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Time-Varying Risk Shocks and the Zero Lower Bound

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Time-Varying Risk Shocks and the Zero Lower Bound*

Abstract

This paper shows that increased volatility of firm-level productivity can push the nominal interest rate to its lower bound with large amplification effects on macroeconomic aggregates. The framework combines a simple canonical financial accelerator model, time varying risk shocks, and a zero lower bound on the nominal interest rate. The amplification mechanism results from a portfolio re-balancing from households, who reduce capital investment in favor of risk-free bonds. Consequently, the capital loan volume decreases which then leads to a large decline in economic activity. We show that a substantial drop in output is accompanied by small changes in inflation. We, thus, also address the "Missing Deflation Puzzle" in the Phillips Curve literature.

- *JEL Classification: E3, E5, E2*
- Keywords: *zero lower bound, credit channel, time-varying risk shocks, missing deflation puzzle, monetary policy*

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1 Introduction

Figure 1 displays three prominent U.S. economic activities during the recent Great Recession period: A large increase in the cross-sectional dispersion of firm productivity, a sharp increase in the risk premium that is measured by the spread between Baa corporate bond yield and 10 - year T-bills, and the Federal Funds Rate at the zero lower bound (ZLB). This paper shows that time-varying risk shocks, which are measured as changes in the cross-sectional dispersion of firm productivity, work as an impulse mechanism that can push an economy to the ZLB. We then show that the ZLB, in turn, amplifies the effects of changes in risk associated with productivity for macroeconomic aggregates. Finally, we also provide a linkage between risk and the ZLB that addresses the "Missing Deflation Puzzle" in the NK Phillips Curve literature: Our result shows a large and persistent drop in GDP with a small decline in inflation.[1]

Our framework combines a simple canonical financial accelerator model, time-varying risk shocks, and a lower bound on the nominal interest rate. This paper contributes to the work of Christiano, Motto, and Rostagno (2014), who demonstrate the importance of risk in a similar model but do not investigate the interaction of credit channel friction and ZLB.[2] More broadly, our results are in line with previous studies highlighting the role of time-varying uncertainty as an important factor for business cycle activity (e.g. Bloom (2009), Bloom, Floetotto, Jaimovich, Saporta-Eksten, and Terry (2018)). In the ZLB literature, the primary role of uncertainty (risk) is often relegated to an amplification mechanism when combined with traditional demand shocks (e.g. uncertainty regarding government spending, as in Fernandez-Villaverde, Gordon, Guerron-Quintana and Rubio-Ramirez (2015), or the discount rate as in Basu and Bundick (2015) or Nakata (2017)). Using the credit channel model of Carlstrom and Fuerst (1997), we show that

[1] See, e.g., Linde and Trabandt (2018) for a detailed investigation of the "Missing Deflation Puzzle".

[2] Christiano et al. (2014) follow the agency problems and debt-contracting framework of Bernanke, Gertler, and Gilchrist (1999). We, however, most closely follow the work of Carlstrom and Fuerst (1997). We do not use dynamically history dependent optimal contract for forward-looking, risk-neutral entrepreneurs as in Carlstrom, Fuerst, and Paustian (2016) and Dmitriev and Hoddenbagh (2017). A simple static financial contract framework suffices for our main purpose in showing the interaction between time-varying risk shocks and the ZLB in a financial accelerator framework.

supply-side risk shocks, changes in a mean-preserving spread in the distribution of the technology shocks affecting capital-good production, can lead to an economy reaching the ZLB and can create large quantitative effects on key business cycle variables.

The amplification mechanism, in our paper, results from a portfolio rebalancing from households. Households can invest either in capital or in bonds and require expected discounted returns to be equal. If a risk shock pushes an economy to or occurs at the ZLB, demand for capital, and therefore the loan volume in the economy, decreases until the price of capital adjusts and the expected discounted returns are equal. More precisely, if a risk shock hits the economy, the capital supply schedule shifts upward, increasing the price of capital and lowering the return. This causes a drop in economic activity and a fall in real marginal costs for firms, lowering inflation and output. The central bank accommodates the shock by lowering the interest rate on bonds. If a shock is sufficiently large, however, the policy rate is pushed to the ZLB where it cannot further fall to accommodate the shock. Therefore, capital investment has to fall in order to reduce the price of capital. This implies, however, that the drop in loans to entrepreneurs is considerably larger if a lower bound constrains the monetary authority. Consequently, a larger drop in reserve capital for production, output, labor and aggregate consumption follows.

The interaction between agency costs and risk shocks is further corroborated by the monotonic relation between the innovation to risk that is needed to push the economy to the ZLB and the magnitude of the agency cost parameter. At our benchmark parameterization of an agency cost of 25%, a 16.25% increase in risk pushes the economy to the ZLB. In comparison, for a relatively small (large) value of agency costs of 5% (50%), an innovation of roughly 55% (12.5%) is needed.[3]

In order to evaluate the quantitative implications, we subject the benchmark economy to a four-period sequence of innovations to risk. Each innovation increases risk by 20%, sufficiently

[3] Agency costs are to capture the difference between a firm's internal (the firm's value as a going concern) and external value (firm's value if all assets were liquidated). E.g. in the steady state, given our benchmark calibration of 25% agency costs and an annualized bankruptcy rate of 3.90%, the expected share of investment in a quarter that is transformed into capital available for production in the next period is 99.76% ($100\% - 3.9\%/4 \times 0.25$) of the investment, while 0.24% are lost due to agency costs.

large enough to push the economy to and keep it at the ZLB. The model implies that the risk premium increases by $2\% - points$ (annualized) per quarter in the initial period of the shock. This impact increases only slightly in the following periods in which the economy is at the ZLB. This magnitude is in line with the data, where the peak of risk premium occurs December 2008 at a value of 5.69%, while the average risk premium in 2008 (2009) was 3.76% (4.04%); roughly $1.9\% - points$ ($2.1\% - points$) above the long-run mean of 1.89%. As for the Inflation, it falls by $0.5\% - points$ on impact (annualized), but does not decrease further as new shocks arrive due to the ZLB. This value underpredicts the change in the data, however, which falls by about of $1.5\% - points$.

In addressing the "Missing Deflation Puzzle", we show that the ZLB constraint has a relatively large impact on the NK Phillips Curve slope. Subjecting the economy to risk shocks only, the slope increases from 0.044 without the ZLB to 0.067. We consider this changes to be large, as the economy is only 1.41% of periods at the ZLB, and the latter slope is the average between periods at and away from the ZLB. Despite the increase in the slope due to the ZLB, the model is still consistent with the past experience of small changes in inflation in combination with large changes in the output gap. For example, the smallest (output gap, inflation)-tuple in the economy with ZLB is $(-3.1\%, 1.49\%)$, while the smallest tuple without ZLB is $(-1.0\%, 1.93\%)$.

Finally, we perform a "pseudo variance decomposition" to decompose the effects of different shocks on key business cycle variables. Because our model is nonlinear, the sum of effects produced by each shock alone does not equal to the effect produced by all the shocks working simultaneously as in the linear case. Consequently, the calculation of an ordinary linear variance decomposition is not possible. However, following Lanne and Nyberg (2014)'s nonlinear VAR estimation method, we provide a simple estimate that is analogous to a conventional variance decomposition and that coincides with linear approximation. We find that after accounting for the non-linearity, the role of time-varying risk shocks increases for key business cycle variables, and accounts for half the variation in nominal interest rates.

2 Related Literature

Our paper falls into three broad categories in the ZLB literature. One strand examines the effects of second moment shocks to preferences, fiscal policy and technology. Nakata (2017), Fernandez-Villaverde et al. (2015) and Basu and Bundick (2015) show that uncertainty amplifies the impact of a first moment shock on an economy - i.e. they examine the impact of variation in the second moment after the economy has reached the ZLB due to a first moment shock. Nakata (2017) uses a New Keynesian model to examine the impact of uncertainty on prices and allocations when the economy is at the ZLB. There is exogenous variation in the household's discount rate that occasionally pushes the interest rate to zero. An increase in uncertainty regarding the future path of exogenous shocks alters the conditional expectations of prices when the economy is at the ZLB. The effects of uncertainty on allocations and prices are measured by their differences between the deterministic (perfect foresight) and stochastic versions of the economy. Basu and Bundick (2015) model uncertainty as a time-varying second moment of the household's discount rate and show that an increase in uncertainty, when the economy is already at the ZLB because of another shock, contributes to contractions in the economy because the monetary authority cannot mitigate adverse shocks. Fernandez-Villaverde et al. (2015) examine the impact of fiscal policy uncertainty and find similar results regarding the amplification as the two previously discussed. Richter and Throckmorton (2018) quantify the effect of supply-side uncertainty of intermediate goods-producing firms and estimate a nonlinear model using Bayesian methods in the context of a New Keynesian model with ZLB.

Another strand of the literature explores the effects of regime switching shocks for optimal inflation rates. Dordal-i-Carrera, Coibion, Gorodnichenko and Wieland (2016) develop a New Keynesian model with a regime switching risk premium shock to generate infrequent but long-lived ZLB episodes. They discuss what different calibrations of their model implies for optimal inflation rates. Aruoba and Schorfheide (2016) and Aruoba, Cuba-Borda, and Schorfheide (2017)

construct a model with a inflation and deflation regimes, with exogenous switching between the two regimes. Lansing (2017) develops a New Keynesian model with two local rational expectations equilibria. This approach is motivated by the work of Benhabib, Schmitt-Grohé and Uribe (2001). Benhabib, Schmitt-Grohé, and Uribe (2001) show that the combination of a Taylor-type rule and a zero bound on nominal interest rates creates a new equilibrium for the economy. This new equilibrium can involve deflation and a very low level of nominal interest rates. Lansing (2017) features endogenous transition between the two equilibria. The transition occurs if the interest rate is below the central banks estimate of the natural rate of interest for over a longer time period. The representative agent in the model, then, places more weight on the possibility that the current equilibrium is the deflationary one, which becomes self-fulfilling.

Works such as Cochrane (2017) focuses on equilibria and the associated selection issues in New Keynesian models and the ZLB. Cochrane (2017) adopts the framework of Werning (2012) and examines the predictions for a depression and deflation at the zero bound, and some unusual policy predictions. Kiley (2016) and Wieland (2014) summarize the predictions of New Keynesian ZLB analysis and implications.

3 The Model

For our analysis, we augment the business cycle model of Carlstrom and Fuerst (1997) with New Keynesian features and a truncated Taylor rule. Carlstrom and Fuerst (1997) introduce endogenous agency costs, due to asymmetric information between lenders (households via capital mutual funds) and borrowers (entrepreneurs), associated with the production of capital goods in an RBC framework.[4] We introduce supply-side risk by varying the second moment of entrepreneurs' idiosyncratic technology shocks that affect capital production over time.

There is a representative household, whose members supply differentiated types of labor and

[4] The informational structure in this model is the costly-state-verification framework of Townsend (1979). As is well known, in this framework the optimal contract is risky debt.

save by investing either in capital or in risk-free one-period bonds, which are in zero net supply. Production of the final good occurs in three steps. Entrepreneurs transform investment into capital goods. Dixit-Stiglitz type intermediate good producers combine capital and labor in order to produce intermediate goods. The intermediate good firms are subject to nominal rigidities as specified by Rotemberg (1982). Competitive final good producing firms aggregate the continuum of intermediate goods. Finally, the monetary authority sets the interest rate according to a truncated Taylor rule, which is bounded from below at zero.

