

A Macroeconomic Model of Liquidity, Wholesale Funding and Banking Regulation

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Recent liquidity regulation intends to prevent asset fire sales and credit crunch as experienced in the financial crisis of 2007-08. We develop a general equilibrium model with regulated banks to analyze the behavior of wholesale funding and the macroeconomic consequences of liquidity regulation. Liquidity regulation relaxes the bank credit constraint and leads to a crowding-in of loans. Flat liquidity regulation (as in Basel III) increases macroeconomic volatility and has ambiguous welfare implications. Cyclically-adjusted liquidity regulation is stabilizing and welfare-improving. Our empirical analysis suggests that holding liquidity when credit spreads are high renders banks less vulnerable to funding withdrawals.

JEL: E44, G21, G32

In the five years prior to the financial crisis of 2007-2009, the growth of U.S. commercial bank assets outpaced that of deposits (77 versus 53 percent). Strong asset growth was driven by a booming housing market and widespread securitization, as described in Gorton and Metrick (2010) and Brunnermeier (2009), among others. Retail deposits, on the other hand, continued to expand along their long-run trend. To achieve the desired expansion in assets, U.S. commercial banks tapped into wholesale funding. Figure 1 displays the evolution of deposits, equity and wholesale funding relative to assets; the data is quarterly Bank Hold-

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ing Company (BHC) balance sheet data from the Federal Reserve Y-9C report (FRY-9C). For every period, we report the average across all banks. Wholesale funding is calculated as funding other than retail deposits and equity and it includes short-term commercial papers, brokered or foreign deposits, repurchase agreements (repos), interbank loans and any other type of borrowing. Banks' reliance on deposits fell until the peak of the financial crisis in the third quarter of 2008, when Lehman Brothers collapsed, which corresponds to the vertical line in our graphs. Up to the financial crisis, equity remained stable as a fraction of assets and the wholesale ratio is the mirror image of the deposit ratio.

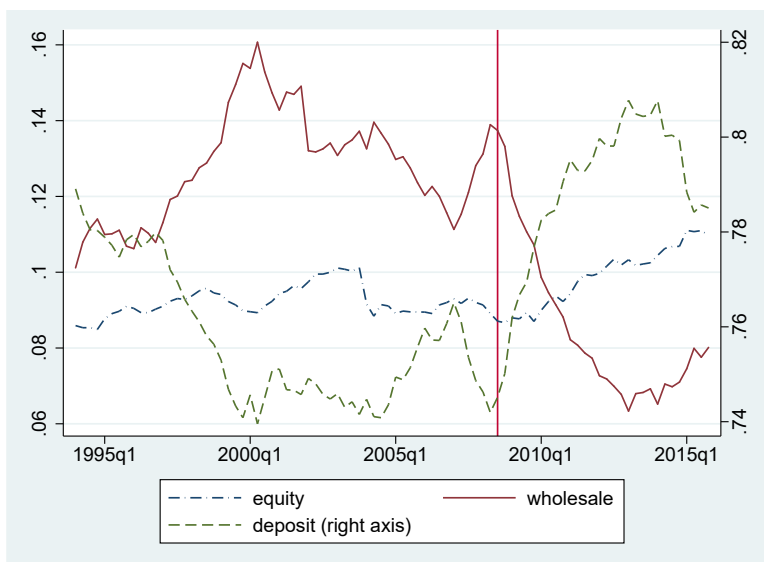


FIGURE 1. WHOLESALE, DEPOSIT AND EQUITY RATIOS

Source: FRY-9C.

The advantage of wholesale funding is that it is flexible, which allows banks to easily expand lending during good times. Dinger and Craig (2013) argue that retail deposits are sluggish and document that more volatile loan demand leads to a larger wholesale funding share. The flexibility of wholesale funding, however, becomes a drawback during periods of stress, as such funding can quickly evaporate and force banks into fire sales of assets. The wholesale ratio indeed fell

dramatically after the collapse of Lehman Brothers and, by the end of 2014, it was still less than half its pre-crisis level, as shown in Figure 1. Gorton and Metrick (2012) trace the core of the financial crisis to a run on repos. Depositors in repo contracts with banks worried about selling the collateral in a tumbling market and either raised haircuts or curtailed lending altogether. Other components of wholesale funding, however, fell even more than repos in the crisis, as shown in Figure 2. Deposits and repos are senior to these debts in case of bank default; when the risk that banks might fail went up, non-repo sources of wholesale funds quickly evaporated.

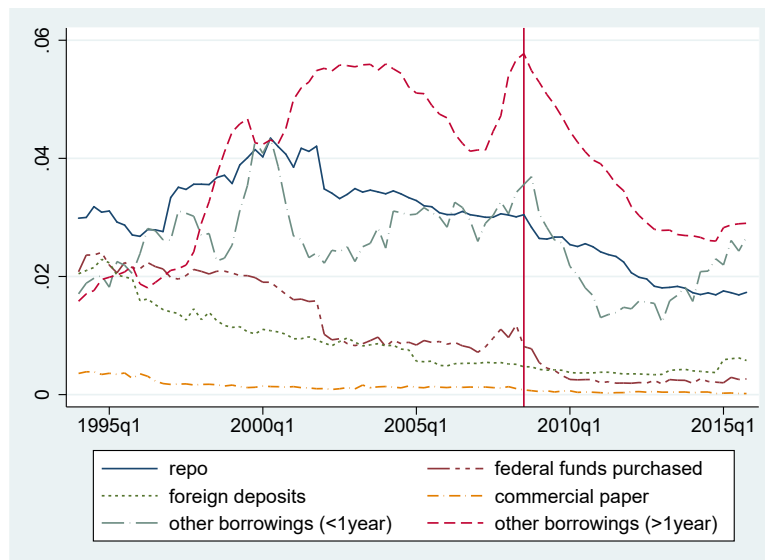


FIGURE 2. WHOLESALE FUNDING COMPONENTS (RATIOS)

Source: FRY-9C.

While increasingly relying on wholesale funds, banks steadily reduced their holdings of liquid assets in the period leading to the financial crisis. Figure 3 reports the evolution of the average BHC's liquidity ratio, i.e. liquid over total assets. Liquid assets are assets that, even during a time of stress, can be easily and immediately converted into cash at little or no loss of value. Our definition of liquid asset follows the high quality liquid asset (HQLA) definition of Basel III.

We include cash, federal funds sold, treasuries and agency securities, subject to a haircut of 15% and a 40% cap. Detailed definitions can be found in Appendix A. The liquidity ratio decreased persistently since the mid-90s and reached its trough at the onset of the financial crisis; the reduction was substantial – from 23 to 5 percent of total assets. When the crisis unfolded, unprecedented low levels of liquidity exacerbated the run by wholesale investors; the interbank market froze, and widespread default was avoided by massive injections of liquidity by the central bank.

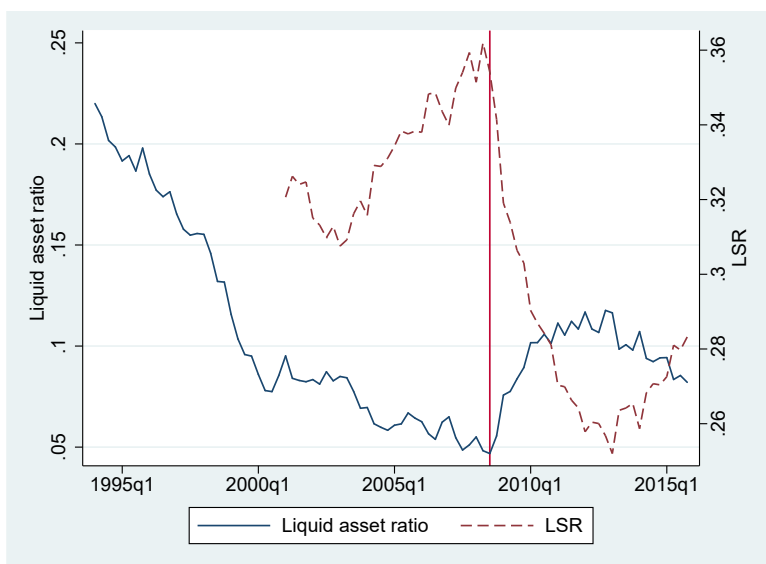


FIGURE 3. LIQUIDITY RATIO

Source: FRY-9C.

As argued above, banks raised short-term wholesale debt and reduced liquidity holdings in the pre-crisis period. At the same time, banks invested in illiquid assets with uncertain valuation. Following Choi and Zhou (2014), we build a Liquidity Stress Ratio (LSR) for the banks.¹ The LSR is the ratio of liquidity-adjusted liabilities and off-balance-sheet items to liquidity-adjusted as-

¹For an alternative measurements of liquidity mismatch, see Berger and Bouwman (2009), Brunnermeier, Gorton and Krishnamurthy (2014) and Bai, Krishnamurthy and Weymuller (2017).

sets. Liquidity-adjusted assets is the weighted average of bank assets where more liquid assets have higher weights. Liquidity-weighted liabilities and off-balance-sheet items are also weighted averages where the weights are smaller for more stable sources of funding. A higher value of the LSR indicates that a bank holds relatively more illiquid assets, relies on less stable funding, and it is therefore more exposed to liquidity mismatch. Further details on how we construct the LSR are provided in Appendix A. Figure 3 displays the evolution of the LSR.² The LSR peaks right before the financial crisis and then falls rapidly, bringing evidence of the build-up of liquidity risk during the years leading to the financial crisis.

Given the low levels of liquidity held by banks before the financial crisis, the Basel Committee on Banking Supervision introduced liquidity regulation requiring banks to hold at all times a minimum stock of liquid assets. The impact of liquidity regulation on macroeconomic variables is unknown. Banking sector advocates argue that higher liquidity holdings will crowd out productive loans, thereby leading to lower levels of economic activity. This is the partial equilibrium view: given liabilities, one dollar increase in liquid assets implies one dollar decrease in other loans. In general equilibrium, however, a bank's ability to borrow depends on its asset composition and liquidity holdings.

