserves reduce the loan-to-deposit and the loan-to-reserve ratio, which in return reduce economic activity and prices in the real sector. The resulting recession reduces inflation and the interest rate (nominal and real) and, given the perceived potential risk, this increases the loan and equity spreads, and it also produces a positive deposit spread, $(R^D - R)$, as the deposit rate rises above the interbank rate. The increased deposit rate affects the intertemporal choices of households and through this channel it further reduces consumption, investment and thus output.

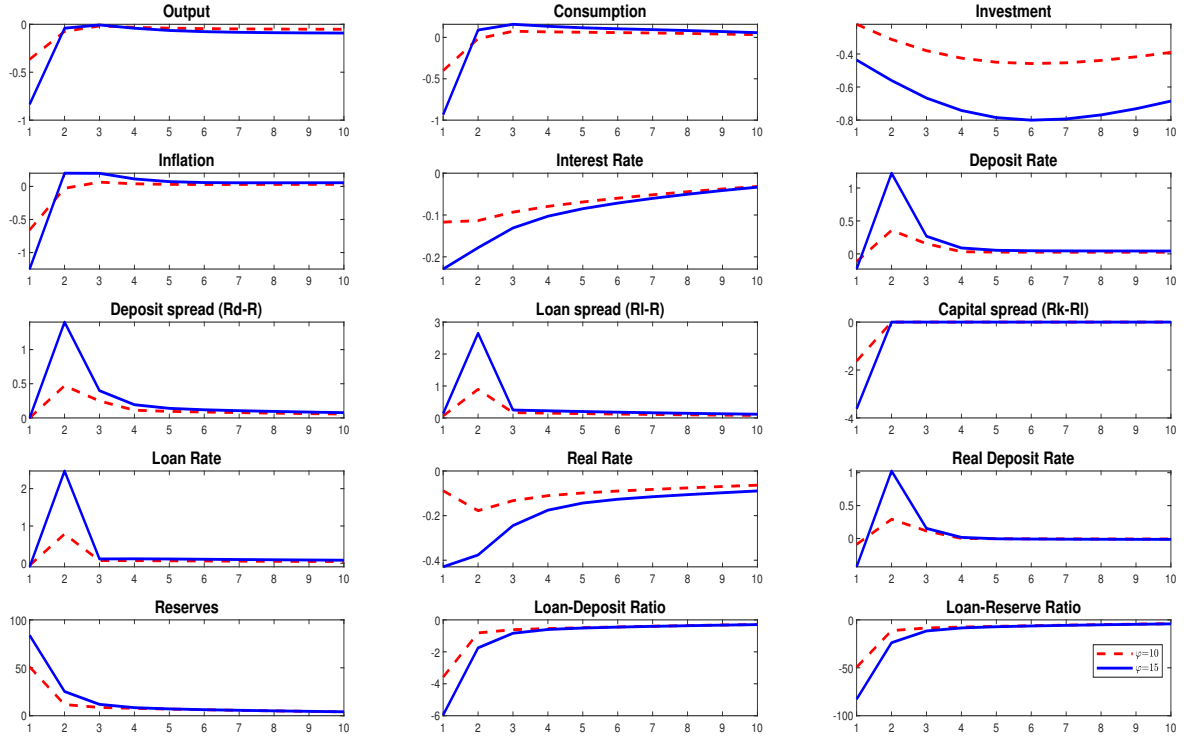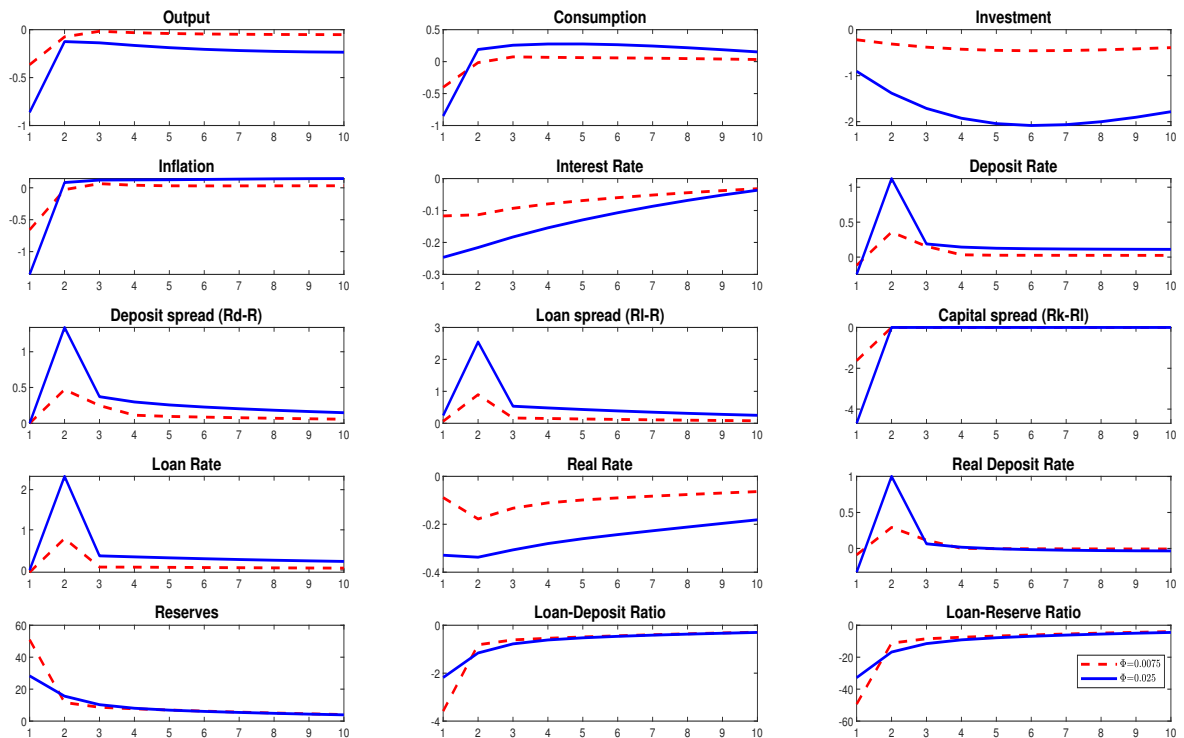Figure 8: Precautionary Liquidity Shock: Bank's responsiveness to potential risk, (φ)