3.1 Household

The representative household, who consists of members indexed by j, maximizes expected lifetime utility by choosing sequences of consumption c_t, labor $l_{j,t}$, (next period's) capital holdings k_{t+1}, risk-free bond holdings, B_{t+1}, as well as wages $w_{j,t}$ to maximize expected discounted future utility

$$E_0 \sum_{t=0}^{\infty} \beta^t d_t U\left(c_t, l_{j,t}\right)$$

where β is the discount factor and subject to shocks via an exogenous stochastic process d_t specified below. E_t is the conditional expectation operator at time t. For the functional form, we assume that consumption and labor are additively separable as $U(c, l_j) = \left(c - b_h c_{-1}\right)^{1-\upsilon_c} / \left(1-\upsilon_c\right) - \psi \int l_j^{1+\upsilon_l} / \left(1+\upsilon_l\right) dj$, where υ_l^{-1} is the Frisch labor supply elasticity, υ_c governs risk aversion and b_h habit formation. The household faces the budget constraint

$$c_t + \frac{B_{t+1}}{R_t P_t} + q_t \left(k_{t+1} - (1-\delta) k_t\right) + y_t \int F_w \left(\frac{w_{j,t}}{w_{j,t-1}}\right) dj = \frac{B_t}{P_t} + \frac{D_t}{P_t} + \int l_{j,t} w_{j,t} dj + k_t r_t + T_t$$

where P_t is the price level, T_t is a lump-sum transfer, B_t is a one-period, risk-free bond that pays a gross nominal interest rate R_t in $t+1$ and r_t is the (real) rental rate of capital. Capital depreciates at rate δ and can be purchased by households at a real relative price of q_t for their

investment plans. As detailed below, $q_t > 1$ to cover expected bankruptcy costs. The household receives dividends D_t of the firms in the economy. The real wage for labor of type j, $w_{j,t}$, is subject to quadratic adjustment cost $F_w(w) = \frac{\varkappa_w}{2}(w-1)^2$. Different types of labor are aggregated into homogeneous labor l_t with the labor packer $l_t = \left(\int l_{j,t}^{\frac{\theta_w - 1}{\theta_w}} dj\right)^{\frac{\theta_w}{\theta_w - 1}}$, where θ_w is the elasticity of demand between different types of labor. Dixit-Stiglitz intermediate goods producers rent labor at real wage $w_t = \left(\int w_{j,t}^{1-\theta_w} dj\right)^{\frac{1}{1-\theta_w}}$. Optimal behavior by the perfectly competitive labor packer implies a demand for each type of labor $l_{j,t} = \left(\frac{w_{j,t}}{w_t}\right)^{-\theta_w} l_t$.

3.2 Production

Turning first to the informational friction on the capital good production side, each entrepreneur i has access to a stochastic technology that transforms $i_{i,t}$ units of consumption into $\omega_{i,t} i_{i,t}$ units of capital. Entrepreneurs observe their own technology shock realization without incurring any cost, while capital mutual funds (CMFs) have to pay a monitoring cost $\mu i_{i,t}$. As in Carlstrom and Fuerst (1997), we assume the technology shock ω is drawn from a log *normal* cumulative distribution function $\Phi(\omega; \sigma_\omega)$ with corresponding density function $\phi(\omega; \sigma_\omega)$. We follow e.g. Dorofeenko et al. (2008) and introduce risk shocks by assuming that the standard deviation of this function is time-varying, i.e. $\Phi(\omega; \sigma_\omega) = \Phi(\omega; \sigma_{\omega,t})$, while maintaining the assumption of a constant expected mean of unity.[5]

Each entrepreneur enters period t with one unit of labor endowment that is supplied inelastically and hence earns them wage income w_t^e, and $k_{i,t}^e$ units of capital. Capital is rented to firms, such that income in a period is $w_t^e + r_t k_{i,t}^e$. This income, along with the undepreciated capital, determines an entrepreneur's net worth as $n_{i,t} = w_t^e + k_{i,t}^e (r_t + q_t (1-\delta))$. With a positive net worth, the entrepreneur borrows $(i_{i,t} - n_{i,t})$ consumption goods and agrees to pay back $\left(1 + r_i^k\right)(i_{i,t} - n_{i,t})$ capital goods to the lender, where r_i^k is the interest rate on loans. It follows that an entrepreneur defaults on his loan if his realization of output is less then the re-payment, i.e.

[5] The notation $\Phi(\omega; \sigma_{\omega,t})$ is used to denote that the distribution function is time-varying as determined by the realization of the random variable, $\sigma_{\omega,t}$.

$\omega_{i,t} < \frac{\left(1+r_i^k\right)(i_{i,t}-n_{i,t})}{i_{i,t}} \equiv \bar{\omega}_{i,t}$. The optimal borrowing contract maximizes expected entrepreneurial income[6]

$$q_t i_t f\left(\bar{\omega}_t; \sigma_{\omega,t}\right)$$

subject to the lender's willingness to participate

$$q_t i_t g\left(\bar{\omega}_t; \sigma_{\omega,t}\right) = \left(i_t - n_t\right).$$

This equation expresses that the income of the lender is equal to the loan volume (all rents go to the entrepreneur). The fraction of expected net capital output going to the entrepreneurs is defined as

$$f\left(\bar{\omega}_t; \sigma_{\omega,t}\right) = \int_{\bar{\omega}_t}^{\infty} \omega \phi\left(\omega; \sigma_{\omega,t}\right) d\omega - \left[1 - \Phi\left(\bar{\omega}_t; \sigma_{\omega,t}\right)\right] \bar{\omega}_t,$$

while the share going to lenders is

$$g\left(\bar{\omega}_t; \sigma_{\omega,t}\right) = \int_{-\infty}^{\bar{\omega}_t} \omega \phi\left(\omega; \sigma_{\omega,t}\right) d\omega + \left[1 - \Phi\left(\bar{\omega}_t; \sigma_{\omega,t}\right)\right] \bar{\omega}_t - \Phi\left(\bar{\omega}_t; \sigma_{\omega,t}\right) \mu.$$

The bankruptcy rate $\Phi\left(\bar{\omega}_t; \sigma_{\omega,t}\right)$ indicates the share of entrepreneurs for which $\omega < \bar{\omega}_t$, such that $\Phi\left(\bar{\omega}_t; \sigma_{\omega,t}\right) \mu$ represents the loss in capital output due to the agency cost friction. This loss reduces capital output, i.e. $f\left(\bar{\omega}_t; \sigma_{\omega,t}\right) + g\left(\bar{\omega}_t; \sigma_{\omega,t}\right) = 1 - \Phi\left(\bar{\omega}_t; \sigma_{\omega,t}\right) \mu$. Solving the optimal contract problem yields the relative price of capital

$$q_t^{-1} = \left[1 - \Phi\left(\bar{\omega}_t; \sigma_{\omega,t}\right) \mu + \phi\left(\bar{\omega}_t; \sigma_{\omega,t}\right) \mu f\left(\bar{\omega}_t; \sigma_{\omega,t}\right) / \frac{\partial f\left(\bar{\omega}_t; \sigma_{\omega,t}\right)}{\partial \bar{\omega}}\right].$$

[6] Note that subscripts are dropped when formulating the contract in anticipation of the solution of the optimal contract.

The incentive compatibility constraint implies

$$i_t = \frac{1}{\left(1 - q_t g\left(\bar{\omega}_t; \sigma_{\omega,t}\right)\right)} n_t. \tag{1}$$

Equation (1) is central as it relates capital supply to the real relative price of capital. From (1), it can be seen that changes in $\sigma_{\omega,t}$, shift the investment supply schedule in the (q_t, i_t) space via changes in $g\left(\bar{\omega}_t; \sigma_{\omega,t}\right)$. One way to see this is to consider the effect of an increase in risk in partial equilibrium. For this analysis, q and n are assumed to be fixed while i and $\bar{\omega}$ are allowed to vary. As σ_ω increases, the default threshold $\bar{\omega}$ and lenders' expected return $g\left(\bar{\omega}; \sigma_\omega\right)$ fall. From the relation $qg\left(\bar{\omega}; \sigma_\omega\right) = \left(i - n\right)/i$ it can be seen that investment has to fall. This partial equilibrium effect carries over to general equilibrium.

Risk-neutral entrepreneurs' capital demand decision follows

$$q_t = \beta\gamma E_t \left(\left(q_{t+1}\left(1-\delta\right) + r_{t+1}\right) \left\{ 1 + \mu \frac{\phi\left(\bar{\omega}_{t+1}; \sigma_{\omega,t}\right)}{f'\left(\bar{\omega}_{t+1}; \sigma_{\omega,t}\right)} \right\} \right),$$

which is derived in detail in the Appendix. Note that while the term in brackets can be interpreted as the market return on capital accumulation, the term in braces represents the additional return on internal funds, which is greater than one. γ is introduced and calibrated to offset this return in the steady state, such that in the entrepreneurs partly rely on external finance.

3.2.1 Firms

Intermediate good producer $f \in [0,1]$ maximizes the expected discounted present value of real dividends,

$$E_t \sum_{s=0}^{\infty} \left(\beta^s \lambda_{t+s}/\lambda_t\right) \left(D_{i,t+s}/P_{t+s}\right)$$

subject to

$$\left(P_{f,t}/P_t\right)^{-\theta_p} y_t = e^{z_t} k_{f,t}^{\alpha} l_{f,t}^{1-\alpha},$$

where θ_p captures the elasticity of demand between intermediate goods, by choosing $\{k_{f,t}, l_{f,t} P_{f,t}\}_{s=0}^{\infty}$. Real dividends are given by $D_{f,t}/P_t = (P_{f,t}/P_t)^{1-\theta_p} y_t - w_t l_{f,t} - r_t k_{f,t} - F_p\left(P_{f,t}/P_{f,t-1}\right) y_t$, with adjustment costs $F_p\left(\frac{P_{f,t}}{P_{f,t-1}}\right) = \frac{\varkappa_P}{2}\left(\frac{P_{f,t}}{(1+\Pi)P_{f,t-1}} - 1\right)^2$. In a symmetric equilibrium, all firms make the same decisions and the optimality conditions reduce to

$$\alpha \chi_t e^{z_t} k_t^{\alpha} l_t^{1-\alpha} = k_t r_t$$

$$(1-\alpha) \chi_t e^{z_t} k_t^{\alpha} l_t^{1-\alpha} = w_t l_t$$

as well as the Phillips Curve

$$\left(1 - \theta_p - (1+\Pi_t) F_p'(\Pi_t) + \theta_p \chi_t\right) y_t = -E_t\left(\beta \frac{\lambda_{t+1}}{\lambda_t} (1+\Pi_{t+1}) F_p'(\Pi_{t+1}) y_{t+1}\right).$$

The bundler problem for the perfectly competitive final goods producer is to choose $y_{f,t}$ units of the intermediate good in order to maximize $P_t y_t - P_{f,t} y_{f,t}$ subject to $y_t = \left[\int y_{f,t}^{\frac{\theta_p - 1}{\theta_p}} df\right]^{\frac{\theta_p}{\theta_p - 1}}$. The necessary optimality conditions are $y_{f,t} = \left(\frac{P_t}{P_{f,t}}\right)^{\theta_p} y_t$ and $P_t^{1-\theta_p} = P_{f,t}^{1-\theta_p}$. Because we assume that the market for final goods is perfectly competitive, final goods producer earn zero profits in equilibrium.

3.2.2 Exogenous Equations

We specify the laws of motion for the exogenous state variables as $\log(d_{t+1}) = \rho_d \log(d_t) + \sigma_d \varepsilon_{d,t+1}$ for the intertemporal preference shock, $\log(z_{t+1}) = \rho_z \log(z_t) + \sigma_z \varepsilon_{z,t+1}$ for the TFP shock and $\log(\sigma_{\omega,t+1}) = (1-\rho_\omega)\log(\sigma_{\omega,0}) + \rho_\omega \log(\sigma_{\omega,t}) + \sigma_{\sigma_\omega} \varepsilon_{\sigma_\omega,t+1}$ for the risk shock. We assume $(\varepsilon_{d,t+1}, \varepsilon_{z,t+1}, \varepsilon_{\sigma_\omega,t+1})' \overset{i.i.d.}{\sim} N(0, I)$, with I a three-by-three identity matrix.

3.3 Monetary Policy

The monetary authority sets the nominal interest rate R_{t+1} to stabilize inflation and output growth and to smooth interest rates. The parameters ρ_Π and ρ_Y control the responses to deviations of inflation from target Π_0 and of steady state output y_0. The central bank is not completely free to set its interest rate however, as it faces a lower bound

$$\begin{aligned} \log\left(\frac{R_t}{R_0}\right) &= \rho_R \log\left(\frac{R_{t-1}}{R_0}\right) + (1-\rho_R)\rho_\Pi \log\left(\frac{\Pi_t}{\Pi_0}\right) + (1-\rho_R)\rho_y \log\left(\frac{y_t}{y_0}\right) + \sigma_R \varepsilon_{R,t} \text{ if } R_t > 1 \\ R_t &= 1 \text{ otherwise} \end{aligned}$$

4 Solution and Parameterization

We solve our model using the procedure described in Guerreri and Iacoviello (2015). This procedure uses first-order perturbation in a piecewise linear fashion to solve DSGE models with occasionally binding constraints, such as the ZLB.[7] Despite the resulting first order approximation, the influence of second moments on equilibrium is not eliminated as the vector of state variables includes the variance of technology shocks buffeting the capital production sector. Moreover, given the large number of state variables, perturbation is well-suited to solve our model in a reasonable amount of time.