This paper proposes a general equilibrium dynamic macroeconomic model with banks and wholesale funding. Commercial banks (banks henceforth) raise external funds via deposits from households and wholesale debt from a wholesale lender that we refer to as the hedge fund; banks also raise internal funds via retained earnings. Each bank makes loans with an uncertain rate of return and, if the realized return is low, it goes bankrupt. In case of bank default, there is limited liability and deposits are senior to wholesale debt. Deposit insurance renders deposits safe from the perspective of the households, who have neither incentive to run on deposits nor to monitor the bank's activities. The hedge fund, on the

²The LSR is calculated since 2001Q1 because of a change in reporting of its components at that date.

other hand, is the junior creditor and its wholesale lending terms: a) ensure that the bank does not take excessive risk; b) are consistent with the expected rate of default and return that guarantees participation by the hedge fund. When bank loans become more risky, wholesale funding is reduced so as to ensure that lending terms are satisfied.

As long as loans to firms dominate liquid assets in terms of expected return, banks choose to hold zero liquidity if free to do so. In this setting, regulation forcing banks to hold some liquid assets has two effects. First, it cuts into banks' revenues and profits; second, it makes banks' asset portfolios safer. The former effect explains why liquidity regulation always binds in our model. The latter effect leads to an expansion of wholesale funding, bank leverage and lending to firms.

Our benchmark regulation is inspired by the Liquidity Coverage Ratio (LCR) of Basel III, and it requires banks to hold a constant fraction of deposits and wholesale funds in the form of liquid assets. In our model benchmark (flat hereafter) liquidity regulation raises steady-state welfare because it expands credit and economic activity at the steady state. When we consider shocks, however, the welfare implications of flat liquidity regulation are ambiguous. Intuitively, a shock that reduces wholesale funding also reduces bank required liquid holdings, which in turn leads to a further decrease in wholesale funding stemming from the increase in riskiness of banks' assets. As a result, wholesale debt is more volatile with flat regulation than without liquidity regulation altogether. A countercyclical liquidity regulation, i.e. with the same steady state as the flat regulation but requiring banks to hold a higher share of liquid assets during downturns, reduces wholesale funding volatility and unambiguously improves welfare both in conditional and unconditional terms.

Our theoretical model predicts that banks holding a higher ratio of liquid assets suffer a milder contraction in wholesale funding during a time of liquidity stress. We seek empirical evidence on this mechanism and carry out an analysis of the

behavior of wholesale funding and its relationship with liquidity holdings for U.S. BHCs between 1996Q1 and 2014Q4. Our empirical strategy relies on the within-bank variation in holding of liquid assets, together with size, equity and loan loss provisions, to explain the growth of wholesale funding. To capture the relationship between wholesale debt and liquidity during periods of elevated credit risk, we interact liquid assets holding with the TED spread. Our identification strategy is that the behavior of wholesale funding when credit risk (as measured by the TED spread) is high, is primarily driven by wholesale suppliers. Our regressions find a positive, significant relationship between the growth of wholesale funding and the liquidity ratio interacted with the TED spread, thereby lending empirical support to the hypothesis that banks with more liquid assets are less likely to suffer a run on their wholesale funding when financial market conditions are tight. The results suggest that holding liquidity when credit spreads are high renders banks less vulnerable to funding withdrawals; this also implies that banks can continue extending loans and avoid a credit crunch. Recent regulation requiring banks to hold minimum amounts of liquid assets can play an important role in reducing the volatility of bank funding and its effects on the economy.

The rest of the paper is organized as follows. In Section I we review the papers connected to our work. Section II presents the model; the calibration and quantitative analysis are in Section III and the welfare implications are in Section IV. The empirical analysis of liquidity and wholesale funding is relegated to Section V and Section VI concludes.

I. Related literature

Starting with Diamond and Dybvig (1983), the literature emphasizes the role of banks as liquidity providers. These authors show that bank liquidity provision improves economic outcomes but banks may be subject to harmful runs. Diamond and Rajan (2000, 2001) further show that bank fragility resulting from demand deposit is an essential feature of the bank. Demand deposits are a disciplining

mechanism for bankers and makes it possible for them to lend more. Angeloni and Faia (2013) introduce banks à la Diamond and Rajan (2001) in a dynamic macroeconomic model. More recently, Gertler and Kiyotaki (2015) develop a macroeconomic model with banks and sunspot bank-run equilibria. In all these papers, the main risk for the bank is a run by depositors. However, the existence of deposit insurance makes deposits a relatively safe source of funding for the bank. In our model there are no bank runs initiated by depositors because deposits are guaranteed by deposit insurance; the risk for the bank comes from wholesale funding.

Calomiris and Kahn (1991) build a model with demandable-debt, short-term wholesale debt falling into this category. In this environment, the banker has an informational advantage over demandable-debt depositors and he can divert realized returns for his own purposes. Early withdrawals and sequential service for depositors make demandable debt the optimal contract, as depositors have an incentive to monitor the banker, who can therefore pre-commit to higher pay-offs. Calomiris, Heider and Hoerova (2014) extend the model to include deposit insurance and argue that liquidity regulation plays a crucial role in mitigating moral hazard stemming from insurance. Huang and Ratnovski (2011) add a costless, noisy public signal as well as passive retail depositors to this setting. If demandable-debt depositors replace costly monitoring with the noisy public signal, early liquidations may exceed the optimal level. In our model retail deposits are insured and senior to demandable debt; information is symmetric. There is moral hazard for banks and demandable-debt depositors curtail loans to limit risk-taking by banks.

Gertler and Kiyotaki (2010) and Gertler, Kiyotaki and Queralto (2012) develop a dynamic macroeconomic model with financial intermediation. Banks are subject to moral hazard due to their ability to divert a fraction of assets. The friction gives rise to an endogenous balance sheet constraint that amplifies the effects of shocks. He and Krishnamurthy (2014) and Brunnermeier and Sannikov (2014)

propose a continuous-time nonlinear macroeconomic model with a financial sector. Both models feature strong amplification of shocks during systemic crises. Adrian and Boyarchenko (2017) consider the interaction of liquidity and capital requirements in a continuous-time nonlinear macroeconomic model and find that liquidity regulation lowers the probability of systemic bank distress without reducing consumption growth. Covas and Driscoll (2015) develop a model with heterogeneous banks and occasionally binding liquidity constraints. They find that liquidity regulation leads to a reduction of loans and output in steady state. These results contrast with the findings in our paper because our model encompasses wholesale funding and how its behavior depends on the composition and riskiness of bank assets.

Our theoretical work is related to Adrian and Shin (2014). The authors propose a theoretical model where financial institutions have the incentive to invest in risky, suboptimal projects; due to limited liability, this incentive becomes stronger with leverage. In equilibrium creditors withhold debt to reduce the leverage of financial institutions and induce them to invest only in safe projects. Nuño and Thomas (2017) implement the financial contract proposed by Adrian and Shin (2014) in a dynamic macroeconomic model. Their model explains bank leverage cycles as the result of risk shocks, namely of exogenous changes in the volatility of idiosyncratic risk. Our work builds on Adrian and Shin (2014) and Nuño and Thomas (2017), which we extend in several ways. First, our banks choose their liability structure, namely they choose between deposits and wholesale funding. Second, our banks are subject to liquidity regulation and deposit insurance.

Some papers have explored the empirical relationship between reliance of wholesale funding and lending during the recent financial crisis. Dagher and Kazimov (2012) use loan-level data from 2005 to 2008 and test whether banks more reliant on wholesale funding were more likely to reject loan applications. They find that banks with higher wholesale funding experienced a significantly larger contraction in the volume of credit in 2008. de Haan, van den End and Vermeulen (2017) use

monthly data of 181 Euro area banks to study the response of shocks in wholesale funding over the period August 2007 to June 2013. Their panel VAR analysis suggests that credit supply to non-financial corporations was significantly curtailed and loan rates raised. They also find evidence that central bank intervention successfully mitigated the adverse effect of wholesale funding shocks. Our empirical investigation aims to capture the relationship between holding of liquid assets and wholesale debt.

Another strand of the literature measures bank's exposure to liquidity risk during the crisis more generally and then exploits its cross-sectional variation to estimate the impact of exposure on the supply of bank credit. Ivashina and Scharfstein (2010) define liquidity risk as exposure to wholesale funding and drawdowns from credit lines; they use the percentage of credit lines co-syndicated with Lehman Brothers to approximate for unexpected drawdowns on credit lines. They find that higher exposure to liquidity risk reduced credit during the financial crisis. Banerjee and Mio (2017) consider the implementation of new liquidity regulation in the United Kingdom and find that tighter liquidity regulation does not lead to bank lending reduction nor to an increase in lending rates. Cornett et al. (2011) use the TED spread as an indicator of credit risk in the economy and interact it with bank-level liquidity exposure measures. The results suggest that banks with higher liquidity risk experience stronger negative effect on lending and credit origination when the TED spread is high. Our empirical analysis builds on Cornett et al. (2011) but analyzes the relationship between liquidity and wholesale funding during normal and stress times.

II. Model

The economy consists of several actors. Households can save using insured deposits, risk-less bonds and shares in the hedge fund. The hedge fund is a financial intermediary that raises funds from households to finance banks. Banks raise deposits from households, subordinated wholesale funding from the hedge fund

and accumulate retained earnings. Banks lend to firms subject to idiosyncratic risk and can default when their asset value is low. There is a continuum of firms subject to idiosyncratic risk; each firm receiving a loan from the local bank. Capital producers transform consumption goods into capital subject to adjustment costs. The government runs the deposit insurance scheme and provides the liquid asset. We now describe each agent in detail.

