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## Oil shocks and the zero bound on nominal interest rates<sup>☆</sup>

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### A B S T R A C T

Beginning in 2008, in many advanced economies, policy rates reached their zero lower bound (ZLB) and almost at the same time, oil prices started rising again. We analyze how the ZLB affects the propagation of oil shocks. As these shocks move inflation and output in opposite directions, their effects on economic activity are cushioned when monetary policy is constrained. The burst of inflation from an oil price increase lowers real interest rates at the ZLB and stimulates the interest-sensitive component of GDP, offsetting the usual contractionary effects. We show that the mitigation of the output decline from the zero lower bound depends on the source of the shock and on the persistence that alternative shocks induce in the price of oil.

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## 1. Introduction

An important, ongoing debate in macroeconomics concerns the influence of oil shocks on aggregate activity. One view is that oil shocks are a principal source of business cycle fluctuations. In this vein, Hamilton (2009) argued that most of the global recession that began in 2008 reflects the preceding run-up in oil prices. In contrast, Blanchard and Galí (2007) attributed a small role to oil shocks as drivers of economic fluctuations in the 1980s and 1990s, and suggested an even smaller role in more recent years.<sup>1</sup>

<sup>☆</sup> The views expressed in this paper are solely the responsibility of the authors and should not be interpreted as reflecting the views of the Board of Governors of the Federal Reserve System or of any other person associated with the Federal Reserve System.

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<sup>1</sup> Jones et al. (2004), Hamilton (2009), and Kilian (2008) carefully surveyed the broad literature on the macroeconomic impact of oil price fluctuations. See also Bodenstein et al. (2011), who placed a greater emphasis on work focusing on oil trade in an international setting.

Within this debate, the systematic response of monetary policy to oil shocks plays a prominent role.<sup>2</sup> Bernanke et al. (1997), for instance, argued that a large part of the effect of increases in oil prices in the 1970s can be attributed to tighter monetary policy in response to these shocks. Beginning in 2008, there has been another important systematic change in monetary policy. Namely, in many advanced economies, policy rates reached their zero lower bound (ZLB) inhibiting their stabilization role. At the same time, the spot price of West Texas Intermediate crude doubled from a trough of a little less than \$40 per barrel in February of 2009 to a peak of \$110 in April 2011. In light of these events, it is a concrete policy concern to understand how the transmission of oil shocks to the macroeconomy is affected by the zero lower bound constraint on policy rates.

To investigate this question, we extend the two-country DSGE model in Bodenstein et al. (2011) by introducing a monetary policy rule that explicitly recognizes the ZLB constraint on nominal interest rates along with price and wage rigidities. This framework is appealing since it recognizes that oil is a globally-traded commodity in which the international linkages of oil to the domestic economy play a key role. The model allows for different sources of oil price fluctuations including changes in supply and demand emanating from both country blocs.<sup>3</sup>

A key finding of our analysis is that oil price shocks propagate differently when policy rates in the oil importing country are at the zero lower bound. In particular, we show that the zero lower bound constraint tends to cushion rather than amplify the fall in GDP that occurs in response to higher oil prices in normal times when monetary policy is unconstrained by the zero lower bound. We show that the mitigation of the output decline from the zero lower bound depends on the source of the shock and on the persistence that alternative shocks induce in the price of oil.

To understand these result, consider the effects of a shock that raises the demand for oil by foreigners, pushing up the price of oil in the home, oil-importing country. When monetary policy is unconstrained, this shock tends to push up inflation and reduce output in the home country. When policy rates are at the zero lower bound, the higher inflation induced by the shock can lead to lower real rates, stimulating the interest-sensitive sectors of the economy, and offsetting the usual contractionary effects of the shock. If the increase in oil prices occurs gradually enough in response to this shock, it can induce a persistent rise in inflation that might even cause GDP to expand temporarily.

We find that the zero lower bound constraint on nominal interest rates plays a much smaller role in altering the effects of oil supply shocks emanating from abroad. Because estimates for these shocks lead to only a one-time increase in the price of oil, they do not have a protracted effect on inflation. Hence, the real interest rate is little changed at the zero bound and the shock has similar effects at the zero bound and in normal times.