We employ, to a large extent, the parameterization of Fernandez-Villaverde et al. (2015) and Carlstrom and Fuerst (1997). An overview over the parameter specification is provided in Table 1. We set the discount rate equal to $\beta = 0.995655$, such that the real long-run risk-free rate is 1.75% (Nakata, 2017). For the parameters governing risk aversion and the (inverse of the) Frisch elasticity of labor supply, we use $\upsilon_c = 2$ and $\upsilon_l = 2$, respectively. The depreciation rate of capital is 6% per year, i.e. $\delta = 1.5\%$, and the elasticity of capital in the production function is $\alpha = 0.36$. With respect to nominal rigidities, the elasticities of demand and the parameters of

[7] See also Richter and Throckmorton (2016), who consider the role of using different solution methods, linear, quasi-linear and nonlinear, to account for the ZLB.

the Taylor rule, we follow Fernandez-Villaverde et al. (2015). We calibrate the price and wage stickiness parameters, χ_p and χ_w, such that the slope of the respective Phillips curve is equal to 0.75. The elasticity of demand for intermediate goods and labor is set to $\theta_p = \theta_w = 21$, implying a mark-up of 5%. The parameters of the Taylor rule are set to $\rho_R = 0.7$, $\rho_\Pi = 1.35$, $\rho_Y = 0.25$ and $\sigma_R = 0.0049$ The annualized inflation rate is set to $\Pi_0 = 2\%$, the nominal annualized interest rate is thus 3.75%.

For the credit channel variables, we target an annual bankruptcy rate of 3.90% and a risk premium of 1.87%, which are the values due to Carlstrom and Fuerst (1997). Note, however, that the latter value hardly deviates from the long-run mean of 1.89%, which is inferred from Moody's Seasoned Baa Corporate Bond Yield Relative to Yield on 10-Year Treasury Constant Maturity. We target these values by setting the steady state of risk $\sigma_{\omega,0} = 0.207$, the steady state default threshold equal to $\varpi = 0.6035$ and the entrepreneurs' discount rate $\gamma = 0.9474$. Finally, the parameter governing the monitoring costs associated with bankruptcy is set, as in Carlstrom and Fuerst (1997), equal to $\mu = 0.25$. Further discussion and sensitivity analysis regarding this parameter follows below. In order to compute the business cycle statistics, we parameterize the exogenous processes using the values of Christiano et al. (2014). The persistence parameters are given by $\{\rho_d, \rho_z, \rho_{\sigma_\omega}\} = \{0.90, 0.81, 0.97\}$, while the standard deviations are $\{\sigma_d, \sigma_z, \sigma_{\sigma_\omega}\} = \{0.023, 0.0048, 0.07\}$. The business cycle statistics are shown in Table 2.

4.1 Variance Decomposition

We perform a "pseudo variance decomposition" to decompose the effects of different shocks on key business cycle variables. In our model, all the shocks are uncorrelated, but our model is nonlinear. Consequently, the sum of effects produced by each shock alone does not equal to the effect produced by all the shocks working simultaneously. In this case, the calculation of ordinary variance decomposition is not possible. However, we provide a simple estimate that is analogous

to a conventional variance decomposition and that coincides with linear approximation.[8] We calculate variances produced by each shock working alone (with the other shocks set to zero) and divide it by the sum of these variances.

More precisely, our model has shocks $\varepsilon_i, i = 1, 2, ..., n$ with standard deviation $\sigma_i, i = 1, 2..., n$. We set all the shocks but the ith one to zero and leave the variance of the non-zero shock unchanged. We, then, solve the model, denoting the corresponding standard deviation of variable v as $\sigma_{v,i}$, and perform the same action for each one of the remaining shocks. The i-th component of variance decomposition $\text{vdc}_i(v)$ of the variable v is then defined by the relation:

$$\text{vdc}_i(v) = \frac{\sigma_{v,i}}{\sum_{k=1}^{n} \sigma_{v,k}}$$

In the case of uncorrelated shocks, the formula above coincides with the definition of linear variance decomposition. However, in the non-linear case, the denominator does not equal to the variance of variable v produced by simultaneous effect of all the shocks. The results are displayed in Table 3; they are markedly different for the model with and without lower bound. Table 3 shows that after accounting for the non-linearity the role of time-varying risk shocks increases for key business cycle variables, and accounts for half the variation in nominal interest rates.

5 Results

In order to gain intuition into the effects of time-varying risk in the context of the ZLB, Subsection 5.1 examines the interaction of agency costs and the ZLB regarding the factors impacting supply and demand. Subsection 5.2 investigates the impulse responses of a risk shock. Subsection 5.3 offers a resolution to the missing deflation puzzle. Subsection 5.4 addresses the amplification due to interaction of nonlinearity and agency cost friction and discusses the quantitative implications

[8] This approach is proposed in Lanne and Nyberg (2014) for nonlinear VAR models.

regarding the risk premium.

5.1 Agency Costs and the ZLB: Stylized Analysis of Supply and Demand

Before analyzing the effects on supply and demand of capital separately, note that final-good and capital market clearing are given by $(1-\eta)c_t+\eta c_t^e+\eta i_t = y_t\left(1-F_p\left(\Pi_t\right)-F_w\left(\frac{w_{t+1}}{w_t}\right)\right)$ and $k_{t+1} = (1-\delta)k_t+\eta i_t\left(1-\mu\Phi\left(\bar{\omega}_t;\sigma_{\omega,t}\right)\right)$, respectively, where η denotes the share of capital-producing entrepreneurs in the economy.[9] Agency costs diminish output via a reduction in investment and thus the available capital stock next period.

Turning now to the household's asset demand, the relevant Euler equations for capital and risk-free bonds are

$$1=\beta E_t\left(\frac{\lambda_{t+1}}{\lambda_t}\left(\frac{(1-\delta)q_{t+1}+r_{t+1}}{q_t}\right)\right) \tag{2}$$

$$1=\beta R_t E_t\left(\frac{\lambda_{t+1}}{\lambda_t}\left(\frac{1}{(1+\Pi_{t+1})}\right)\right) \tag{3}$$

where $\lambda_t = d_t/\left(c_t-b_hc_{t-1}\right)^{\upsilon_c}-E_t\left(\beta d_{t+1}b_h/\left(c_{t+1}-b_hc_t\right)^{\upsilon_c}\right)$ is the Lagrange-Multiplier on consumption. The upper panel (a) in Figure 2 shows that, corresponding to the above discussion in context of equation (1), a risk shock adversely affects capital supply by shifting the supply schedule upward (shift from S to S' in the Figure). This results in a higher price of capital but a smaller quantity of investment for any given demand.

The change in the demand for capital, in turn, is represented as an inward shift because of a fall in both the real rental rate of capital r_t and the available income. The latter effect is due to an increase the bankruptcy rate and thus total agency costs, as well as a decrease in the share of expected net capital output going to the lender, $g\left(\bar{\omega}_t;\sigma_{\omega,t}\right)$, as shown below. The former effect is because of a fall in output and labor, given that wages are very slow to adjust. The impact on the

[9] We note that the parameter η does not play a role in the characteristics of equilibrium and, in particular, the behaviour of investment or consumption.

demand side partially offsets the supply-effect regarding the price of capital, but further reduces capital. Graphically, this effect is represented by a shift from D to D' in Figure 2.

Shocks operating at the ZLB strongly amplify this drop in capital demand (shift from D to D' *at ZLB* in the Figure) because the central bank cannot further reduce R_t to mitigate the adverse effects of the risk shock: household demand for capital drops much more compared to a hypothetical economy in which R_t can further fall, in order to equate expected discounted returns as implied by (2) and (3). Therefore, while the return per unit of investment is below steady state but relatively higher in the ZLB economy, the loan volume $(i_t - n_t)$ drops much more, as indicated by the difference between K' and K' *at ZLB*. Associated with this larger drop is a relatively smaller increase in the risk premium and bankruptcy rate, as lenders demand less compensation because of the decrease in lending. This is understood by noting that the risk premium can be rewritten as $riskpr = q_t(1 + r_t^k) - 1 = \bar{\omega}_t / g\left(\bar{\omega}_t; \sigma_{\omega,t}\right) - 1$, and reflected in a larger drop in the default threshold and the share of expected net capital output going to the lender $g\left(\bar{\omega}_t; \sigma_{\omega,t}\right)$. The corresponding dynamics are displayed in the impulse response functions (IRFs) in Figures 3 and 4.

The effect on the demand for risk-free bonds is displayed in the lower panel (b) in Figure 2. This Figure looks similar to Nakata (2017), but for different reasons. The shift from D *w/ ZLB* to D' *w/ ZLB* is hypothetical and can be understood as impact on R that would prevail given the changes in other variables, most notably, inflation and output. (Of course, these larger changes are *caused* by R *not* moving in the first place.)

5.2 Impulse Response Functions

The impulse we depict is a four-period sequence of unexpected exogenous supply-side risk shocks.[10] As shown in Figure 3 in the uppermost left panel, the first innovation of this sequence occurs in period two. We examine a four-period sequence for two reasons. Firstly, the economy moves away

[10] Figures 8 and 9 in the Appendix display the IRFs of TFP and preference shock, for comparability. Figure 10 shows the IRFs for the model without consumption habit ($b_h = 0$).

from the ZLB after a shock has occurred. More importantly, however, a sequence of shocks is instructive to illustrate the effect of a shock on the economy both upon reaching and at the ZLB. Although these effects are not qualitatively different, quantitatively the differences are significant. Considerably larger effects are induced by shocks that push the economy to the ZLB − which highlights the importance of which shock brings the economy to the ZLB − and in the initial period after reaching the ZLB. Effects in periods two, three and onwards after reaching the lower bound (but subjecting the economy to further shocks) on interest rates are quantitatively smaller and very similar.

The IRFs confirm the above discussion, showing that with greater risk, bankruptcy rate and risk premium increase (this is verified in Figure 4), which implies that agency costs increase − but not as much with ZLB due to the larger drop in i_t shown in Figure 3. The reason is that, as explained above, the household lowers capital investment until expected rates of return are equalized, as shown in Figure 4. Thus, q_t adjusts accordingly, increasing less in the economy with ZLB.

Entrepreneurs are affected by the ZLB as follows. Their net worth n_t is slow to adjust in the period of the initial shock (see also Figure 4) as it consists mostly of capital holdings carried over from the previous period. The loan volume $(i_t - n_t)$ thus drops faster if a ZLB constrains monetary policy. Because the contract specifies that all rents go to entrepreneurs, the participation constraint (1) implies that $g(\bar{\omega}_t; \sigma_{\omega,t})$ has to decrease and is expected to stay below the steady state value from households, which aggravates the decrease in capital demand. In other words, the household decreases demand for capital and invests instead in risk-free bonds.

The strongly amplified impact on investment in the ZLB economy is accompanied by adverse effects on output, and aggregate consumption. In the ZLB economy, risk-neutral entrepreneurs lower consumption for a much longer time-period to build up their capital stock and to increase n_t in order to attract investment. This explains, jointly with the large drop in income and habit in consumption, the negative deviation of aggregate consumption on impact of a shock in this

setup.[11]

Because wages are sticky in the economy and investment falls, there is a drop in labor, output and in the rental rate of capital r_t. Overall, because of the deteriorating macroeconomic conditions, real marginal costs fall as well, such that firms decrease their prices. The inflation rate, therefore, decreases which jointly with the drop in output induces the monetary authority to cut interest rates. If the fall in real marginal costs is sufficiently large (e.g. because the shock is sufficiently large), the economy ends up at the ZLB.[12]

5.3 A Resolution to the "Missing Deflation Puzzle"

The "Missing Deflation Puzzle" refers to almost non-existing Phillips Curve (PC) relationship during the Great Recession period, i.e. the fact that there was a large and persistent drop in GDP, while inflation fell very little. As shown in the IRFs in Figure 3, (annualized) inflation decreases from the steady state of 2% to 1.5% upon reaching the ZLB, but remains around this level as further shocks hit the economy. In contrast, output decreases much more strongly, deviating between 2.5% and 3% from steady state. To illustrate this point further, Figure 5 displays the relation between inflation rate and output gap (measured as deviation of output in period t from steady state) induced by risk shocks in our model. This Figure is constructed as follows. We simulate the economy for 10,000 periods and subject it to risk shocks only. The standard deviation of risk is set to 7%, based on Christiano et al.'s (2014) estimate for unanticipated innovations. We plot the resulting PC for an economy with (upper panel (a)) and without (lower panel (b)) ZLB. The slope is obtained by regressing inflation on a constant and the output gap, which is computed as output's deviation from steady state.

[11] Most studies that examine risk shocks in the context of an agency cost friction experience difficulties in generating co-movement between consumption and output. Chugh (2016), for example,reports a 0.6% increase in consumption following a 4% shock to stochastic volatility - but with consumption remaining above the steady state for more than ten years, while Dmitriev and Hoddenbagh (2017) report an increase of about 0.1% in consumption following a 2.8% volatility shock. A notable exception is Christiano et al. (2014); their model produces a procyclical response of consumption.