A. Households

We look at a representative household that maximizes utility. The household chooses how much to consume (C_t) and how many hours to work (L_t) at the wage w_t . Household can save using insured bank deposit (D_t), treasury bills (TB_t^h) and hedge fund equity (M_t). The maximization problem of the household can be written as follows:

$$(1) \quad \max_{C_t, D_t, M_t, L_t, TB_t} E_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{C_t^{1-\gamma}}{1-\gamma} - \eta \frac{L_t^{1+\varphi}}{1+\varphi} \right]$$

$$(2) \quad \text{s.t.} \quad C_t + D_t \left(1 + \frac{\chi_d}{2} (D_t - \bar{D})^2 \right) + M_t + TB_t^h = \\ L_t w_t + R_{D,t-1}^H D_{t-1} + R_{M,t} M_{t-1} + R_{TB,t-1} TB_{t-1}^h + \Pi_t - T_t,$$

where γ is the intertemporal elasticity of substitution, η is the disutility from labor and φ is the inverse of the Frisch elasticity of labor supply. Π_t are net transfers from the banks and the capital producers and T_t are lump-sum taxes. All variables in our model are real.

The rate of return on deposits ($R_{D,t-1}^H$) and treasury bills ($R_{TB,t-1}$) are perfectly safe and predetermined, which is why we index them by $t-1$. Hedge fund equity is “risky” in the sense that the return on the hedge fund equity ($R_{M,t}$) is

state contingent, so it is indexed by t . The household faces quadratic adjustment costs to deposits; these costs capture the fact that deposits are relatively inflexible, as documented by Flannery (1982) and Song and Thakor (2010). The idea is that households hold deposits (\bar{D}) in steady state and changing the allocation implies costs χ_d that can be interpreted as fees stemming from low balances or from opening an additional account. The first order conditions of the households are in Appendix B.

B. Firms

Firms are perfectly competitive and segmented across a continuum of islands indexed by $j \in [0, 1]$. Firms are subject to an idiosyncratic capital quality shock ω_t^j that changes the effective capital of firm j to $\omega_t^j K_t^j$. There is also an aggregate capital quality shock Ω_t . Firm j produces the final good Y_t^j using capital K_t^j , labor L_t^j , the aggregate technology Z_t and a standard Cobb-Douglas production function. Firms choose labor to maximize their their operating profit:

$$(3) \quad \max_{L_t^j} Z_t (\Omega_t \omega_t^j K_t^j)^\alpha (L_t^j)^{1-\alpha} - w_t L_t^j.$$

Labor is perfectly mobile across islands, which ensures that wages are equalized. At time $t - 1$, firms purchase capital K_t^j at price Q_{t-1} from the capital producer. They finance their purchase of capital using loans from banks. Following Gertler and Kiyotaki (2010) bank loans are modeled as state contingent securities, like equity: each unit of the security is a state contingent claim on the future return on capital. After production takes place in period t , firms pay labor, sell back depreciated capital to the capital producer and repay loans from banks. Firms' operating profit and proceeds from sale of depreciated capital are used to repay banks. Perfect competition and constant return to scale ensure zero profit for firms state by state. Firms can only borrow from the bank situated on the same island; hence, their balance sheet constraint is given by $K_t^j = A_{t-1}^j$. Therefore,

banks in our model are also subject to non-diversifiable risk. The equations of the firms are in Appendix B.

On each island there are two types of firms: standard and substandard. The two types of firms differ only in the distribution of idiosyncratic risk, which at time t is $F_{t-1}(\omega)$ for the standard firm and $\tilde{F}_{t-1}(\omega)$ for the substandard firm. We follow Nuño and Thomas (2017) and assume that the distribution of the idiosyncratic shocks is known one period in advance.³ The substandard distribution has lower mean but higher variance than the standard one. Substandard firms never operate in equilibrium but create a moral hazard problem for the banks. The distribution of the standard and the substandard firms at time $t + 1$ are

$$(4) \quad \begin{aligned} \log(\omega) &\overset{iid}{\sim} N\left(\frac{-\sigma_t^2}{2}, \sigma_t\right), \\ \log(\tilde{\omega}) &\overset{iid}{\sim} N\left(\frac{-v\sigma_t^2 - \vartheta}{2}, \sqrt{v}\sigma_t\right). \end{aligned}$$

The parameter $\vartheta > 0$ captures the difference in the mean and the parameter $v > 0$ captures the difference in the variance between the distributions.

C. Capital producer

There is a representative capital producer. The capital producer buys the final good in amount I_t at the (real) price of one and transforms it into new capital subject to adjustment costs $S(\frac{I_t}{I_{t-1}})$. The new capital is then sold at the price Q_t . The capital producer chooses investment optimally to maximize its expected profits. The maximization problem of the capital producer is

$$(5) \quad \max_{I_t} E_0 \sum_{t=0}^{\infty} \Lambda_{0,t} \left(Q_t (1 - S(\frac{I_t}{I_{t-1}})) I_t - I_t \right).$$

³This assumption simplifies the analysis: at time t the agents know the distribution of idiosyncratic risk in the next period and form their expectations accordingly.

Profits of the capital producer (Π_t^{cap}) are transferred to the households in a lump-sum fashion. We use the households pricing kernel $\Lambda_{0,t} = \beta^t \frac{C_t^{-\gamma}}{C_0^{-\gamma}}$ to discount the profits of the capital producer. The first order condition of the capital producer is given in Appendix B.

D. Banks

Banks are segmented across a continuum of islands indexed by $j \in [0, 1]$. Each bank raises external funds in the form of deposits from households and wholesale funding from a hedge fund; it also accumulates net worth by retaining earnings. Bank funds are either lent to the firm located on the same island or invested in the risk-free bond issued by the government. The balance sheet constraint of bank j in t is

$$(6) \quad Q_t A_t^j + T B_t^j = N_t^j + B_t^j + D_t^j,$$

where D_t^j are deposits, B_t^j is wholesale debt, N_t^j is net worth, $Q_t A_t^j$ is the loan to the local firm and $T B_t^j$ is holding of the risk-free bond. As explained in Section II.B, bank loans are state-contingent securities subject to idiosyncratic risk.⁴ Bank loans pay the realized gross rate of return $\omega_{t+1}^j Q_t A_t^j R_{t+1}^A$, where R_{t+1}^A is the aggregate return and it is equal to

$$R_{t+1}^A \equiv \frac{\alpha Z_{t+1} \Omega_{t+1} (L_{t+1} / (\Omega_{t+1} K_{t+1}))^{1-\alpha} + (1 - \delta) \Omega_{t+1} Q_{t+1}}{Q_t}.$$

The risk-free bond, on the other hand, pays the pre-determined rate $R_{TB,t}$. On the liability side, the bank borrows B_t^j from the hedge fund under the promise to repay \bar{B}_t^j in the following period. Barring default, the net worth of bank j in

⁴In this economy there is a strong case for pooling all bank loans into a single security paying the aggregate return to capital, which we assume not to be feasible.

period $t + 1$ is given by

$$(7) \quad N_{t+1}^j = \omega_{t+1}^j R_{t+1}^A Q_t A_t^j + R_{TB,t} T B_t^j - R_{D,t}^B D_t^j - \bar{B}_t^j,$$

where $R_{D,t}^B$ is the gross cost per unit of deposit that we explain in detail below.

Banks retain all earnings so as to overcome their financial constraint. To keep them relying on external funding, we assume banks exit with exogenous probability $1 - \epsilon$, at which point their accumulated earnings are paid out as dividends to households. In our model banks exit also due to default, in which case retained earnings are used to repay depositors and the hedge fund. We assume limited liability, i.e. banks are responsible only up to their assets in case of default. Default happens when bank asset returns are not sufficient to cover liabilities. We define $\bar{\omega}_{t+1}^j$ to be the threshold of idiosyncratic risk such that

$$(8) \quad R_{t+1}^A \bar{\omega}_{t+1}^j Q_t A_t^j + R_{TB,t} T B_t^j = R_{D,t}^B D_t^j + \bar{B}_t^j.$$

Banks experiencing realizations of idiosyncratic risk below $\bar{\omega}_{t+1}^j$ are unable to repay deposits and wholesale debt and declare bankruptcy.

We assume that wholesale debt is uncollateralized and junior to deposits in the event of bank default. This means that, in case of default, bank assets are liquidated to pay depositors first and then (partially) the hedge fund. Defaulting banks are replaced by new ones. Seniority among bank creditors leads to a second threshold $\bar{\bar{\omega}}_{t+1} < \bar{\omega}_{t+1}$ such that

$$(9) \quad R_{t+1}^A \bar{\bar{\omega}}_{t+1}^j Q_t A_t^j = R_{D,t}^B D_t^j - R_{TB,t} T B_t^j.$$

For idiosyncratic realizations between $\bar{\bar{\omega}}_{t+1}$ and $\bar{\omega}_{t+1}$ depositors are fully repaid and the hedge fund is the residual, partial claimant of remaining assets. For realizations below $\bar{\bar{\omega}}_{t+1}$, however, bank assets are not even sufficient to cover

deposits.