Beyond the distinction between demand and supply shocks, the key assumption in our analysis is that some sources of fluctuations can lead to persistent anticipated increases in oil prices. The empirical findings in Kilian (2009) and Kilian and Murphy (2010) provide further support for this stance. Using identified vector auto-regressions, they also disentangle alternative sources of fluctuations for oil prices. One of the identified demand shocks is found to lead to a gradual increase in the price of oil – the peak effect shown by the point estimates in Kilian (2009) is reached after 20 months. By contrast, the response of the price of oil to oil supply shocks is found to be front-loaded.

We consider sensitivity of our results along several dimensions, including the specification of monetary policy and the economy's interest rate sensitivity. We show that the interest rate reaction function plays an important role in buffering the effects of oil shocks. In the benchmark simulation, we use an interest rate rule that responds to inflation and the output gap and gives a prominent role to interest rate smoothing through the inclusion of the lagged policy rate. Relative to this benchmark rule, we show that a rule with no interest-rate smoothing term further cushions the effects at the zero lower bound.

<sup>2</sup> See Bernanke et al., 1997, Hamilton and Herrera (2004), and Leduc and Sill (2004).

<sup>3</sup> In addition, Bodenstein and Guerrieri (2011) demonstrate that a version of the model estimated with full information maximum likelihood provides a reasonable characterization of both oil market and macroeconomic data, making it well-suited to quantifying the effects of oil price shocks and the role of the zero lower bound in influencing the transmission of these shocks.

The particular inflation measure included in the rule can also affect the extent to which the ZLB cushions the economy from oil shocks. Our benchmark rule responds to current core inflation; however, some central banks appear to have a focus on headline inflation.<sup>4</sup> We find that rules that respond to a forecast of headline inflation may induce a larger rise in inflation in reaction to shocks that boost oil prices. As a result, they lead to a larger drop in real rates at the zero lower bound and a greater cushioning of the effects of oil shocks on activity.

Our work is related to the literature that has analyzed the effects of demand shocks, such as government spending shocks, at the zero lower bound. This literature has emphasized that the effects of these shocks are amplified at the zero lower bound.<sup>5</sup> While the underlying mechanism that we stress in this paper is similar to Christiano et al. (2009) and Bodenstein et al. (2009), our emphasis in this paper is on oil shocks in which we find the opposite result: namely, the zero lower bound tends to mitigate the effects of these shocks on output. This difference reflects that a demand shock such as an increase in government spending induces both greater resource utilization and higher inflation. In normal times, monetary policy offsets the stimulative effects of the shock by raising interest rates. However, if the ZLB has been reached because the economy is mired in a deep recession, policy rates remain unvaried and the higher inflation induces a fall in real rates. These lower real rates in turn crowd in investment, amplifying the effects of the government spending shock. In contrast, the ZLB constraint on policy rates tends to cushion the effects of oil shocks on activity, since these shocks move output and inflation in opposite directions.

The rest of this paper proceeds as follows. Section 2 describes the model, Section 3 the calibration and solution method. Our results for oil demand shocks are presented in Section 4, which includes sensitivity analysis. Section 5 contrasts oil demand shocks with oil supply shocks as well as government spending shocks. Section 6 offers concluding remarks.

## 2. Model description

Following Backus and Crucini (1998), the model allows for trade in oil and nonoil goods. However, departing from Backus and Crucini (1998) along the lines suggested in Bodenstein et al. (2011), international financial markets are incomplete. Furthermore, our model incorporates nominal rigidities in price and wage setting and monetary policy is subject to a zero lower bound constraint.<sup>6</sup> There are two countries, a home country (calibrated based on U.S. data) and a foreign country (rest-of-the-world). Because the structure of the country blocs is symmetric, we focus on the home country, although our calibration allows for differences in population size, oil intensities, the per capita oil endowments, and nonoil trade flows. In each country a continuum of firms produces differentiated varieties of an intermediate good under monopolistic competition. These firms use capital, labor, and oil as factor inputs. Goods prices are determined by Calvo-Yun staggered contracts. Trade occurs at the level of intermediate goods and within each country the varieties are aggregated into a (nonoil) consumption, and an investment good. Households consume oil, the nonoil consumption good, save and invest, and supply differentiated labor services under monopolistic competition. For ease of presentation, we assume competitive bundlers whose technology mimics the preferences of the households over oil and the nonoil consumption good. While asset markets are complete at the country level, asset markets are incomplete internationally. Finally, both the home and foreign country are endowed with a non-storable supply of oil each period with the home country calibrated to be an oil importer.