[12] We find that persistent risk shocks, as introduced in Strobel (2018) or risk news shocks as in Christiano et al. (2014) are not - for any reasonable parameter configuration - able to push interest rates to zero from the steady state.

In line with the previous discussion, Figure 5 reflects the amplification of the ZLB and the resolution to the missing deflation puzzle. Although both economies produce a relatively flat PC, the ZLB has a relatively large impact on the slope, increasing it from 0.044 to 0.067. We consider this to be large, as the economy is only 1.41% of periods at the ZLB, and the latter slope is the average between periods at and away from the ZLB. Despite the increase in the slope due to the ZLB, the model is still consistent with the past experience of small changes in inflation in combination with large changes in the output gap. For instance, the smallest (output gap, inflation)-tuple in the economy with ZLB is $(-3.1\%, 1.49\%)$, while the smallest tuple without ZLB is $(-1.0\%, 1.93\%)$.

5.4 Quantifying the Interaction of ZLB and Agency Cost Friction

In order to analyze the amplification of the agency cost friction in the context of the nonlinearity, Figure 6 presents the innovations that are necessary to push the economy to the ZLB for different values of the agency cost parameter μ. This parameter captures the difference between a firm's internal (the firm's value as a going concern) and external value (firm's value if all assets were liquidated). E.g. in the steady state, given our benchmark calibration of $\mu = 0.25$ and an annualized bankruptcy rate of 3.90%, the share of investment in a quarter is transformed into capital available for production in the next period is 99.76% $(100\% - 3.9\%/4 \times 0.25)$ of the investment, while 0.24% are lost due to agency costs.

The vertical axis of Figure 6 shows the innovation that is necessary to push the economy from steady state to ZLB conditional on different values for $\mu \in \{0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.40, 0.50\}$. There is a clear, monotonically decreasing relation between these two values. The larger μ, the lower the innovation in risk needed to push the economy to the ZLB. At the benchmark value of $\mu = 0.25$, a 17.5% increase in risk pushes the economy to the ZLB. In comparison, an innovation of roughly 60% (12.5%) is needed if $\mu = 0.05$ (0.50). Moreover, corresponding to intuition, the larger μ, the stronger the propagation of a given impulse in the economy.

This point is illustrated in the upper panel (a) in Figure 7. Contained in this Figure is the comparison of the difference in IRFs of an economy with and without ZLB (green minus red line in Figure 3 above), for $\mu = 0.20$ (dashed line) and $\mu = 0.25$ (straight line). The comparison is based on an identical four-period sequence of innovations of 20% in both economies.[13] For instance, the uppermost left panel shows the difference, measured in percentage points, in the uncertainty shock. Because all four economies are perturbed by identical impulses, the difference is zero. Consider as further example output, displayed in the uppermost right panel. The difference in the impact on output because of the ZLB for $\mu = 0.25$ (straight line), is $-0.96\% - points$ in the period of the first shock and about $-2.2\% - points$ in the periods of shocks two to four.

If the nonlinearity of the model had no impact, the straight and the dashed line would coincide. However, as shown in the lower panel (b) in Figure 7, the difference in the dashed and straight line for output is about $0.5\% - points$ if a shock occurs, i.e. the difference in the impact on output in the economy with vs. without ZLB is about $-0.4\% - points$ initially, and then falls to values of $1.7\% - points$ if $\mu = 0.20$. For investment, this difference-in-difference is even larger with about $1.70\% - points$ in the period the economy reaches the ZLB and $1.20\% - points$ each period a shock occurs. Consequently, we conclude that the nonlinearity interacts with the agency cost friction, strongly aggravating the adverse impact of a risk shock.

5.4.1 Quantitative Implications

In light of the quantitatively large amplification due to interaction of agency cost friction and truncated Taylor Rule, this section addresses the plausibility of our results. To this end, we consider the quantitative response of the risk premium, as this variable reflects variation in key credit channel variables, relevant for the transmission of agency cost friction to the real side of the economy. In our model, the annualized risk premium $riskpr$ is computed as $riskpr = \left(q_t(1 + r^k) - 1\right) \times 400 = (\bar{\omega}_t / g\left(\bar{\omega}_t; \sigma_{\omega,t}\right) - 1) \times 400$.The empirical counterpart of the risk premium

[13] We specify an innovation of 20% as this magnitude is just sufficient to push the economy to the ZLB for the smaller value of $\mu = 0.20$.

is Moody's Seasoned Baa Corporate Bond Yield Relative to Yield on 10-Year Treasury Constant Maturity from 1953 until 2017, which exhibits a long-run mean of 1.89%.

Our model implies that a risk shock increases the risk premium by (annualized) $2\% - points$ per quarter in the period of the shock. This level of impact remains stable in the following periods in which a shock occurs. Quantitatively, this prediction is consistent with the data, which peak in December 2008 at a value of 5.69%, while the average risk premium in 2008 (2009) was 3.76% (4.04%) - roughly $1.9\% - points$ ($2.1\% - points$) above the long-run mean. The time series is displayed in Figure 1.

6 Conclusion

Using the credit channel model of Carlstrom and Fuerst (1997), we show that risk shocks, changes in a mean preserving spread in the distribution of the technology shocks affecting capital-good production, can lead to an economy reaching the ZLB and can have large quantitative effects on key business cycle variables. Moreover, the interaction of agency cost friction and ZLB amplifies the adverse effects of a risk shock on aggregate variables. We also provide a linkage between risk and the ZLB that addresses the "Missing Deflation Puzzle" in the NK Phillips Curve literature. Our result shows that the large and persistent drop in output along with the small decline in inflation could be due to tightening of financial conditions and credit. Consequently, our model produces dynamics that fit the description of a "financial accelerator, in that endogenous developments in credit markets work to amplify and propagate shocks to the macroeconomy." (Bernanke, Gertler, and Gilchrist, 1999, p. 1342).

Future research that examines whether endogenous uncertainty (Fajgelbaum, Schaal, and Taschereau-Dumouchel (2017)) can also push the economy to the ZLB and endogenously keep the economy at the ZLB is left for future analysis.

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A Appendix

B Complete System of Equations

Households:

$$\lambda_t = \frac{d_t}{(c_t - b_h c_{t-1})^{\upsilon_c}} - E_t\left(\frac{\beta d_{t+1} b_h}{(c_{t+1} - b_h c_t)^{\upsilon_c}}\right) \tag{4}$$

$$\begin{aligned}(\theta_w - 1)\, w_t l_t + y_t \frac{w_t}{w_{t-1}} F_w'\left(\frac{w_t}{w_{t-1}}\right) &= \frac{d_t}{\lambda_t}\psi\theta_w l_t^{1+\upsilon_l} + E_t\left(\beta\frac{\lambda_{t+1}}{\lambda_t} y_{t+1}\frac{w_{t+1}}{w_t} F_w'\left(\frac{w_{t+1}}{w_t}\right)\right) \quad \text{(B.5)}\\ F_w(w) &= \frac{\varkappa_w}{2}(w-1)^2 \quad \text{(B.6)}\end{aligned}$$

$$q_t = E_t\left(\beta\frac{\lambda_{t+1}}{\lambda_t}\left((1-\delta)q_{t+1} + r_{t+1}\right)\right) \tag{7}$$

$$\lambda_t = \beta E_t\left(\lambda_{t+1}\frac{R_t}{(1+\Pi_{t+1})}\right) \tag{8}$$

where

$$U(c,l) = \frac{(c - b_h c_{-1})^{1-\upsilon_c}}{1-\upsilon_c} - \psi\frac{l^{1+\upsilon_l}}{1+\upsilon_l}$$

$$q_t^{-1} = 1 - \mu\Phi(\varpi_t) + \mu f(\varpi_t)\frac{\phi(\varpi_t)}{f'(\varpi_t)} \tag{9}$$

$$i_t = \frac{1}{1 - q_t g(\varpi_t)} n_t \tag{10}$$

Table 1: Parameter values.

Parameter	Value	Source
	Preferences	
β	0.995665	Nakata (2017)
b_h	0.75	Fernandez Villaverde et al. (2015)
υ_l	2	Fernandez Villaverde et al. (2011)
υ_c	2	Fernandez Villaverde et al. (2015)
	Rigidities	
χ_w	4868	Fernandez Villaverde et al. (2015)
χ_p	235.75	Fernandez Villaverde et al. (2015)
θ_w	21	Fernandez Villaverde et al. (2015)
θ_p	21	Fernandez Villaverde et al. (2015)
	Technology	
α	0.36	Carlstrom and Fuerst (1997)
δ	0.015	Carlstrom and Fuerst (1997)
η	0.1	Carlstrom and Fuerst (1997)
	Monetary Policy	
Π_0	0.005	Fernandez Villaverde et al. (2015)
ρ_R	0.7	Fernandez Villaverde et al. (2015)
ρ_Π	1.35	Fernandez Villaverde et al. (2015)
ρ_Y	0.25	Fernandez Villaverde et al. (2015)
σ_R	0.0049	Fernandez Villaverde et al. (2015)
	Credit Channel	
μ	0.25	Carlstrom and Fuerst (1997)
$\sigma_{\omega,0}$	0.207	Carlstrom and Fuerst (1997)
γ	0.9474	Carlstrom and Fuerst (1997)
ϖ	0.6035	Carlstrom and Fuerst (1997)
	Exogenous Processes	
ρ_β	0.90	Christiano et al. (2014)
ρ_z	0.81	Christiano et al. (2014)
ρ_{σ_ω}	0.97	Christiano et al. (2014)
σ_d	0.023	Christiano et al. (2014)
σ_z	0.0048	Christiano et al. (2014)
σ_{σ_ω}	0.07	Christiano et al. (2014)

Note: See also the description in the text for further elaboration.

Table 2: Business cycle characteristics.

Volatility relative to y							
	σ_y	c^{agg}	i	h	w	Π	R
Model	0.035	0.59	10.83	0.19	1.06	0.01	0.16
U.S. Data	1.54	0.82	4.59	1.27	0.60	0.40	0.61
Correlation with y							
	y	c^{agg}	i	h	w	Π	R
Model	1	0.15	0.84	0.85	0.53	−0.13	−0.28
U.S. Data	1	0.88	0.92	0.87	0.09	0.11	0.20
AR(1)							
	y	c	i	h	w	Π	R
Model							
U.S. Data	0.87	0.89	0.84	0.92	0.68	0.89	0.96

Note: The US figures are from Fernandez-Villaverde et al. (2015). The innovations are $\{\sigma_R, \sigma_d, \sigma_z, \sigma_{\sigma_\omega}\} = \{0.0049, 0.023, 0.0048, 0.07\}$. The share of states at the ZLB is 4.83% of periods, the longest spell at the ZLB 4 periods. The results are computed after simulating the model for 100,000 periods.

Table 3: Variance Decomposition for the model without and with Zero Lower Bound.