The government provides deposit insurance. Fees are collected from all banks and channeled to the government who covers losses to households in case of bank default on deposits. In our model deposit insurance premia have two features. First, they increase with the expected probability of default $E_t F_t(\bar{\omega}_{t+1})$. In the United States, Federal Deposit Insurance Corporation (FDIC) fees are indeed based on banks' overall conditions as measured by the Camels rating system, with riskier and less-capitalized banks paying higher premia. Second, deposit insurance premia rise when default is expected to be above average. FDIC fees have indeed been countercyclical, since they are raised during recessions, when the deposit insurance fund is drawn down and vice versa during expansions. Formally, our deposit insurance fee is given by

$$(10) \quad DI_t = \left(1 + \iota + \frac{E_t(\omega_{t+1}^{\bar{\omega}}) - \bar{\omega}^{ss}}{\bar{\omega}^{ss}} \right) E_t(F_t(\bar{\omega}_{t+1})),$$

where ι is a positive constant and $\bar{\omega}^{ss}$ is the steady-state value of $\bar{\omega}$. The unit cost of deposit is therefore equal to

$$(11) \quad R_{D,t}^B = R_{D,t}^H(1 + DI_t).$$

We follow Adrian and Shin (2014) and assume that banks can finance standard or substandard firms, as argued in Section II.B. Limited liability causes moral hazard: the bank prefers to invest in the substandard firm because it offers higher upside risk relative to the standard firm. Since households are atomistic and perceive deposits as safe, they have no incentive to monitor the bank. This is not the case for the hedge fund. The wholesale rate is pre-determined and it reflects the probability of default, which depends on the bank's lending choice. The hedge fund sets the wholesale rate *conditional* on the standard firm being financed and then it chooses wholesale debt to ensure the bank is indeed better off by doing

so. As explained in Section II.B, the distributions of the idiosyncratic shocks are known one period in advance. When lending to the banks, the hedge fund then knows how risky their assets will be under either the standard or substandard distributions and can ensure they invest optimally. As in principal-agent models à la Holmstrom and Tirole (1997), the hedge fund sets \bar{B}_t^j to limit the option value of limited liability:⁵

$$(12) \quad \begin{aligned} E_t \Lambda_{t,t+1} \int_{\bar{\omega}_{t+1}^j} \left(\epsilon V_{t+1}(N_{t+1}^j) + (1 - \epsilon) N_{t+1}^j \right) dF_t(\omega) &\geq \\ E_t \Lambda_{t,t+1} \int_{\bar{\omega}_{t+1}^j} \left(\epsilon V_{t+1}(N_{t+1}^j) + (1 - \epsilon) N_{t+1}^j \right) d\tilde{F}_t(\omega). \end{aligned}$$

Equation (12) is the incentive-compatibility constraint (ICC) ensuring that the bank is better off lending to the standard firm relative to the nonstandard one. The expected return to wholesale funding must be at or above $R_{TB,t}$ since the hedge fund has the option to invest in risk-free government bonds. Hence the hedge fund chooses B_t^j to satisfy its participation constraint.

$$(13) \quad \begin{aligned} E_t \Lambda_{t,t+1} \left\{ \bar{B}_t^j (1 - F(\bar{\omega}_{t+1}^j)) + R_{t+1}^A Q_t A_t^j \int_{\bar{\omega}_{t+1}^j}^{\bar{\omega}_{t+1}^j} \omega_{t+1} dF_t(\omega) \right. \\ \left. - \left(F(\bar{\omega}_{t+1}^j) - F(\bar{\omega}_{t+1}^j) \right) (R_{D,t}^B D_t^j - R_{TB,t} T B_t^j) \right\} \geq E_t \left\{ \Lambda_{t,t+1} R_{TB,t} B_t^j \right\}. \end{aligned}$$

In our benchmark model without liquidity regulation, the objective of continu-

⁵The bank expected profit can be written as

$$R_{t+1}^A Q_t A_t^j \left(E(\omega) - \bar{\omega}_{t+1}^j + \underbrace{\int_0^{\bar{\omega}_{t+1}^j} (\bar{\omega}_{t+1}^j - \omega) dF_t(\omega)}_{\equiv \pi_t(\bar{\omega}_{t+1}^j)} \right),$$

where $\pi_t(\bar{\omega}_{t+1}^j)$ is the value of a put option with strike price $\bar{\omega}_{t+1}^j$. Under our distributional assumptions, $\bar{\pi}_t(\bar{\omega}_{t+1}^j) > \pi_t(\bar{\omega}_{t+1}^j)$ so the option value of limited liability is greater under the substandard technology.

ing bank j at the end of period t can be written as

$$(14) \quad V_t(N_t^j) = \max_{A_t^j, B_t^j, \bar{B}_t^j, D_t^j, TB_t^j} E_t \Lambda_{t,t+1} \int_{\bar{\omega}_{t+1}^j} \left(\epsilon V_{t+1}(N_{t+1}^j) + (1 - \epsilon) N_{t+1}^j \right) dF_t(\omega),$$

where $V(N_t^j)$ is the value of the bank at t . The bank maximizes its value, namely the expected discounted value of its final dividend payment subject to the bank balance sheet constraint (6), the evolution of net worth (7), the incentive-compatibility constraint (12) and the participation constraint (13).

LIQUIDITY REGULATION. — The Basel Committee on Banking Supervision introduced the LCR in 2013 to promote short-term resilience of banks to liquidity stress. The LCR is the stock of high-quality liquid assets (HQLA) over the total net cash outflow over the next 30 days. Basel III requires this ratio to be at least 100%. The goal is to ensure that the bank has enough liquid assets to withstand a 30-days liquidity stress scenario. In order to qualify as HQLA, assets should be liquid in markets during a time of stress and, in most cases, be eligible for use in central bank operations. Certain types of assets within HQLA are subject to a range of haircuts. Expected cash outflows are calculated by multiplying the outstanding balances of various types of liabilities and off-balance sheet commitments by the rates at which they are expected to run off or be drawn down under a stress scenario. In the United States, Federal Banking Regulators issued the final version of the LCR in September 2014; the main difference relative to Basel III's LCR standard is in the shorter implementation period requiring U.S. banks to be fully compliant by January 2017.

We introduce liquidity regulation on banks in the spirit of the LCR of Basel III. In our model, the high-quality liquid asset is the government bond; the stress scenario is a withdrawal rate on deposits and wholesale funding equal to ξ_t . Formally

the LCR constraint is

$$(15) \quad TB_t^j \geq \xi_t(D_t^j + B_t^j).$$

We first consider a LCR-type regulation, which we refer to as flat, where ξ is constant; then we go beyond the LCR and propose a countercyclical liquidity regulation where the coefficient ξ_t vary with the business cycle as follows:

$$(16) \quad \xi_t = \bar{\xi} - \chi_y(Y_t - \bar{Y}),$$

where \bar{Y} is steady-state output and χ_y is a positive constant. Intuitively, the stress scenario envisions higher withdrawal rates of deposits and wholesale funding during economic downturns.⁶

In the economy with liquidity regulation, continuing bank j maximizes (14) subject to (6), (7), (12), (13) and the LCR constraint (15). The problem and the relevant first-order conditions can be found in Appendix B.

E. Hedge fund

The hedge fund is an institution that issues equity (M_t) to households and lends to banks in the form of uncollateralized debt (B_t). Hedge fund equity pays a state-contingent rate of return ($R_{M,t+1}$). The payoff of the hedge fund from lending to bank j can be written as

$$(17) \quad \min(\bar{B}_t^j, \max(0, R_{t+1}^A \omega_{t+1}^j Q_t A_t^j + R_{TB,t} TB_t^j - R_{D,t} D_t^j)).$$

The first term (\bar{B}_t^j) is the payoff to the hedge fund when bank j does not default. The second term indicates the payoff to the hedge fund when bank j defaults. In

⁶Bai, Krishnamurthy and Weymuller (2017) argue it is important to account for the macroeconomic conditions when calculating bank liquidity shortfall.

this case, the hedge fund receives the residual value of assets after paying depositors $(R_{t+1}^A \omega_{t+1}^j Q_t A_t^j + R_{TB,t} TB_t^j - R_{D,t} D_t^j)$ if it is positive and zero otherwise. Since the hedge fund lends to all banks, it is exposed to aggregate but not to idiosyncratic risk. Aggregating across all banks, the gross return to the hedge fund is

$$(18) \quad R_{M,t+1} M_t = \bar{B}_t^j (1 - F(\bar{\omega}_{t+1})) + R_{t+1}^A Q_t A_t^j \int_{\bar{\omega}_{t+1}}^{\bar{\omega}_{t+1}} \omega_{t+1} dF_t(\omega) \\ - (F(\bar{\omega}_{t+1}) - F(\bar{\omega}_{t+1})) (R_{D,t}^B D_t^j - R_{TB,t} TB_t^j).$$

Bank liquidity TB_t^j has a positive impact on the gross return to the hedge fund because it increases the liquidation value in case of default. Deposits, on the other hand, have a negative impact on the gross return to the hedge fund. Since deposits are paid first in case of default, more deposits reduce the resources available to the hedge fund to cover its losses.