<sup>4</sup> The Bank of England and the European Central Bank, for example, focus on headline inflation both in framing objectives, and as an operational guide to policy; while others appear relatively more concerned with the behavior of core inflation, at least in describing the basis for policy decisions. For example, the Bank of England has a target of 2% that is expressed in terms of headline inflation. It describes operational policy as adjusting interest rates so that its forecast of headline inflation reverts to target within a reasonable time frame without inducing undue instability in real activity (see <http://www.bankofengland.co.uk/monetarypolicy/framework.htm>).

<sup>5</sup> See, for example, Eggertsson (2006), Christiano et al. (2009).

<sup>6</sup> Our model could also be viewed as extending the models in Christiano et al. (2005) or in Smets and Wouters (2007) to a two-country setting that incorporates trade in oil and nonoil goods, as well as incomplete financial markets across countries.

2.1. Households

The utility functional of a representative household is

$$\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j \left[ \frac{1}{1-\sigma} \left( C_{t+j} - \phi_c \frac{C_{t+j-1}^A}{\zeta} - \nu_{ct} + \frac{\chi_0}{1-\chi} (1 - N_{t+j})^{1-\chi} \right)^{1-\sigma} + V \left( \frac{MB_{t+j+1}}{P_{t+j}} \right) \right], \tag{1}$$

where the discount factor  $\beta$  satisfies  $0 < \beta < 1$ . Our benchmark preference specification follows Greenwood et al. (1988) but we also consider additively separable preferences over consumption and leisure. As in Smets and Wouters (2003), we allow for the possibility of external habits. At date  $t$ , a household cares about her consumption relative to lagged aggregate consumption per capita,  $C_{t-1}^A$ . The preference shock  $\nu_{ct}$  follows an exogenous first order process with a persistence parameter of  $\rho_\nu$ . The parameter  $\zeta$  controls for population size. The household’s period utility function depends on current leisure  $1 - N_t$ . The parameter  $\chi_0$  pins down the amount of time devoted to leisure in steady state. The parameter  $\chi$  determines the elasticity of labor supply to changes in the real wage. Utility also depends on end-of-period real money balances,  $MB_{t+1}/P_t$ . The liquidity-service function  $V(\cdot)$  is increasing in real money balances at a decreasing rate up to a satiation level. Beyond the satiation level, utility from liquidity services is constant. With this specification of the utility function, the demand for real money balances is always positive regardless of the level of the nominal interest rate.<sup>7</sup>

Each household faces a budget constraint in period  $t$  which states that the combined expenditure on goods and the net accumulation of financial assets must equal disposable income

$$P_{Ct}C_t + P_{It}I_t + \frac{e_t P_{Bt}^* B_{Ft+1}}{\phi_{Bt}} - e_t B_{Ft} + MB_{t+1} - MB_t = W_t N_t + R_{Kt} K_t + \Gamma_t + T_t - P_{Dt} \phi_{It}. \tag{2}$$

Final consumption goods are purchased at the price  $P_{Ct}$ , and final investment goods at the price  $P_{It}$ . Investment in physical capital augments the per capita capital stock  $K_{t+1}(h)$  according to a linear transition law of the form

$$K_{t+1} = (1 - \delta)K_t + I_t, \tag{3}$$

where  $\delta$  is the depreciation rate of capital.

Individuals accumulate financial assets by purchasing a complete set of state-contingent domestic bonds, and a non state-contingent foreign bond. Given the representative agent structure at the country level, we omit terms involving the former from the budget constraint. The term  $B_{Ft+1}$  in the budget constraint represents the quantity of the non state-contingent bond purchased by a household at time  $t$  that pays one unit of foreign currency in the subsequent period,  $P_{Bt}^*$  is the foreign currency price of the bond, and  $e_t$  is the exchange rate expressed in units of home currency per unit of foreign currency. To ensure that net foreign assets are stationary, we follow Turnovsky (1985) and assume there is an intermediation cost  $\phi_{Bt}$  paid by households in the home country for purchases of foreign bonds.<sup>8</sup> Specifically, the intermediation costs depend on the ratio of economy-wide holdings of net foreign assets to nominal output ( $P_{Dt} Y_t$ , defined below)

$$\phi_{Bt} = \exp \left( -\phi_b \left( \frac{e_t B_{Ft+1}^A}{P_{Dt} Y_t} \right) \right). \tag{4}$$

If the home economy has an overall net lender position, a household will earn a lower return on any holdings of foreign bonds. By contrast, if the economy has a net debtor position, a household will pay a higher return on any foreign debt.