	Shock	y	c	i	h	w	R	Π	$\Phi(\varpi)$	$riskpr$
No ZLB	Interest Rate (σ_R)	0.22	0.02	0.12	0.75	0.01	0.26	34.73	0.19	0.13
	Risk (σ_{σ_ω})	1.23	3.98	1.4	1.56	4.21	59.17	31.54	67.59	78.23
	Preferences (σ_d)	22.26	80.7	46.97	14.7	63.12	2.37	2.57	1.49	1.00
	TFP (σ_z)	76.3	15.29	51.51	82.99	32.66	38.2	31.15	30.73	20.64
ZLB	Interest Rate (σ_R)	3.13	1.07	2.27	5.67	0.69	3.21	27.09	2.85	2.44
	Risk (σ_{σ_ω})	8.12	13.75	7.89	10.34	13.24	48.22	37.39	53.13	59.79
	Preferences (σ_d)	30.82	60.41	43.81	24.74	50.71	9.68	7.25	7.99	6.86
	TFP (σ_z)	57.93	24.77	46.03	59.25	35.34	38.89	28.26	36.02	30.90

Note: The US figures are from Fernandez-Villaverde et al. (2015). The innovations are $\{\sigma_R, \sigma_d, \sigma_z, \sigma_{\sigma_\omega}\} = \{0.0049, 0.023, 0.0048, 0.07\}$. The share of states at the ZLB is 4.83% of periods, the longest spell at the ZLB 4 periods. The results are computed after simulating the model for 100,000 periods.

$$q_t = \beta\gamma E_t \left((1-\delta) q_{t+1} + r_{t+1} \right) \left\{ \frac{q_{t+1} f(\varpi_{t+1})}{1 - q_{t+1} g(\varpi_{t+1})} \right\} \tag{11}$$

$$\eta n_t = k_t^e \left((1-\delta) q_{t+1} + r_{t+1} \right) \tag{12}$$

Entrepreneur capital accumulation:

$$k_{t+1}^e = \eta n_t \left\{ \frac{f(\varpi_{t+1})}{1 - q_{t+1} g(\varpi_{t+1})} \right\} - \eta \frac{c_t^e}{q_t} \tag{13}$$

$$\eta c_t + (1-\eta) c_t^e + \eta i_t + \frac{\varkappa_P}{2} \left(\frac{1+\Pi_t}{1+\Pi} - 1 \right)^2 y_t + \frac{\varkappa_w}{2} (\frac{w_t}{w_{t-1}} - 1)^2 y_t = y_t \tag{14}$$

$$y_t = z_t k_t^{\alpha} \left((1-\eta) l_t \right)^{1-\alpha} \tag{15}$$

$$\alpha \chi_t \frac{y_t}{k_t} = r_t \tag{16}$$

$$(1-\alpha) \chi_t \frac{y_t}{(1-\eta) l_t} = w_t \tag{17}$$

$$\left(1 - \theta_p - (1+\Pi_t) F_p'(\Pi_t) + \theta_p \chi_t \right) y_t = -\beta E_t \left(\frac{\lambda_{t+1}}{\lambda_t} (1+\Pi_{t+1}) F_p'(\Pi_{t+1}) y_{t+1} \right) \tag{18}$$

where

$$F_p(\Pi_t) = \frac{\varkappa_P}{2} \left(\frac{1+\Pi_t}{1+\Pi} - 1 \right)^2$$

Capital accumulation equation:

$$k_{t+1} = (1-\delta) k_t + \eta i_t \left(1 - \mu \Phi(\varpi_t) \right) \tag{19}$$

Taylor rule

$$\begin{cases} \log\left(\frac{R_{t+1}}{R_0}\right) = \rho_R \log\left(\frac{R_t}{R_0}\right) + (1-\rho_R)\rho_\Pi \log\left(\frac{\Pi_{t+1}}{\Pi_0}\right) + (1-\rho_R)\rho_Y \log\left(\frac{Y_{t+1}}{Y_0}\right) + \sigma_R \varepsilon_{R,t+1}, & R_{t+1} > 1 \\ R_{t+1} = 1, & \text{otherwise} \end{cases} \tag{20}$$

There are 15 endogenous equations

Endogenous variables: $w_t, r_t, R_t, q_t, c_t, l_t, \Pi_t, y_t, i_t, k_t, Z_t, \varpi_t, c_t^e, \chi_t, \lambda_t$ (15 variables)

Exogenous equations:

$$\log(d_{t+1}) = \rho_d \log(d_t) + \sigma_d \varepsilon_{d,t+1} \tag{21}$$

$$\log(z_{t+1}) = \rho_z \log(z_t) + \sigma_z \varepsilon_{z,t+1} \tag{22}$$

$$\log\left(\sigma_{\omega,t+1}\right) = (1-\rho_\omega)\log\left(\sigma_{\omega,0}\right) + \rho_\omega \log\left(\sigma_{\omega,t}\right) + \sigma_{\sigma_\omega} \varepsilon_{\sigma_\omega,t+1} \tag{23}$$

There are 3 exogenous equations

Exogenous variables: d, z, σ_ω (3 variables)

B.1 Entrepreneur's Consumption Choice

To rule out self-financing by the entrepreneur (which would eliminate the presence of agency costs), it is assumed that the entrepreneur discounts the future at a faster rate than the household. This is represented by following expected utility function:

$$E_0 \sum_{t=0}^{\infty} (\beta\gamma)^t c_t^e \tag{24}$$

where c_t^e denotes entrepreneur's consumption at date t, and $\gamma \in (0,1)$. This new parameter, γ, will be chosen so that it offsets the steady-state internal rate of return to entrepreneurs' investment.

At the end of the period, the entrepreneur finances consumption out of the returns from the investment project implying that the law of motion for the entrepreneur's capital stock is:

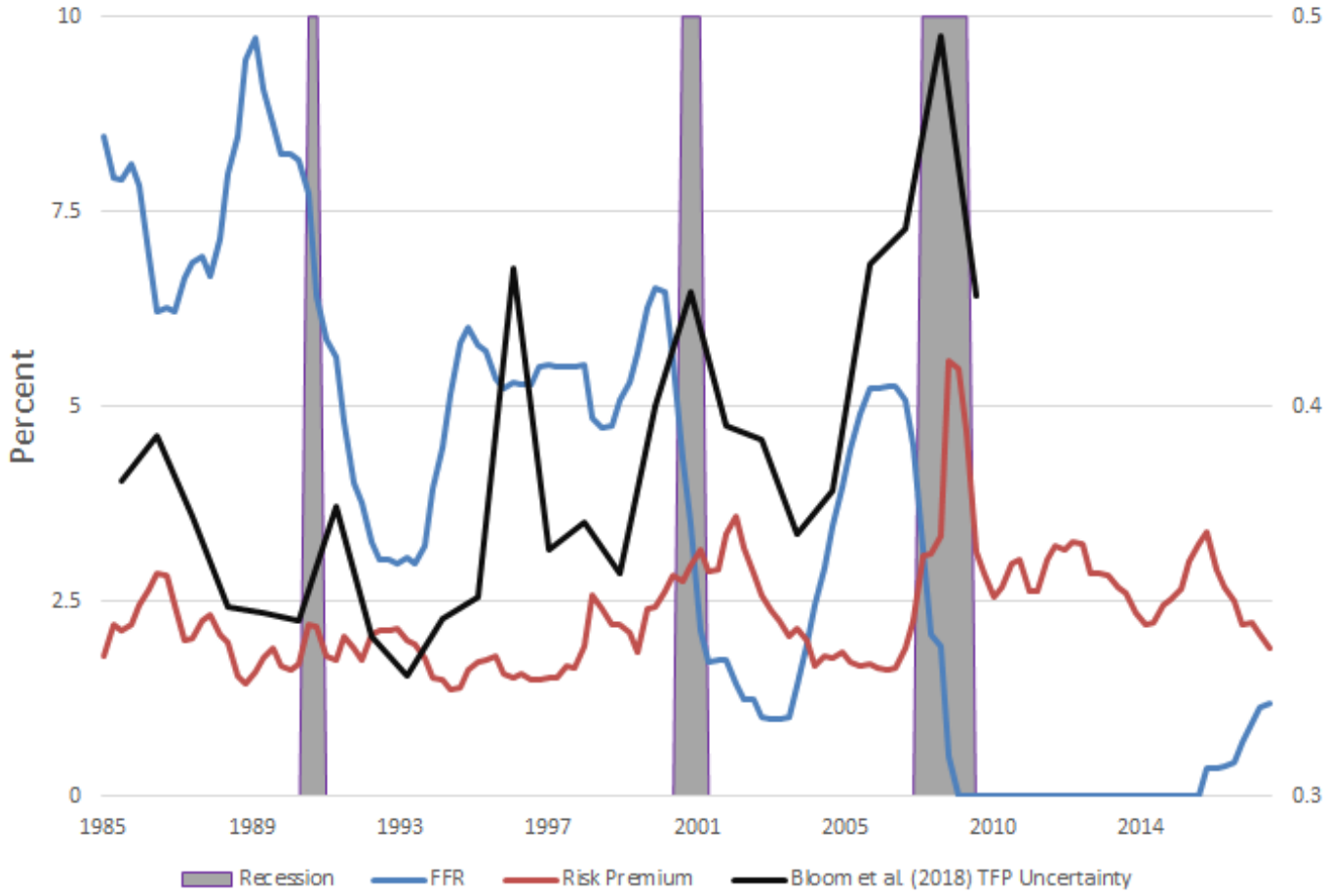
$$Z_{t+1} = \frac{1 - \delta + q_t^{-1} r_t}{\left(1 + \mu \frac{\phi(\bar{\omega}_t; \sigma_{\omega,t})}{f'(\bar{\omega}_t; \sigma_{\omega,t})}\right)} Z_t - q_t^{-1} c_t^e \tag{25}$$

The representative entrepreneur maximizes his expected utility function in equation (24) over consumption and capital subject to the law of motion for capital, equation (25). The resulting Euler equation is as follows:

$$q_t = \beta \gamma E_t \left\{ \left(q_{t+1}\left(1 - \delta\right) + r_{t+1}\right) \left(\frac{q_{t+1} f\left(\bar{\omega}; \sigma_{\omega,t}\right)}{\left(1 - q_{t+1} g\left(\bar{\omega}; \sigma_{\omega,t}\right)\right)} \right) \right\}$$

Figures

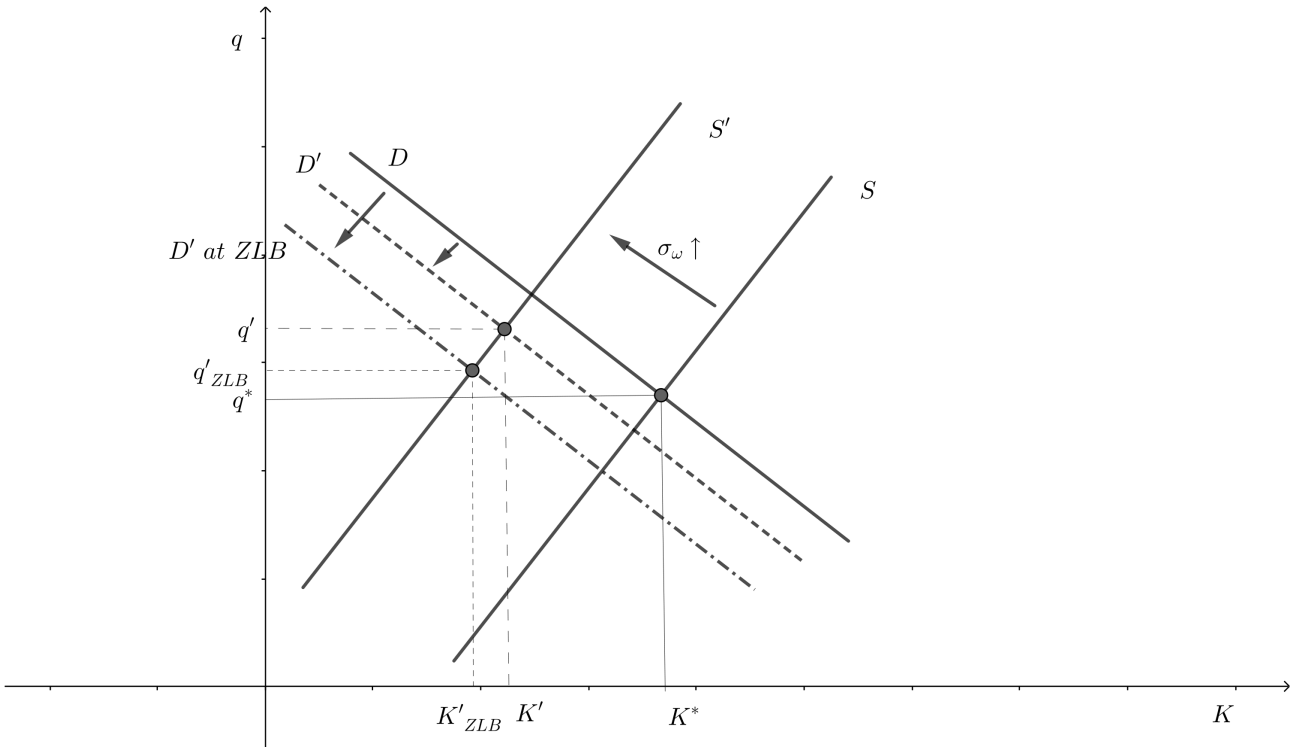
Figure 1: Effective Federal Funds Rate, Risk Premium, and Interquartile Range of Plant TFP "shocks" due to Bloom et al. (2018)