F. Government

The government issues the safe asset (TB) in fixed supply, provides deposit insurance and raises lump-sum taxes T_t . Its budget constraint is as follows:

$$(19) \quad TB^{supp} + T_t + Ins_t^{fee} = R_{TB,t-1} TB^{supp} + Ins_t^{pay},$$

Ins^{fee} is deposit insurance fees collected from banks and Ins^{pay} is insurance payout to households. The two are not necessarily equal, so the difference is collected or redistributed to households via lump-sum taxes. The government must balance its budget every period. Ins^{fee} and Ins^{pay} are given by

$$(20) \quad Ins_t^{fee} = R_{D,t-1}^H D_{t-1} D I_{t-1} (1 - F_{t-1}(\bar{\omega}_t)),$$

$$(21) \quad Ins_t^{pay} = R_{D,t-1}^H D_{t-1} F_{t-1}(\bar{\omega}_t).$$

Treasury bills are either held by the households or by the banks. The bank holding of treasury bills is determined by liquidity regulation while households hold the residual supply:

$$(22) \quad TB_t^{supp} = TB_t^h + TB_t.$$

G. Solution and aggregation

A solution to the model is an equilibrium where banks, households, firms and capital producers are optimizing and all markets clear. Following Nuño and Thomas (2017), we guess and verify the existence of a solution where bank balance sheet ratios and default thresholds are equalized across all islands. Banks in different islands are different in terms of size, but they all choose the same leverage, deposit, wholesale funding and safe asset ratios; hence, we can aggregate the banking sector. Aggregating the flow of funds constraint across all continuing banks we find that the evolution of aggregate net worth of continuing non-defaulting banks is given by

$$(23) \quad N_t^{cont} = \epsilon R_t^A Q_{t-1} A_{t-1} \int_{\bar{\omega}_t}^{\infty} (\omega - \bar{\omega}_t) dF_{t-1}(\omega).$$

Every period, new banks enter to replace exiting ones. Each new bank receives a transfer $\tau(Q_t A_{t-1} + TB_{t-1})$ from households. The transfer corresponds to the fraction τ of total assets in the banking sector at the beginning of the period. We assume that the new banks start with the same balance sheet ratios as the continuing banks. The total net worth of new banks is

$$(24) \quad N_t^{new} = [1 - \epsilon(1 - F_{t-1}(\bar{\omega}_t))] \tau(Q_t A_{t-1} + TB_{t-1}).$$

The net transfer from banks to households (Π_t^{banks}) is equal to the net worth of

exiting non-defaulting banks minus the transfer to new banks:

$$(25) \quad \Pi_t^{banks} = \frac{(1 - \epsilon)}{\epsilon} N_t^{cont} - N_t^{new}.$$

Total transfers to households are given by the profit from the capital producers and the transfer from the banks: $\Pi_t = \Pi_t^{banks} + \Pi_t^{cap}$. The model can be reduced to a set of 28 equations that are given in Appendix B.

III. Quantitative analysis

A. Calibration

The standard real business cycle parameters $(\alpha, \beta, \gamma, \delta, \chi, \varphi, \eta)$ follow Nuño and Thomas (2017) and are set in line with the macro literature. The steady-state level of technology \bar{z} is chosen to normalize steady-state output to 1. The fraction of total assets transferred to new banks τ is set to target an investment to output ratio of 20%.

Our model economy is calibrated to obtain steady-state values of the bank balance sheet ratios in the unregulated model in line with average pre-regulation values in the data. Table 1 shows summary statistics for the leverage, wholesale funding and deposit ratios as well as the LSR. The empirical moments are calculated using quarterly BHC balance sheet data from the FR Y-9C from 1994Q1 to 2012Q4. The liquidity, wholesale funding and deposit ratios are calculated by dividing the relevant measure by total assets. Leverage ratio is total assets divided by equity. The LCR regulation started being phased in in 2015, but banks anticipated it and adjusted in advance. Hence, we end our sample in 2012Q4 to ensure data is not affected by regulation.⁷

The steady-state idiosyncratic volatility $\bar{\sigma}$ is calibrated to target a leverage ratio of 10 and the variance of the substandard technology v is chosen to generate a

⁷We also ended the sample in 2011Q4 and 2010Q4 and the summary statistics are barely affected.

TABLE 1—BALANCE SHEET RATIO MOMENTS

	mean		standard deviation	
	Data	Model	Data	Model
Deposit ratio	0.763	0.80	0.024	0.024
Leverage ratio	10.82	10	0.048	0.033
Wholesale ratio	0.12	0.10	0.2	0.2
Liquidity Stress Ratio	0.315	0.36	0.099	0.1

Sample: 1994Q1 to 2012Q4

Empirical mean and standard deviation are calculated by first taking the average across all banks for every quarter and then taking respectively the average and the standard deviation for all quarters.

Model and empirical standard deviations are calculated on logged variables.

wholesale funding ratio of 10%. Consistent with Adrian and Shin (2014) and Nuño and Thomas (2017), we find that leverage is procyclical. The correlation with output is 0.21 in the data and 0.31 in the model. The variable ϑ is set so as to ensure it is never optimal for the economy to let the banks invest in the substandard technology to avoid the cost related to moral hazard (see Appendix D).

Table 1 shows that deposits were considerably less volatile than wholesale funding; this evidence points towards stickiness of deposits, as argued in Section II.A, which is a feature that helps us calibrate the model. The scaling factor of shocks ς and the parameter for deposit stickiness χ_d are chosen to match the volatilities of output and deposit ratio, respectively. The volatility of output is 0.012 in the data and the model.⁸ The parameters $(\theta, \rho_z, \sigma_z, \rho_\sigma, \sigma_\sigma)$ follow Nuño and Thomas (2013) and $(\rho_\kappa, \sigma_\kappa)$ follow Nuño and Thomas (2017).

The model LSR is calculated as

$$(26) \quad LSR_t = \frac{B_t + 0.1 \times D_t}{0.5 \times Q_t A_t + TB_t}$$

The weights on deposits, treasury bills and wholesale funding follow directly from our empirical measure of LSR.⁹ We calibrate the weight on loans so that our

⁸The real GDP and population data comes from the Federal Reserve Bank of St Louis Economic Data (FRED); We calculate the log of real GDP per capita and hp-filter it.

⁹The weight of one on B_t mirrors the empirical weight on the most illiquid type of wholesale funding. See Appendix A for the data calculations.

model steady-state LSR matches the average value of the LSR in the data.

Basel III specifies a 5% run-off rate on deposits under stress scenario; we use this number for our liquidity regulation. In the model with regulation, banks are required to hold 5% of liquid assets against their deposits and wholesale funding ($\bar{\xi}=0.05$). In the version of the model with countercyclical regulation, banks are required to hold an additional 0.5% of liquid assets for every percentage point of GDP below steady state ($\chi_y = 0.5$). All the regulatory parameters are set to zero in the unregulated model. The total supply of treasury bills is set at 2, i.e. 200% of GDP. This parameter does not have any impact on the model behavior but it needs to be high enough to ensure that banks have access to treasury bills to cover their regulatory requirements. The full calibration is given in Table 2.

TABLE 2—CALIBRATION

Parameter	Value	Description
Standard RBC parameters		
β	0.99	discount factor
α	0.36	share of capital in production
δ	0.025	depreciation rate
χ	0.5	adjustment cost on investment
χ_d	0.00008	adjustment cost on deposits
φ	1	inverse elasticity of labor supply
γ	1	intertemporal elasticity of substitution
η	1	disutility of labor
\bar{z}	0.5080	steady-state TFP
ρ_z	0.9297	serial correlation TFP shock
σ_z	0.0067	standard deviation TFP shock
Financial parameters		
$\bar{\sigma}$	0.06988	steady-state idiosyncratic volatility
v	4.2899	variance substandard technology
ϑ	0.04	shift in mean of substandard technology
τ	0.05846	share of asset transfer into new banks
θ	0.75	survival probability of banks
ρ_σ	0.9457	serial correlation risk shock
σ_σ	0.0465	standard deviation risk shock
ι	0.0005	deposit insurance fee parameter
ρ_κ	0.3591	serial correlation capital quality shock
σ_κ	0.0081	standard deviation capital quality shock
ς	0.115	scaling parameter for all shocks
Regulatory parameters		
ξ	0.05	steady-state regulatory parameter
χ_y	0.5	cyclical regulatory parameter
TB^{supp}	2	total supply of treasury bills

B. Steady-state analysis

The steady-state values of the key variables of the model are given in Table 3. Regulation requires banks to hold safe assets to cover 5% of their deposits and wholesale funding. In the unregulated model, banks do not hold safe assets and the liquidity ratio is zero. Indeed, since the return on treasury bills is lower than the return on loans, banks choose not to hold any treasury bill in the absence of liquidity regulation. Thus, liquidity regulation is always binding in our model and it implies an increase in the liquidity ratio.

TABLE 3—STEADY STATE

	Unregulated	Regulated
Bank balance sheet ratios		
Deposit ratio	0.8000	0.8084
Wholesale ratio	0.1000	0.0954
Liquidity ratio	0.0000	0.0452
Leverage ratio	10.000	10.3996
Liquidity Stress Ratio	0.3600	0.3373
Bank balance sheet items (levels)		
Total deposits	6.4000	6.9859
Total Wholesale funding	0.8000	0.8247
Net worth	0.8000	0.8309
rates of return and default probabilities		
R^A	1.0200	1.0192
wholesale rate	1.0251	1.0251
Default probability	0.0568	0.0568
Default on deposit probability	0.0005	0.0005
Real variables		
Consumption	0.8000	0.8064
Labor	0.8944	0.8965
Capital	8.0000	8.2510
Output	1.0000	1.0127

The default probabilities and default thresholds $\bar{\omega}$ and $\bar{\bar{\omega}}$ are independent from liquidity regulation. $\bar{\omega}$ is pinned down by the ICC, Equation (12), which in steady state simplifies to

$$(27) \quad E(\omega) - \tilde{E}(\omega) = \tilde{\pi}(\bar{\omega}) - \pi(\bar{\omega}).$$

Intuitively, the ICC is satisfied (with equality) when the higher expected return

from standard firm is exactly compensated by the lower put option value relative to nonstandard firm. Equation (27) depends only on the distribution of returns and there is a unique value of $\bar{\omega}$ that solves this equation. $\bar{\omega}$ is pinned down by deposit demand of households and deposit supply of banks, which simplify as follows:

$$(28) \quad F(\bar{\omega}) = 1 - \frac{1}{1 + \iota}.$$

The steady-state probability of default on deposits depends only on ι . In steady state, bank payment to deposit insurance must cover payment to depositors of failed institutions ($Ins_t^{fee} = Ins_t^{pay}$). The higher ι , the more resources there are to cover failed institutions, and banks can raise more deposits and default on them. Hence, the probability of default on deposits is an increasing function of the insurance fee.