Figure 9: Precautionary Liquidity Shock: Steady state probability of default, (Φ)

The overall result is a downward co-movement in output, consumption, investment and prices. These effects are shown to be amplified the higher is the responsiveness of the bank to potential risk (φ), and the higher is the steady state risk (Φ). The latter effect is shown in figure 9, where the steady state probability of default increases to 10% annually (blue line), from 3% in the baseline case, (red dotted line). Note that here reserves appear to increase by a smaller amount the higher is the steady state of default. This is because a higher steady state of default implies also a higher steady state level of reserves and thus, as a deviation from this higher level, the increase in reserves appears to be smaller. However, in this case, reserves are also shown to remain longer at a higher level, which captures the effects of higher long-run uncertainty and risk.

4   Conclusion

This paper identifies a credit supply disturbance that reflects changes in the banking system's preferences about liquidity. The shock is identified by employing sign, zero and forecast variance restrictions imposed only on bank related variables. It is shown to have significant macro-economic effects and to co-move GDP, consumption and investment. Using a threshold VAR model, we illustrate that the effects of the shock are state dependent and they arise only when the level of financial volatility in the economy is beyond a threshold level. That is, bankers are concerned about liquidity only when the level of uncertainty in the economy is high and they respond to this situation by restricting funding to the real economy. This latter effect, together with the specific restrictions imposed in identifying the shock, indicate that our credit supply shock is not a normal 'risk shock', but one that reflects sudden and exogenous changes in the way the banking system perceives risk, which result in an increase in precautionary liquidity, a higher return on safe liquid assets and an overall reluctance to lend. The transmission mechanism of the shock is explained with a DSGE model, that places this shock in the way that banks assess the cost of holding reserves for any given level of potential risk. A higher precautionary liquidity shock is shown to overturn what banks would normally perceive as a cost of hoarding reserves to a desired effect of precautionary liquidity, that increases reserves and the deposit rate. These two effects are shown to affect the balance sheet and the intertemporal decisions of households and firms, respectively, and result in a downward co-movement in output, consumption, investment and prices. Consistently with our threshold VAR results, these effects are shown to be amplified the more sensitive is the banking system to potential losses of liquidity and the higher is the long-run risk and thus uncertainty in the economy.

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