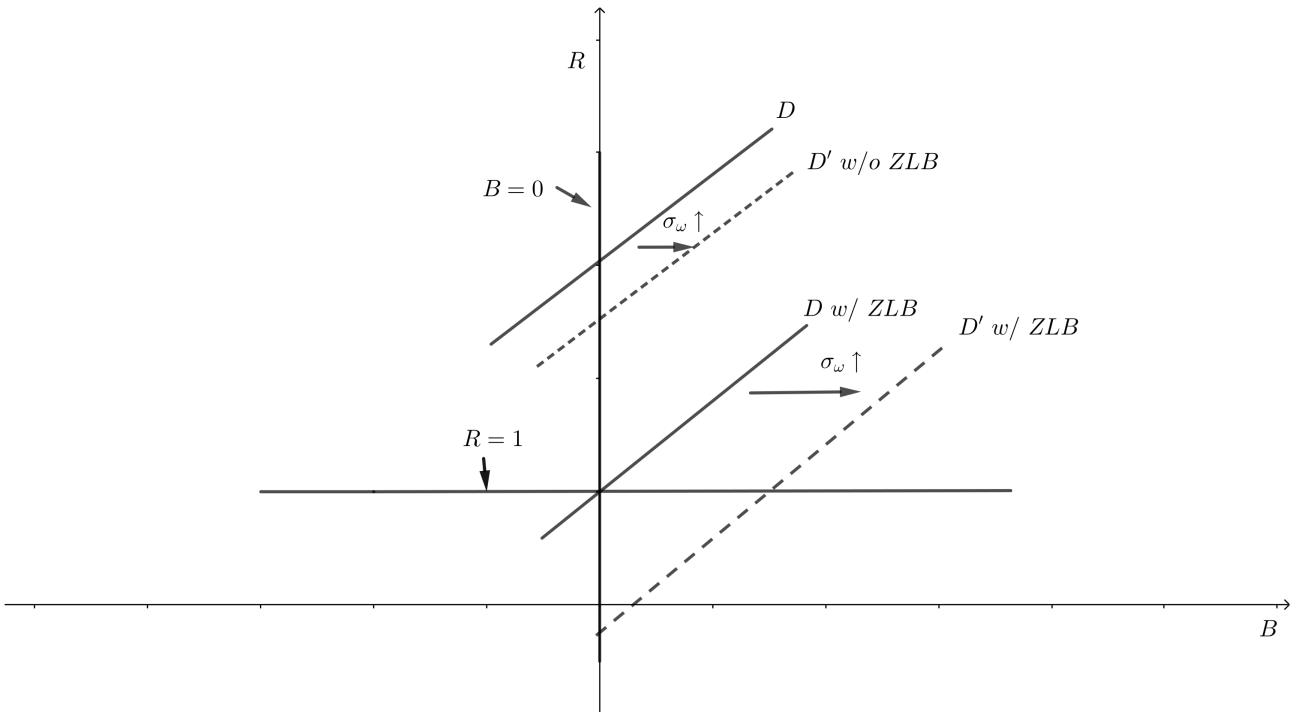
Notes: Bloom et al. (2018) construct the interquartile range of plant TFP "shocks"from the Census of Manufactures and the Annual Survey of Manufactures establishments. The risk premium is Moody's Seasoned Baa Corporate Bond Yield Relative to Yield on 10-Year Treasury Constant Maturity. Federal funds rate and risk premium are plotted on the left axis.

Figure 2: Stylized effects of an increase in risk on supply and demand of capital and bonds in the context of the ZLB.

(a) Supply and Demand Effects for Capital

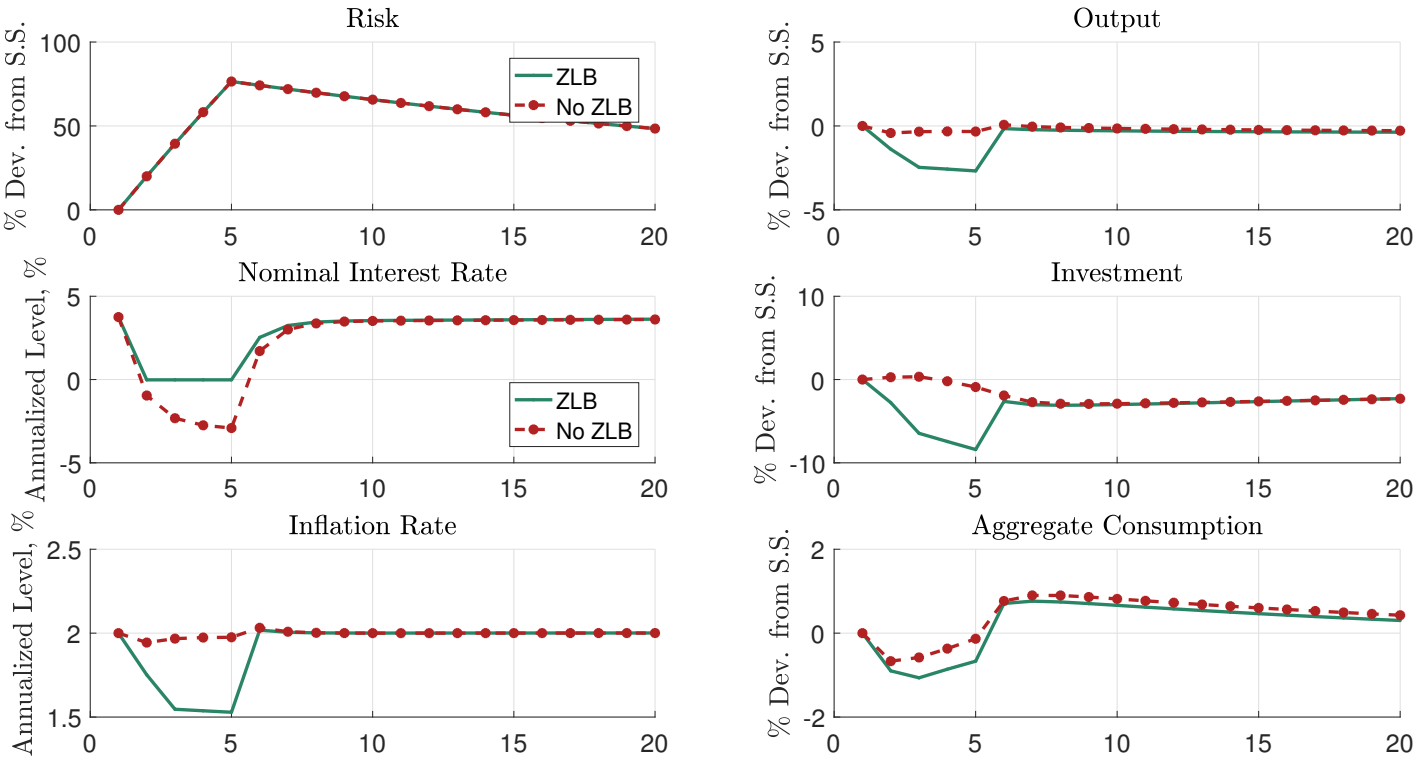


(b) Supply and Demand Effects for Bonds



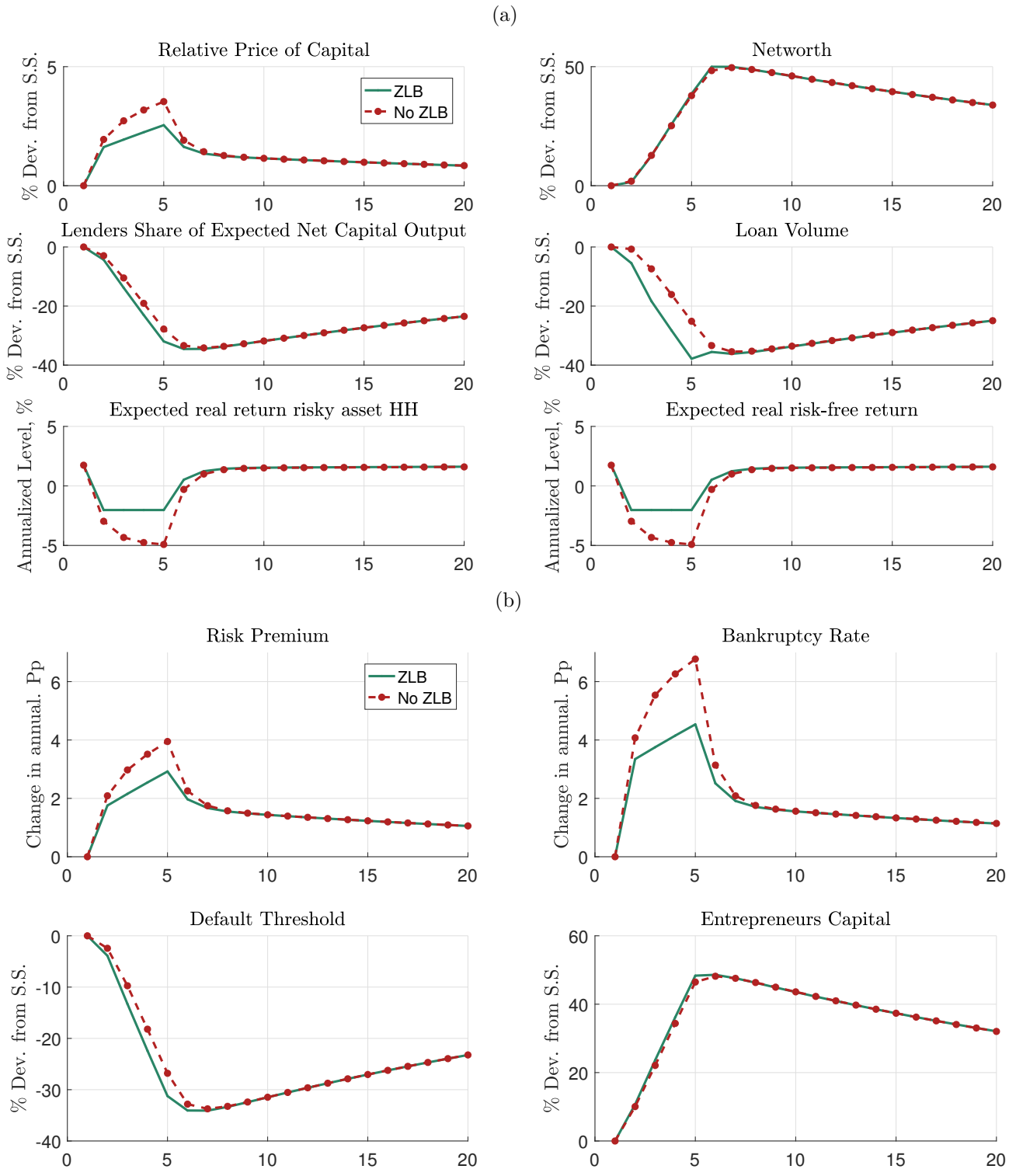
Note: This is a stylized representation that displays only shifts in supply and demand, the change in the slope is not shown.

Figure 3: Impulse Response Functions of risk, output, aggregate consumption, investment, nominal interest rate and inflation following a four-period sequence of 20% risk shocks.



Note: The vertical and horizontal axes display the unit of measurement for each one of the variables. We specify a sequence of risk shocks of 20% per period from period two to five, in order to illustrate the impact of a shock that pushes the economy to the ZLB, and to examine the effect at the ZLB. We investigate an innovation of 20% as this impulse is sufficiently large to push the economy to the ZLB.

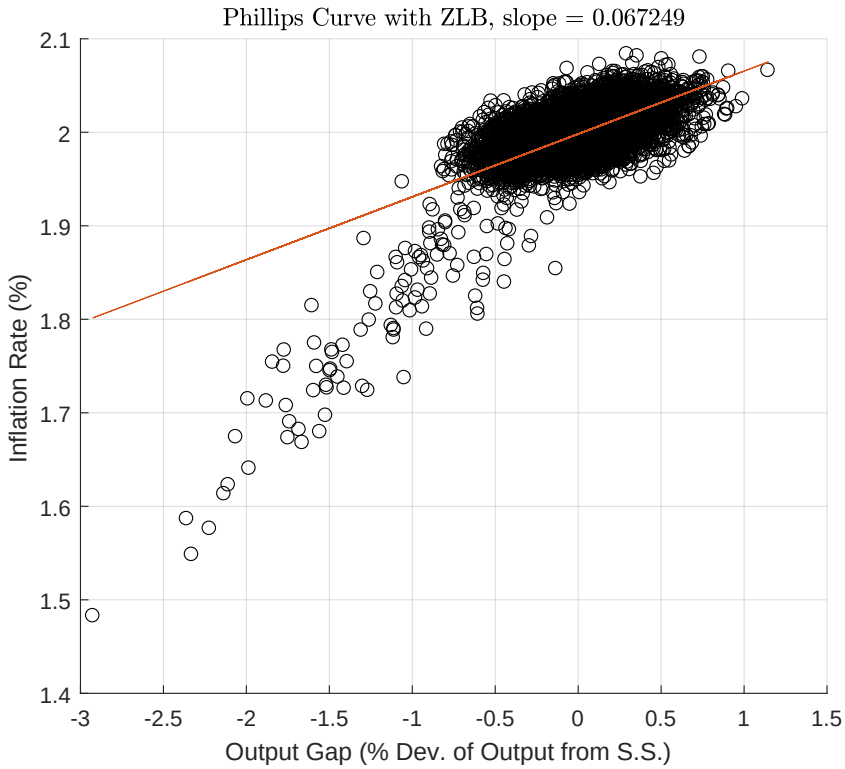
Figure 4: Impulse Response Functions of key credit channel variables (upper panel (a)) as well as key financial variables (lower panel(b)) following a four-period sequence of 20% risk shocks.