The portfolio of assets held by the regulated bank is safer relative to the portfolio held by unregulated banks because a positive fraction is invested in the safe asset. Since bank assets are safer, the moral hazard problem is reduced and banks can increase their leverage. This is to say that holding safe assets does not crowd out credit to firms but rather crowds it in: total loans (Capital) is higher in the regulated model relative to the unregulated one. The reason is that the bank is able to leverage up while keeping the same probability of default because its portfolio of assets is safer. Regulated banks borrow more; both deposits and wholesale funding increase, although deposits go up more than wholesale funding, so that the deposit ratio increases with regulation. Liquidity regulation reduces the steady-state value of the LSR: banks are more leveraged but, at the same time, they carry less liquidity mismatch on their balance sheet.

Since liquidity regulation allows the bank to expand its assets and to leverage up, one may wonder why the bank chooses not to hold liquidity in the absence of regulation. The reason is that the bank is less profitable when it holds liquid, low-

return assets and its expected value is therefore lower under liquidity regulation. The value function of the bank in steady state can be written as

$$(29) \quad V(N) = \frac{\beta(1 - \epsilon)\Phi R^A(1 - \bar{\omega} + \pi(\bar{\omega}))}{1 - \beta\epsilon\Phi R^A(1 - \bar{\omega} + \pi(\bar{\omega}))} N,$$

where $\Phi \equiv K/N$ (see Appendix C for proof). We know that $\bar{\omega}$ is not affected by the regulation, so the term $(1 - \bar{\omega} + \pi(\bar{\omega}))$ is unchanged. However, the higher level of capital in the economy with liquidity regulation makes R^A smaller. Moreover Φ is 10 in the unregulated and 9.93 in the regulated. This means that out of each unit of net worth, fewer risky loans are given out. The lower values of R^A and Φ capture the reduced profitability of the banks. Although the banks are bigger and have higher net worth in the regulated case, their value function is lower because each unit of net worth is valued less. $V(N)$ is 1.219 in the unregulated and 1.211 in the regulated model. Even though regulation expands financial intermediation and thereby output and consumption, the bank's objective function is to maximize its value, namely its final transfer to households, and it does not internalize the effect of liquidity holding on aggregate consumption level.

The banks must choose its funding between deposits and wholesale funding. Deposits are cheaper than wholesale funding because the wholesale rate \bar{B}/B is higher than the deposit rate. However, a higher deposit ratio implies a higher probability of default on deposits and thereby a higher deposit insurance payment for the bank. Moreover, the wholesale rate increases with the deposit ratio. This is due to the fact that a higher deposit ratio implies a lower liquidation value for the hedge fund in case of default. Since the hedge fund recuperates less after default, it demands a higher rate of return, hence a higher wholesale rate. Banks face a trade-off: they would prefer to use deposits, which are cheaper, but the cost of both deposit and wholesale funding goes up with the deposit ratio. Banks choose the liability structure that minimizes their cost of external funding.

Liquidity regulation affects the real economy in our model. Liquidity regulation

generates an increase in loans, i.e. in capital. More capital implies higher marginal productivity of labor, so that labor goes up as well. Output as well as consumption increase. A lower marginal product of capital implies a lower interest rate on the loans.

C. Response to a risk shock

The financial crisis was characterized by a sharp increase in the riskiness of bank assets. Figure 4 reports the evolution of the VIX index. The VIX is an index of volatility in the stock market, namely it is a weighted average of prices of a range of options on the S&P 500. It captures expectations of volatility in the market over the next 30 days. The unprecedented increase in the VIX marks the peak of the financial crisis.

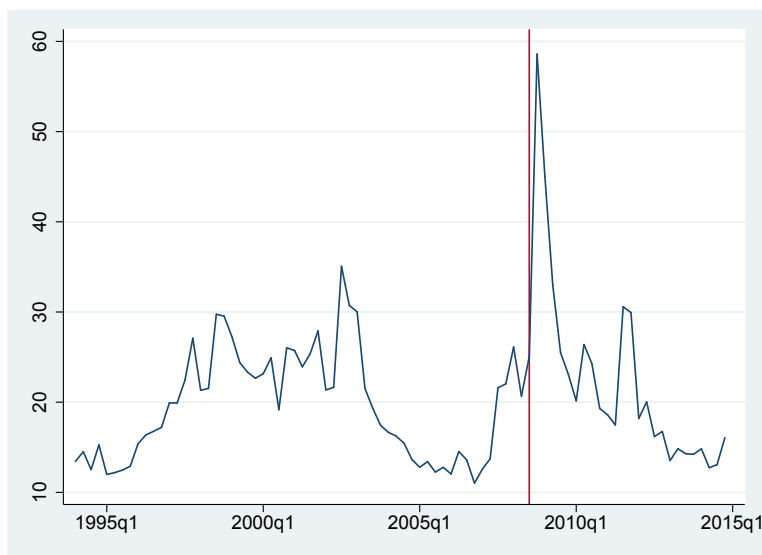


FIGURE 4. VIX

Source: FRED.

We analyze the dynamics of the model under a risk shock, which is an increase in the cross-sectional volatility of the idiosyncratic capital quality shock. Since the distribution is known one period in advance, the risk shock acts as a news

shock: at time t the agents learn that at $t + 1$ their assets will become more risky. The impulse responses are reported in Figure 5 and are in percent deviation from steady state. We compare the behavior of the model without regulation and with liquidity regulation, flat and countercyclical.

Banks learn that next period the return to their assets is going to be more volatile. An increase in asset riskiness makes the moral hazard problem of banks more severe. The hedge fund cuts wholesale lending to banks recognizing their stronger incentives to invest in the suboptimal firm. The total amount of wholesale funding B falls by about 15% on impact and banks are forced to deleverage. The default threshold $\bar{\omega}$ remains below steady state from $t + 1$ onwards. With a sizable portion of wholesale funding gone, banks end up with a higher deposit ratio. The probability of default on deposit remains persistently higher and so are deposit insurance payments, thereby raising costs for banks. An increase in the deposit ratio means a reduction in the recuperation value by the hedge fund in case of default. As a result the hedge fund imposes a higher wholesale rate. Thus, banks pay more for both their deposits and their wholesale funding. The LSR falls after the shock, driven by the sharp fall in wholesale funding.

The risk shock has real effects because deleveraging leads to a reduction in credit to firms. Fewer loans from banks lead to lower investment and a reduction in the price of capital. The marginal productivity of labor falls since capital is lower, so that hours worked are also reduced. Output therefore falls as well. The fall in asset prices has an immediate impact on the return on loans: R_t^A falls on impact, which in turn raises $\bar{\omega}_t$ and $\bar{\bar{\omega}}_t$. Following a risk shock, investment falls more than output, so that consumption actually goes up.

We now turn to the analysis of the dynamic implications of liquidity regulation. The LCR-type flat liquidity regulation requires banks to keep at least 5% of liquid assets against deposits and wholesale funding at all times. While flat liquidity regulation leads to higher steady-state consumption and output, it amplifies fluctuations after shocks. The reduction in wholesale lending B after the risk shock

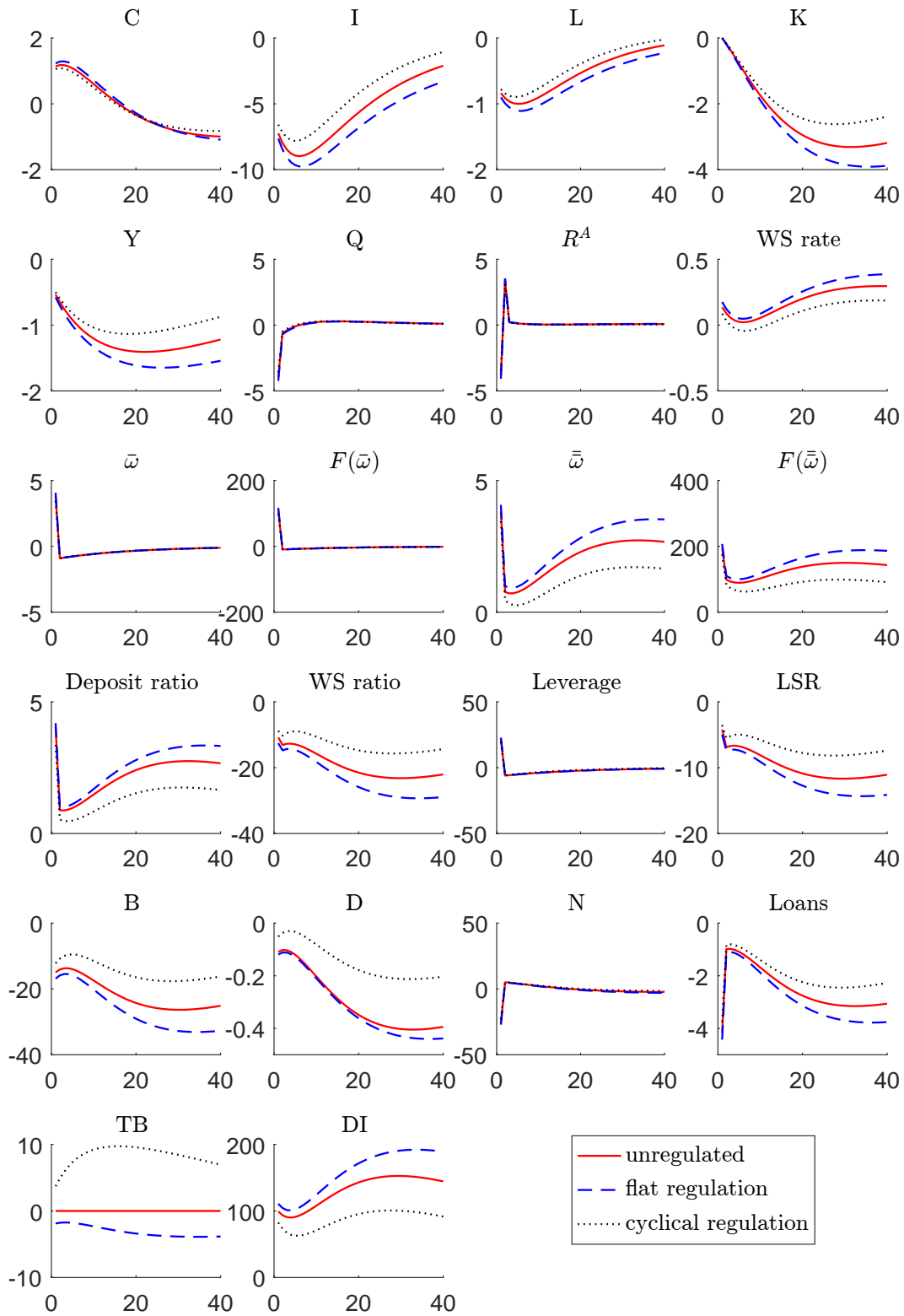


FIGURE 5. RISK SHOCK

is more pronounced in the economy with flat liquidity regulation relative to the unregulated one, which in turn leads to a more severe and persistent deleveraging and fall in output, investment and capital. Flat liquidity regulation ties the behavior of liquid assets, deposits and wholesale funding, which makes the dynamics of bank ratios more persistent. Since wholesale funding and deposits are lower after the shock, flat liquidity regulation allows banks to reduce their safe asset holdings, which intensifies moral hazard and its adverse effect on the economy.