<sup>7</sup> More formally, we follow Jeanne and Svensson (2007) in assuming that  $V(MB_{t+1}/P_t) < V_0$ ,  $V'(MB_{t+1}/P_t) > 0$ ,  $V''(MB_{t+1}/P_t) < 0$  for  $MB_{t+1} < \bar{m}$ , the satiation level of real money. And  $V(MB_{t+1}/P_t) = V_0$  for  $MB_{t+1} \geq \bar{m}$ , and  $V'(MB_{t+1}/P_t) \rightarrow \infty$  for  $MB_{t+1}/P_t \rightarrow 0$ .

<sup>8</sup> For an extended discussion of this issue, see Bodenstein (2011).

Each household earns labor income  $W_t N_t$  and capital income  $R_{kt} K_t$ . The household also receives an aliquot share  $\Gamma_t$  of the sum of firm profits and the sale of oil services, and receives net transfers of  $T_t$ . Finally, as in [Christiano et al. \(2005\)](#), it is costly to change the level of gross investment from the previous period,

$$\phi_{it} = \frac{1}{2} \phi_i \frac{(I_t - I_{t-1})^2}{I_{t-1}}. \tag{5}$$

In every period  $t$ , a household maximizes the utility functional (1) with respect to consumption, labor supply, investment, end-of-period capital stock, and holdings of foreign bonds, subject to its budget constraint (2), and the transition equation for capital (3). In doing so, prices, rental rates for capital and labor, net transfers, and aggregate variables are taken as given.

### 2.2. Nominal wage rigidities

The modeling of nominal wage rigidities follows the approach in [Smets and Wouters \(2007\)](#). Each household supplies its homogenous labor to an intermediate employment agency which differentiates the household’s labor services. Employment agencies are indexed by  $h \in [0,1]$ , and each agency is a monopolistic competitor that works with one household, paying that household its desired wage  $W_t$ . An agency transforms the otherwise homogenous labor services into proprietary differentiated services and resells them at a wage  $W_t^d(h)$ . Employment agencies are monopolistic competitors. Their wages are set according to Calvo contracts. Specifically, employment agency  $h$  readjusts the wage it charges,  $W_t^d(h)$ , with probability  $1 - \xi_w^j$  in each period. If the wage is not reset, then it is updated according to  $W_{t+j}^d(h) = W_t^d(h) \omega_{t,j}^l$ , where

$$\omega_{t,j}^l = \prod_{i=1}^j \left\{ (\omega_{t-1+i})^{\iota_w} (\pi^*)^{1-\iota_w} \right\}. \tag{6}$$

The term  $\pi^*$  represents the inflation target and the parameter  $\iota_w$  is constrained to lie between 0 and 1. When the agencies are allowed to reset the wage, they take into account the demand schedule of bundlers, described below. The agencies also receive an employment subsidy  $\tau_w$  from the government, which acts to offset the monopolistic distortion. In particular, in the absence of nominal wage rigidities, each household’s marginal rate of substitution would equal the consumption real wage. Each household receives an aliquot share of the profit or losses of the employment agencies.

Perfectly competitive bundlers acquire labor services from the employment agencies and assemble these services to produce a labor bundle  $L_t$ :

$$L_t = \left[ \int_0^1 L_t(h)^{\frac{1}{1+\theta_w}} dh \right]^{1+\theta_w},$$

where  $\theta_w > 0$ . The profit maximization problem for the labor bundlers implies that the demand for each labor variety is given by

$$L_t(h) = \left[ \frac{W_t^d(h)}{W_t} \right]^{-\frac{1+\theta_w}{\theta_w}} L_t.$$

Combining the demand equation above with a zero profit condition, one obtains the price  $W_t^d$  that the bundlers charge to the intermediate goods producers for the labor bundle:

$$W_t^d = \left[ \int_0^1 W_t^d(h)^{-\frac{1}{\theta_w}} dh \right]^{-\theta_w}.$$

2.3. Firms and production

The production of goods involves several layers. Monopolistic competitors produce a continuum of intermediate good varieties. Perfectly competitive distributors in each country purchase the varieties and create an aggregate over the varieties for each origin of intermediates, i.e., an aggregate of domestic and foreign varieties, respectively. Using the home and foreign aggregates as inputs, competitive bundlers produce a nonoil consumption good, government consumption good and an investment good. In order to produce the final consumption good, a last set of firms combines the nonoil consumption good with oil.