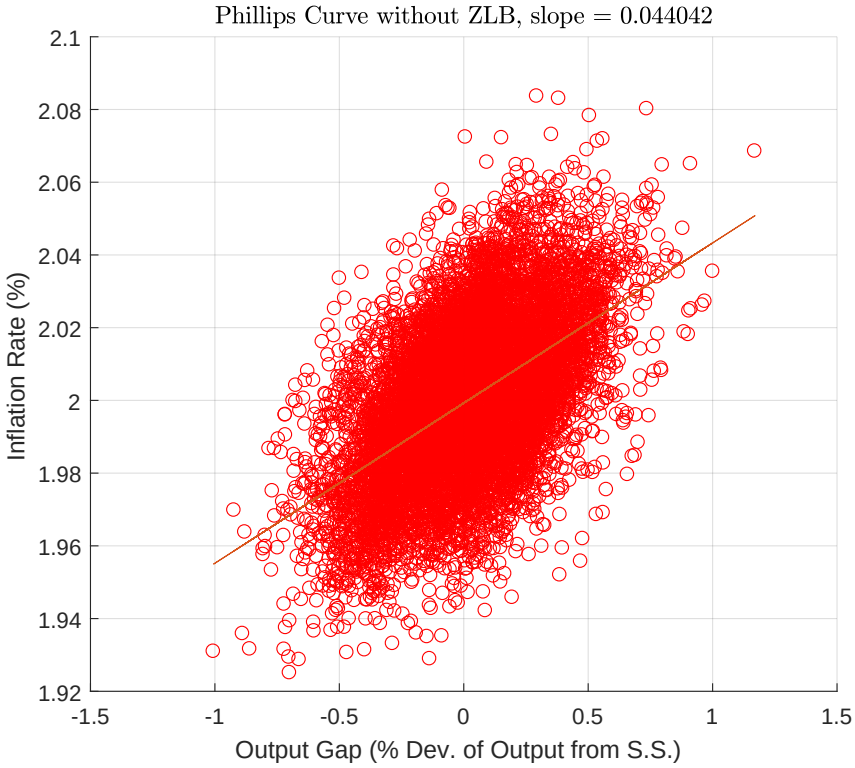
Note: The vertical and horizontal axes display the unit of measurement for each one of the variables.

Figure 5: Phillips Curve relation induced by risk shock.

(a)

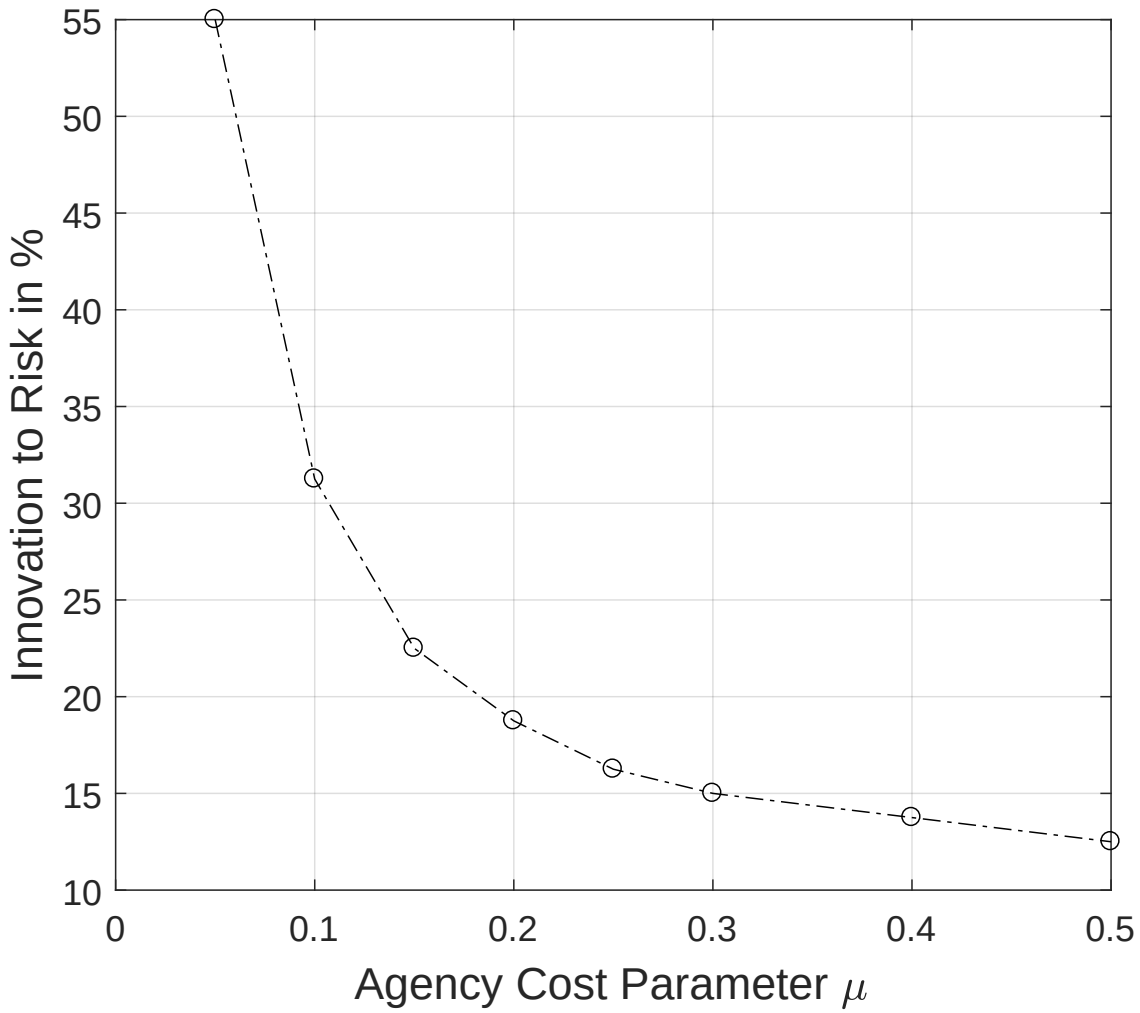


(b)



Note: The vertical axis shows the annualized inflation rate in %, the vertical axis the output gap, measured as the percentage deviation of output from the steady state. The inflation-output gap combinations are based on a simulation of 10,000 periods, hitting the economy with risk shocks only. The innovation to risk is 7%, based on the esimate of Christiano et al. (2014). The economy is 1.41% of periods at the ZLB.

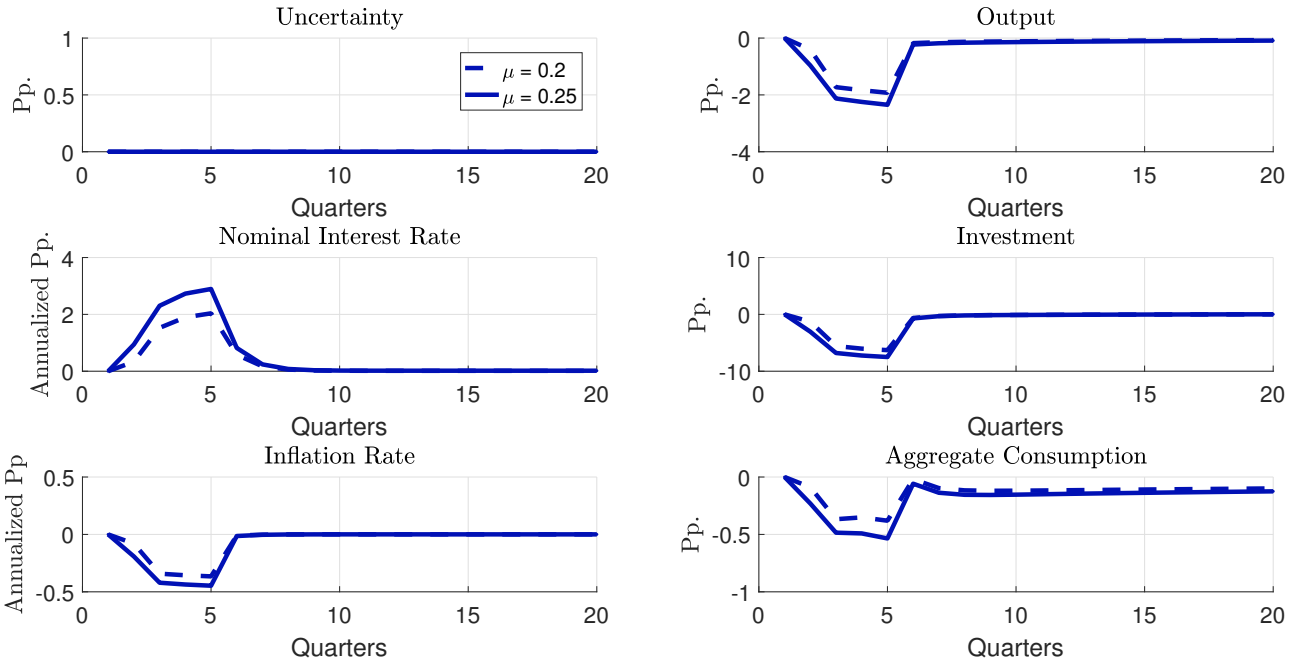
Figure 6: Innovation to risk needed to push the economy to the ZLB for different values of μ.



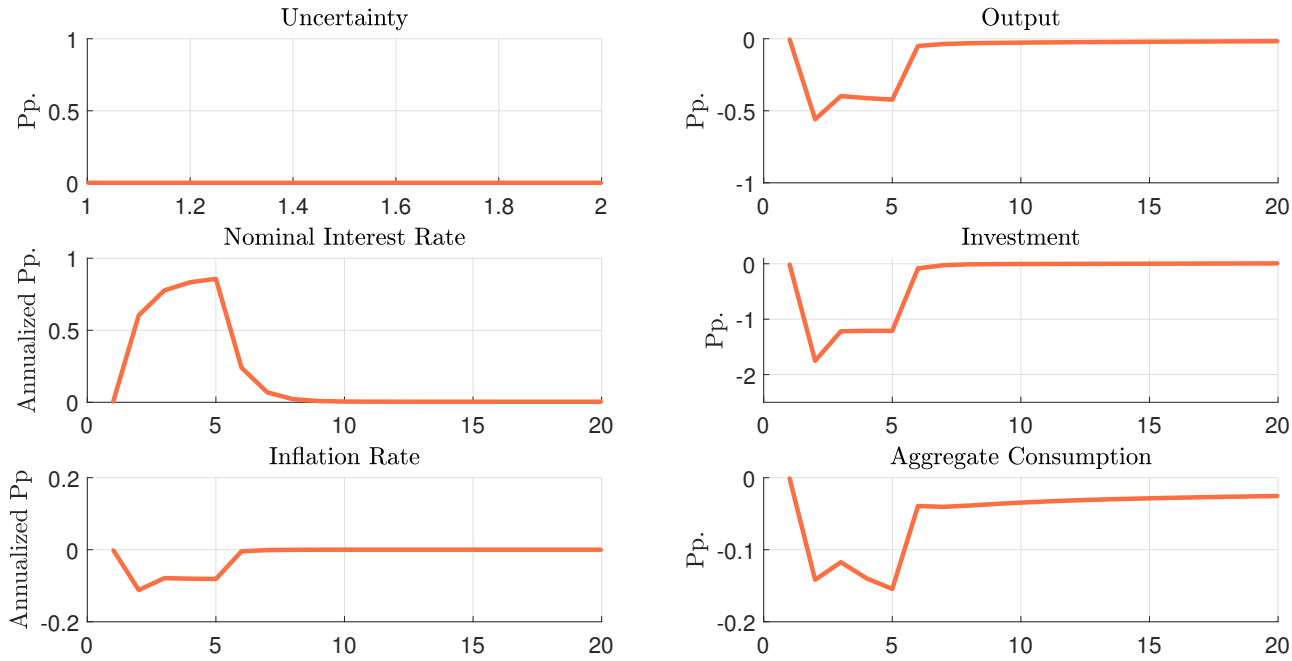
Note: The vertical axiss display the innovation to risk that is just sufficient to push the economy to the ZLB for a given value of μ

Figure 7: Difference (panel (a)) and difference-in-difference (panel (b)) in IRFs in economies with and without ZLB in an economy where $\mu = 0.25$ (straight line) and $\mu = 0.20$ (dashed line).