Countercyclical liquidity regulation requires banks to hold a larger fraction of liquid assets when output is below steady state. It may seem counterintuitive at first to require banks to hold on to more safe assets during a recession, but this regulation has a stabilizing effect on the economy. After a risk shock banks are forced to become safer, which relaxes their moral hazard problem. Since banks have less incentive to invest in the suboptimal firm, the hedge fund cuts wholesale funding less. In other words, countercyclical liquidity regulation makes wholesale funding more stable over the business cycle by reducing moral hazard exactly at the time when it is most acute. Banks do not need to rely as heavily on deposits (the deposit ratio goes up less), so the deposit insurance fee increases less. Banks pay lower wholesale and deposit rates relative to flat regulation. The LSR is still procyclical but less so. Banks do not curtail credit as much, so the transmission of a risk shock to the real economy is mitigated.

The result is not specific to risk shocks. We analyze the impulse response of the economy with and without regulation under TFP and capital quality shocks (see Appendix E). The effects of flat and countercyclical liquidity regulations are similar to those under the risk shock.

The model predicts that a risk shock leads to a wholesale run and a credit crunch. We analyze how wholesale funding and loans react to an increase in risk using vector autoregression (VAR), where the risk shock is captured by an increase in the VIX. Our structural VAR comprises three variables: VIX, wholesale growth and loan growth, and includes a constant term. Wholesale growth and loan growth

are quarter-on-quarter and averaged across all banks. We winsorize wholesale growth at 1% to get rid of outliers. Since wholesale and loan growth display seasonal pattern, they are deseasonalized by taking residuals from a regression on quarterly dummies. The ordering of the variables is based on our model: the risk shock is ordered first, then wholesale funding growth and last loan growth. Based on selection criteria, we choose a VAR model with two lags. The impulse responses and confidence intervals are plotted in Figure 6. We find that an increase in risk leads to a decline in wholesale growth and loan growth. This evidence supports our theoretical findings: an increase in risk makes wholesale funding provider less willing to lend to banks. Banks find it harder to access wholesale funding, which in turn forces them to curtail lending.

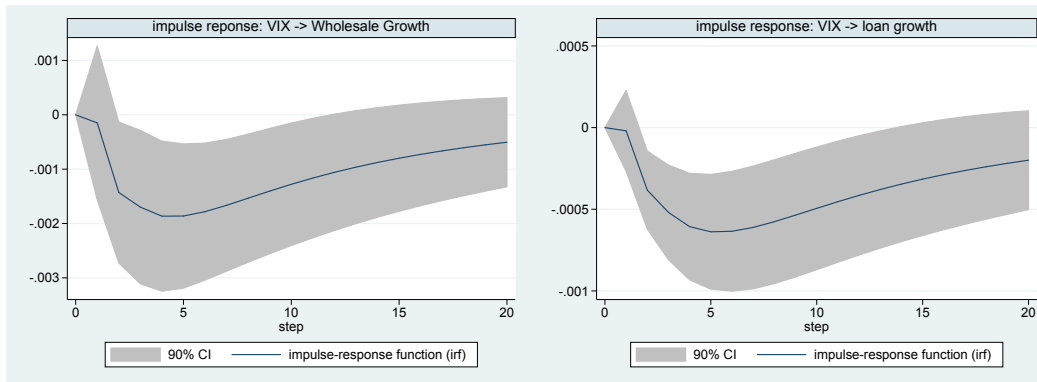


FIGURE 6. IMPULSE RESPONSE, ONE-UNIT SHOCK TO VIX

IV. Welfare

Flat and cyclical regulation generate different dynamic responses to shocks. Table 4 reports the volatility of macroeconomic and financial variables in the economy without regulation, with flat regulation and with cyclical regulation. Flat regulation makes macroeconomic and financial variables more volatile, whereas countercyclical regulation reduces their volatility. We consider welfare conditional on the initial state of the economy being the deterministic steady state; we also

consider unconditional welfare.¹⁰ Welfare results are reported in Table 5. In

TABLE 4—STANDARD DEVIATIONS (IN %)

	Unregulated	Flat	Cyclical
Output	1.21	1.55	0.90
Consumption	0.96	1.16	0.77
Investment	4.37	5.20	3.45
Deposit ratio	2.41	3.19	1.44
Wholesale ratio	19.95	27.68	12.58
Leverage ratio	3.31	3.42	2.96
Liquidity Stress Ratio	10.03	13.53	6.53

steady state, either flat or cyclical liquidity regulation improve welfare by 0.614% in consumption equivalent terms, driven by the increase in steady-state consumption (as explained in Section III.B). Flat regulation entails an improvement in deterministic steady-state welfare but a worsening of volatility. The overall welfare implications of the flat liquidity regulation are ambiguous. Flat regulation implies an improvement of conditional welfare but a worsening of unconditional welfare. In the conditional welfare case, the steady-state effect dominates the volatility effect and overall conditional welfare improves. High persistency in the model implies that the macroeconomic variables remain away from steady state for a long time following shocks; unconditional welfare predicts that the volatility effect dominates so welfare worsens. Countercyclical liquidity regulation has the same positive effect on steady-state welfare but it also reduces volatility in the macroeconomic variables. This implies an unambiguous improvement in conditional and unconditional welfare, of 0.748% and 1.117% respectively.

TABLE 5—WELFARE BENEFITS

	unregulated to flat	unregulated to cyclical
Steady-state welfare	0.614	0.614
Conditional welfare	0.354	0.748
Unconditional welfare	-0.780	1.117

¹⁰Welfare is calculated as in Schmitt-Grohé and Uribe (2007).

V. Empirical analysis

A. Data

We build a quarterly panel data set using BHC balance sheet data from the FR Y-9C. To eliminate outliers, we drop observations for which wholesale funding growth is more than 500% in one year, which results in a loss of 696 observations. Extremely large growth of wholesale funding in a given year could be due to a bank just starting to use wholesale funding or to large mergers and acquisitions. We use quarterly data from 1996Q1 to 2014Q4. Our sample includes 1415 BHCs and 39525 observations. Variable definitions and detailed calculations can be found in Appendix A. We capture aggregate bank funding stress in the market by the TED spread. The TED spread is the difference between the 3-month London Interbank Offered Rate (LIBOR) and the 3-month treasury bills rate and it is an indicator of credit risk in the financial system.¹¹ Treasury bills are considered risk-free whereas LIBOR reflects the risks that large banks face when they lend to each other. The TED spread is a good proxy for funding stress of banks: it is low when banks believe there is little risk in lending to each other in the short run and it increases when banks worry about counterparty risk. Quarterly data for real GDP, inflation (GDP deflator), federal funds rate and TED spread are from Federal Reserve Bank of St Louis Economic Data (FRED).

B. Empirical specification

Our empirical specification builds upon the work of Cornett et al. (2011), but while they look at the relationship between liquidity risk and loans, we focus on the relationship between liquidity and wholesale funding. We regress wholesale funding growth on the lagged liquidity ratio, the interaction term between the lagged liquidity ratio and the TED spread and a number of other control variables.

¹¹See Brunnermeier (2009) for a discussion of the TED spread as an indicator for market stress.

Our baseline empirical specification is as follows:

$$(30) \quad \frac{Wholesale_{i,t} - Wholesale_{i,t-4}}{Wholesale_{i,t-4}} = B_i + \beta_1 LiquidityRatio_{i,t-4} + \beta_2 LiquidityRatio_{i,t-4} * TED_t + \beta_3 BC_{i,t-4} + \beta_4 X_{t-4}.$$

Our hypothesis is that in periods of stress as measured by elevated credit risk, banks with lower holdings of liquid assets suffered more severe wholesale runs. Hence we expect β_2 to be positive.

We use a panel-data fixed-effect model to account for heterogeneity at the bank level. We cluster the error term at the bank level to estimate standard errors that are robust to serial correlation at that level. We measure the growth rate of wholesale funding over four quarters because quarter-on-quarter growth is more noisy and subject to seasonality. Note however that our results are robust to using quarter-on-quarter wholesale funding growth. We use the four-quarter lag of the liquidity ratio to avoid potential endogeneity issues. The variable X is a set of macroeconomic variables meant to control for the state of the economy, lagged by four quarters to avoid potential endogeneity issues. Our macroeconomic controls are the annualized GDP growth, the TED spread, inflation (measured as the percent change in the GDP deflator over the previous four quarters) and the federal funds rate. $BC_{i,t}$ are bank-specific controls, also lagged by four quarters; we control for the size (total assets), asset riskiness (loan loss provision (LLP) over total assets) and capital adequacy (equity over risk-weighted assets) of each bank. Finally, B_i are bank fixed effects. Summary statistics on all the variables used in the regression can be found in Table F1 of Appendix F.