(a) Difference in IRFs in an economy with and without ZLB



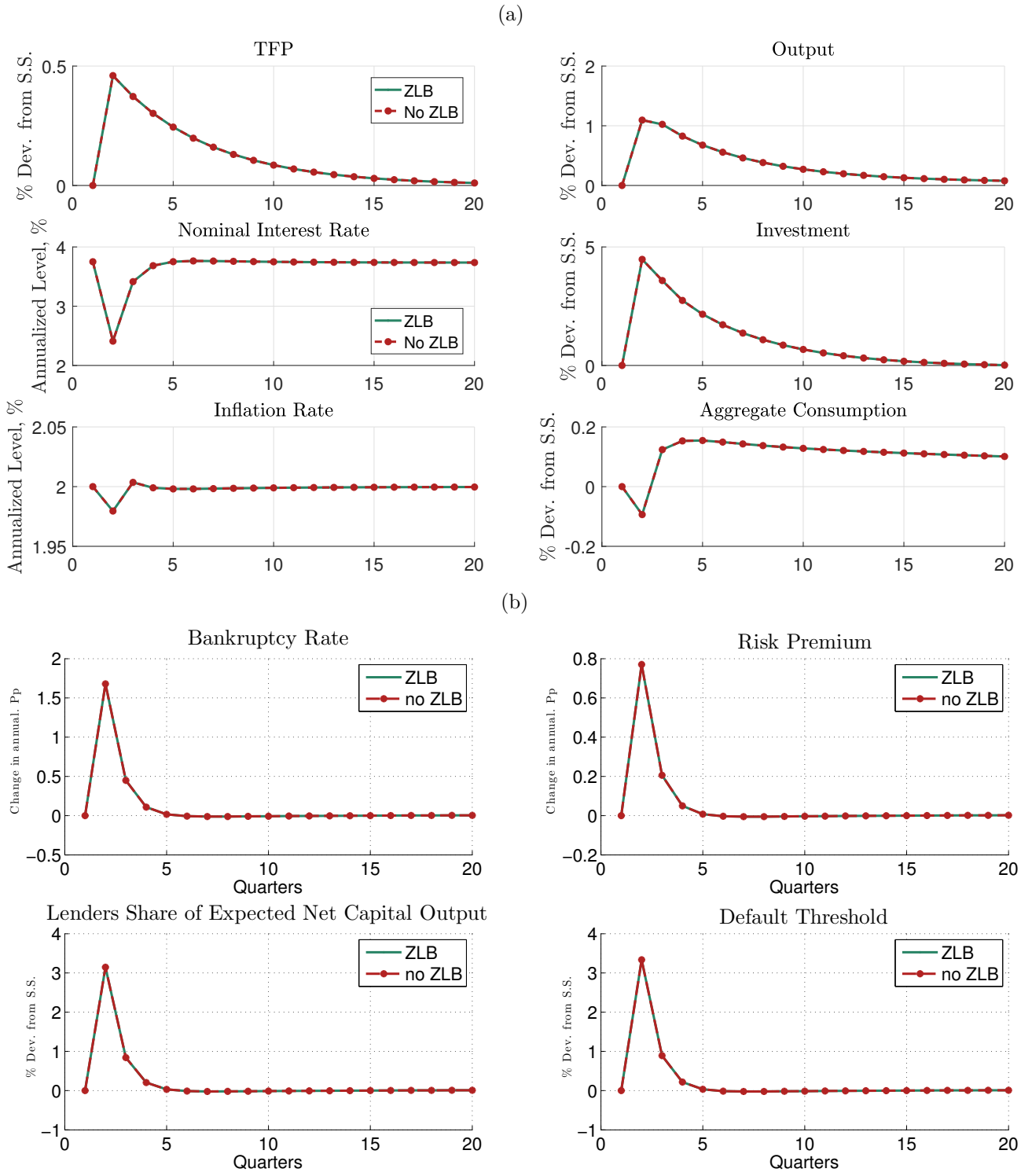
(b) Difference-in-difference across economies where $\mu = 0.25$ and $\mu = 0.20$ (straight minus dashed line from panel (a))



Note: the upper panel shows the difference in IRFs in an economy with and without ZLB (green line minus red line in the above Figure 3) for $\mu = 0.25$ (straight line) and $\mu = 0.20$ (dashed line). The lower panel shows the difference between the dashed line and the straight line. The innovation to risk is 20%, such that both economies are at the ZLB on impact of the initial shock that occurs in period two. The vertical axis measures percentage points (Pp.), as the difference is computed in the percentage deviation from steady.

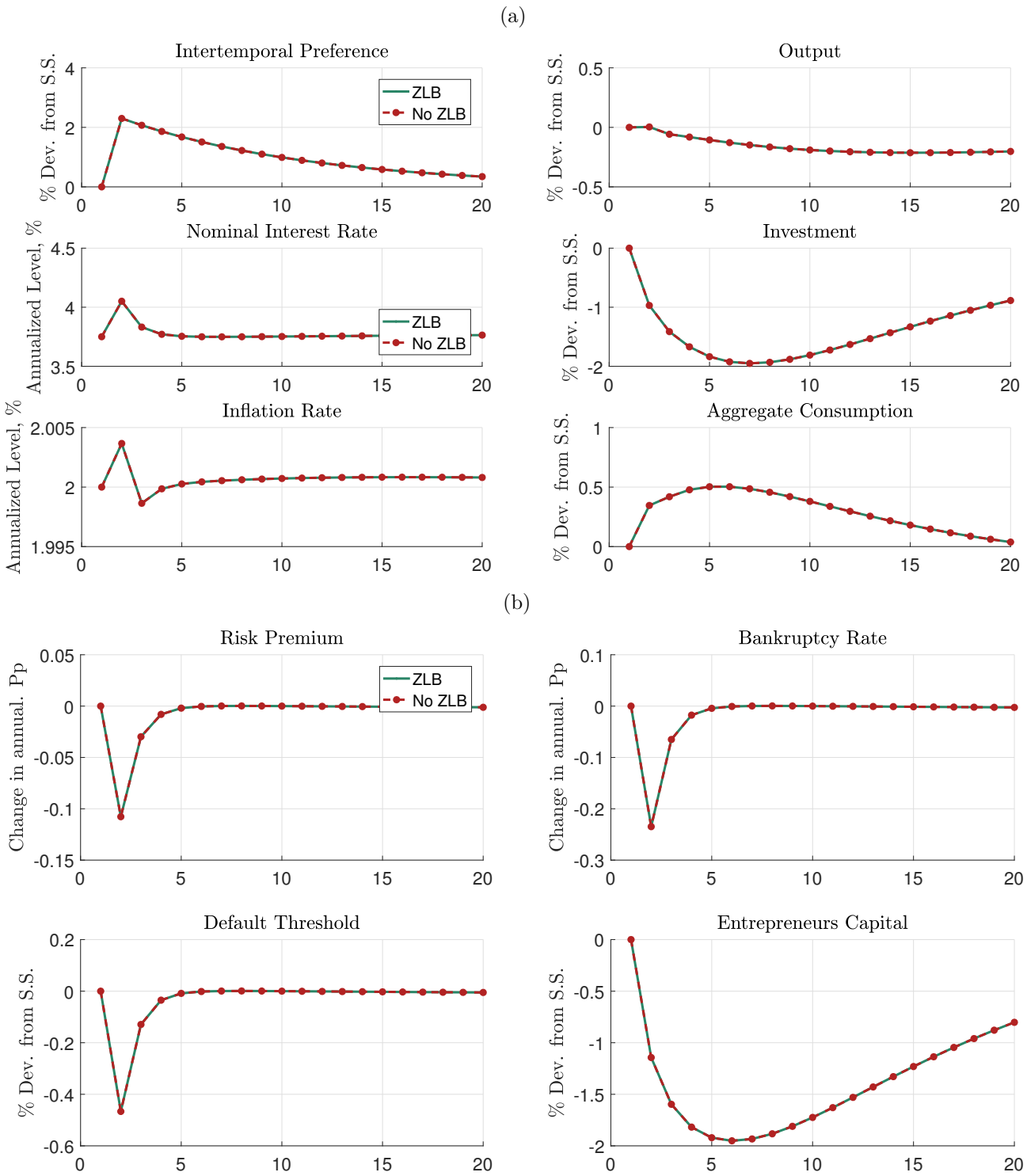
A Figures Appendix

Figure 8: Impulse Response Functions of output, aggregate consumption, investment, nominal interest rate and inflation (upper Panel (a)) as well as key financial variables (lower Panel(b)) following a 0.7% TFP shock.



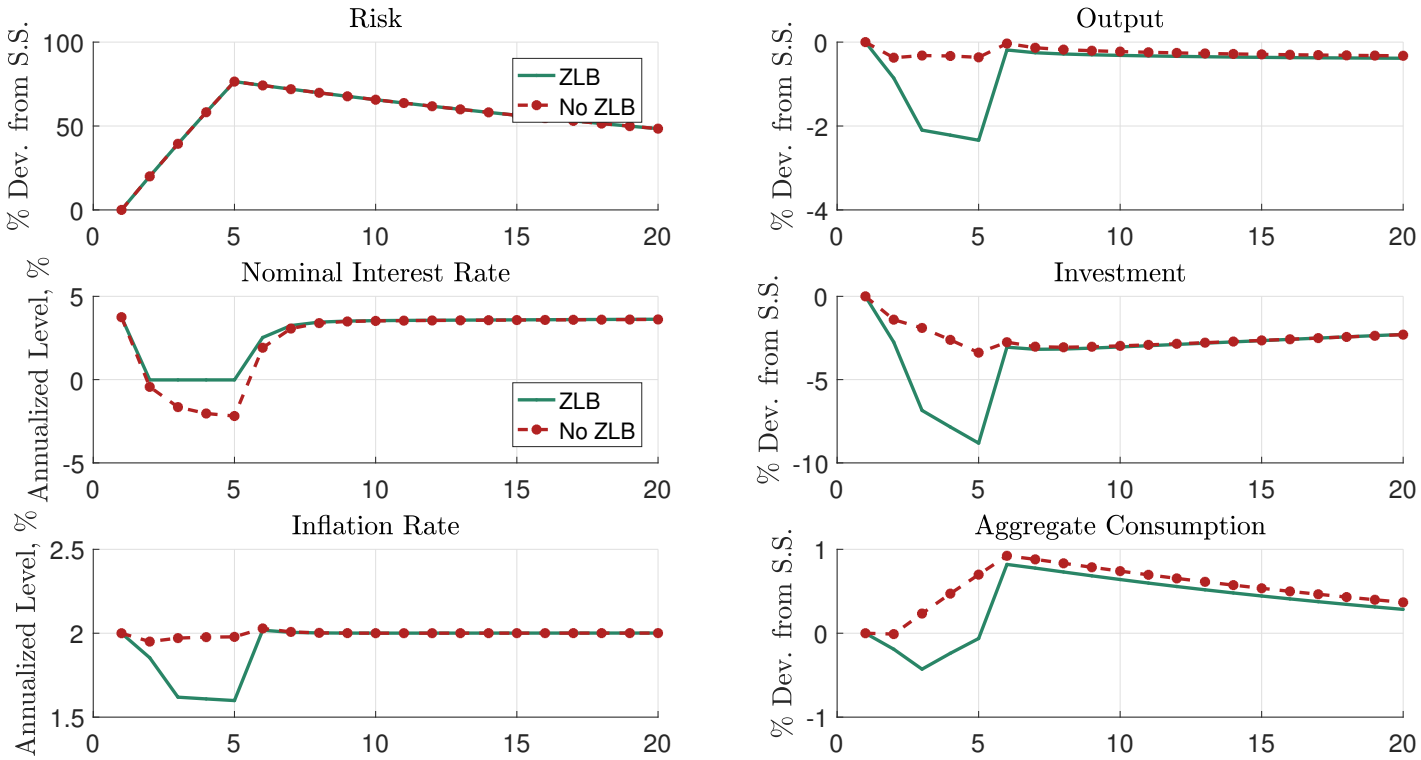
Note: The vertical and horizontal axes display the unit of measurement for each one of the variables.

Figure 9: Impulse Response Functions of output, aggregate consumption, investment, nominal interest rate and inflation (upper Panel (a)) as well as key financial variables (lower Panel(b)) following a -30% preference rate shock.



Note: The vertical and horizontal axes display the unit of measurement for each one of the variables.

Figure 10: Impulse Response Functions of risk, output, aggregate consumption, investment, nominal interest rate and inflation following a four-period sequence of 20% risk shocks for the model **without** consumption habit ($b_h = 0$).



Note: The vertical and horizontal axes display the unit of measurement for each one of the variables. We specify a sequence of risk shocks of 20% per period from period two to five, in order to illustrate the impact of a shock that pushes the economy to the ZLB, and to examine the effect at the ZLB. We investigate an innovation of 20% as this impulse is sufficiently large to push the economy to the ZLB.