Our identifying assumption is that during a time of stress (high TED), it is the supply effects that drive the behavior of wholesale funding. In normal time, supply and demand of wholesale funding will determine the equilibrium outcome. However, during a time of stress supply falls sharply, forcing banks to a harmful fire sale of assets, as documented in Gorton and Metrick (2012).

C. Regression results

Our baseline regression is reported in Table 6. The coefficient on the liquidity ratio is negative but the coefficient on the interaction term between liquidity and TED is positive. Hence, liquidity has a different impact on wholesale growth during normal (low TED) and stressed (high TED) periods. In normal times banks with higher liquidity ratio have lower wholesale growth. Intuitively, banks that choose to hold on to a larger fraction of liquid, lower-return assets will also choose a lower growth in wholesale funding, which typically represents an expensive source of funds. When the TED spread is elevated a higher liquidity ratio is associated with higher wholesale growth (or a smaller decline in wholesale funding). This suggests that banks with higher liquidity buffers suffered more contained wholesale runs during the financial crisis. We also run our benchmark regression on a sample that excludes the financial crisis (1994Q1 to 2007Q4). The interaction term between the liquidity ratio and the TED spread still enters positively and significantly. We take this as evidence that our mechanism is general and not only driven by the financial crisis. Real GDP growth enters positively and confirms that wholesale funding is procyclical. As expected, the TED spread has a negative effect on wholesale growth. The federal funds rate is high when the economy is booming, hence it also affects positively wholesale growth. Inflation however enters negatively as it is a sign of increased macroeconomic uncertainty. As for the bank-specific controls, equity over risk-weighted assets is positive and significant whereas LLP is negative and significant. The result suggests that it is easier for safer banks to attract wholesale funding; intuitively, lenders may be more reluctant to provide wholesale funding to risky banks, since they may suffer a loss if the bank defaults. Bank size is not significant.

To understand whether our results are driven by financial institutions at either tail of the distribution of holdings of liquidity, we divide banks in quartiles according to their liquidity ratios. In every quarter, banks with a liquidity ratio above the 75th percentile belong to the first quartile and similarly for the

TABLE 6—BASELINE REGRESSION

	Until 14Q4	Pre-crisis
Liquidity ratio	-0.560 (0.106)	-0.312 (0.185)
Liquidity*TED	0.886 (0.136)	0.767 (0.192)
Total assets	-9.85e-11 (6.19e-11)	-1.58e-10 (1.53e-10)
LLP	-16.30 (2.437)	-9.530 (7.501)
Equity/RWA	0.795 (0.176)	0.886 (0.343)
TED	-0.0978 (0.0102)	-0.0830 (0.0470)
GDP growth	1.139 (0.261)	0.992 (0.620)
FF rate	0.0565 (0.00319)	0.0204 (0.00586)
Inflation	-3.470 (0.762)	-13.93 (1.272)
Constant	0.0233 (0.0290)	0.364 (0.0651)
Observations	39525	18307

Standard errors in parentheses

second, third and fourth quartiles. We run our baseline regression on the four groups of banks and report the results in Table 7. For all liquidity quartiles, we find that the coefficient on the interaction term is positive and significant. We further observe that the size of this coefficient is smallest for banks in the most liquid quartile and it increases as we move to less liquid quartiles. This means that banks in the highest liquidity group are less vulnerable to wholesale runs. For banks in lower liquidity quartiles, however, additional liquidity plays an increasingly important role during times of stress. We also find that equity over risk-weighted assets and LLP play a more important role for illiquid banks than for liquid banks. Hence, for illiquid banks, a higher equity ratio (or lower LLP) helps them attract more wholesale funding. It is also interesting to note that

the procyclicality of wholesale growth appears to be mainly driven by the illiquid banks. Moreover, the negative effect of the TED rate on wholesale growth is more severe when we consider illiquid banks. Hence, banks with higher liquidity holdings can maintain a stronger wholesale growth during stress times. We can test whether the regression coefficients obtained from the different quartiles are significantly different from each other using the baseline specification, introducing dummies for the liquidity quartiles and interacting the dummies with all regressors. We test whether the coefficient on liquidity interacted with TED for the first (most liquid) quartile equals that of the second, third and fourth quartiles respectively. The t-test results are respectively 3.93, 4.74 and 3.43, so the null is rejected and we conclude that those coefficients are significantly different. We find that the regression coefficients of the second, third and fourth quartiles are significantly different from that of the first quartile also for the following regressors: equity/RWA (t-tests are 2.9, 2.29, 2.23), LLP (t-tests are -2.36, -3.19, -3.76) and TED (t-tests are -2.21, -2.01, -2.25). The other regressors do not significantly differ across quartiles. The empirical evidence supports the theoretical findings in Section III that higher liquidity helps stabilize wholesale funding in response to shocks.

D. Robustness checks

As a first robustness check, we replace macroeconomic controls by time fixed effects:

$$(31) \quad \frac{Wholesale_{i,t} - Wholesale_{i,t-4}}{Wholesale_{i,t-4}} = B_i + \beta_1 LiquidityRatio_{i,t-4} + \beta_2 LiquidityRatio_{i,t-4} * TED_t + \beta_3 BC_{i,t-4} + \beta_4 T_t,$$

where T_t are time-fixed effects. The advantage of this approach is its robustness: we control for all period-specific factors that could contaminate our results. Table F2 confirms that liquidity has a positive effect on wholesale growth when the

TABLE 7—REGRESSION BY LIQUIDITY QUANTILES

	1st Quartile (liquid)	2nd Quartile	3rd Quartile	4th Quartile (illiquid)
Liquidity ratio	-0.440 (0.130)	-0.519 (0.211)	-0.00911 (0.300)	0.476 (0.421)
Liquidity*TED	0.467 (0.139)	1.708 (0.277)	2.766 (0.432)	2.456 (0.575)
Total assets	-8.18e-11 (6.03e-11)	-1.76e-10 (7.83e-11)	-5.30e-11 (1.16e-10)	-2.04e-09 (6.34e-10)
LLP	-5.390 (2.956)	-14.94 (2.791)	-22.64 (3.391)	-27.54 (4.608)
Equity/RWA	0.395 (0.220)	1.082 (0.322)	1.441 (0.344)	1.452 (0.394)
TED	-0.0610 (0.0179)	-0.106 (0.0191)	-0.112 (0.0198)	-0.120 (0.0192)
GDP growth	0.584 (0.480)	0.300 (0.486)	0.380 (0.488)	1.168 (0.488)
FF rate	0.0453 (0.00677)	0.0453 (0.00561)	0.0491 (0.00604)	0.0445 (0.00693)
Inflation	-3.645 (1.613)	-2.112 (1.209)	-0.203 (1.409)	-3.577 (1.342)
Constant	0.0350 (0.0477)	-0.0630 (0.0510)	-0.172 (0.0564)	-0.0291 (0.0651)
Observations	9225	9787	10248	10131

Standard errors in parentheses

TED spread is high for the third and fourth liquidity quartiles. As in the baseline regression, LLP and equity/RWA play a bigger role for illiquid banks.

As another robustness exercise, we replace the TED spread with a dummy that takes the value one when the TED is above its 75th percentile and zero otherwise. The advantage of the TED dummy is that it guarantees that results are not solely driven by extreme values of the TED. The results of the regression with TED dummy are in Table F3 and are consistent with the baseline estimation.

Table F4 reports regression results using different definitions of wholesale funding. The first column displays the baseline regression results. In the second column we use a wider definition of wholesale funding, namely total liabilities minus deposits. The wider definition of wholesale funding includes trading lia-

bilities, hybrid debt/equity instruments and other liabilities which are excluded from the baseline definition. In the third column, we only consider short-term wholesale funding, i.e. with a maturity of less than one year. Our results are qualitatively similar when we use these alternative definitions.

In Table F5, we report regression results using different definitions of liquidity ratio. Our baseline definition includes agency-backed securities in the pool of liquid assets with a haircut of 15% and a cap of 40% and it is reported in the first column. The second column uses a stricter definition of liquid assets excluding all agency securities. The third uses a wider definition of liquidity including the entire stock of agency securities. The results using the three specifications of liquidity are broadly similar.

VI. Conclusions

This paper develops a DSGE model with depository institutions (banks) and a hedge fund and analyzes the macroeconomic implications of imposing liquidity requirements on banks. Due to limited liability, banks prefer high-return, high-risk investments. The hedge fund provides wholesale funding to banks that is junior to deposits in the event of bank default. Since the hedge fund is the residual claimant when bankruptcy arises, it uses wholesale funding to control bank leverage and risk-taking. Regulation requiring banks to hold a fraction of their deposits and wholesale funding in the form of liquid assets has real consequences for the economy. By making bank portfolios safer, liquidity regulation leads to an increase in wholesale funding and credit supply.

We analyze two types of liquidity regulation: flat, which does not depend on the business cycle, and countercyclical, which requires banks to hold a higher fraction of liquid assets during economic downturns. Flat liquidity regulation raises credit supply and consumption at the steady state but it also increases macroeconomic volatility; hence its welfare effects are ambiguous. On the other hand, countercyclical regulation improves welfare unambiguously because it mitigates

the transmission of shocks to the real economy in addition to retaining expansionary steady-state effects. Following an adverse risk shock, the contraction in wholesale funding and thereby in leverage is less severe.

We test empirically the implications of our model and find that banks with higher liquidity ratios face a lower reduction in wholesale funding during time of stress as captured by an elevated TED spread. The effect of additional liquidity on wholesale and loan growth is strongest for banks with liquidity ratios in the lowest quartile. Since these banks are most likely to be affected by liquidity regulation, our results suggest that liquidity regulation could help contain wholesale runs and credit crunches.

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