2.3.1. Production of domestic intermediate goods

There is a continuum of differentiated intermediate goods (indexed by  $i \in [0,1]$ ) in the home country, each of which is produced by a single monopolistically competitive firm. Firms charge different prices at home and abroad, i.e., they practice pricing-to-market. In the home market, firm  $i$  faces a demand function that varies inversely with its output price  $P_{Dt}(i)$  and directly with aggregate demand at home  $Y_{Dt}$ .

$$Y_{Dt}(i) = \left[ \frac{P_{Dt}(i)}{P_{Dt}} \right]^{-\frac{(1+\theta_p)}{\theta_p}} Y_{Dt}, \tag{7}$$

where  $\theta_p > 0$ , and  $P_{Dt}$  is an aggregate price index defined below. Similarly, in the foreign market, firm  $i$  faces the demand function

$$X_t(i) = \left[ \frac{P_{Mt}^*(i)}{P_{Mt}^*} \right]^{-\frac{(1+\theta_p)}{\theta_p}} M_t^*, \tag{8}$$

where  $X_t(i)$  denotes the foreign quantity demanded of home good  $i$ ,  $P_{Mt}^*(i)$  denotes the price, denominated in foreign currency, that firm  $i$  sets in the foreign market,  $P_{Mt}^*$  is the foreign import price index, and  $M_t^*$  is aggregate foreign imports.

Each producer utilizes capital services  $K_t(i)$ , a labor index  $L_t(i)$ , and oil  $O_t(i)$  to produce its respective output good. The representative firm’s technology can be characterized as a nested constant-elasticity of substitution specification of the form

$$V_t(i) = K_t(i)^{\omega_k} (Z_t L_t(i))^{1-\omega_k}, \tag{9}$$

$$Y_t(i) = \left( (1 - \omega_{oy})^{\frac{\rho_o}{1+\rho_o}} V_t(i)^{\frac{1}{1+\rho_o}} + \omega_{oy}^{\frac{\rho_o}{1+\rho_o}} \left( \frac{O_{Yt}(i)}{\mu_{OYt}} \right)^{\frac{1}{1+\rho_o}} \right)^{1+\rho_o}. \tag{10}$$

Each producer utilizes capital and labor services,  $K_t(i)$  and  $L_t(i)$ , to make a “value-added” input  $V_t$ . This composite input is combined with oil services  $O_{Yt}(i)$  to produce the domestic nonoil good  $Y_t(i)$ . The term  $Z_t$  represents a stochastic process for the evolution of technology. The term  $\mu_{OYt}$  represents a stochastic process for the oil intensity in production, which might capture a switch in the composition of capital towards machines with different energy intensities.

The prices of intermediate goods are determined by Calvo-style staggered contracts, see Calvo (1983) and Yun (1996). Each period, a firm faces a constant probability,  $1 - \xi_p$ , to reoptimize its price at home  $P_{Dt}(i)$  and probability of  $1 - \xi_{px}$  to reoptimize the price that it sets in the foreign country of  $P_{Mt}^*(i)$ . These probabilities are independent across firms, time, and countries. When domestic or export prices are not reset, they are updated according to a scheme analogous to that for wages, described in Equation (6), but governed by the parameters  $\iota_p$  and  $\iota_{px}$ , respectively, instead of  $\iota_w$ . To offset the distortion due to monopolistic competition, firms receive production subsidies. Together with the wage subsidies, the production subsidies make the allocations under flexible prices and wages Pareto-optimal.

2.3.2. Production of domestic goods indices

A representative aggregator combines the differentiated intermediate products into a composite home-produced good  $Y_{Dt}$  according to

$$Y_{Dt} = \left[ \int_0^1 Y_{Dt}(i)^{\frac{1}{1+\theta_p}} di \right]^{1+\theta_p} \tag{11}$$

The optimal bundle of goods minimizes the cost of producing  $Y_{Dt}$  taking the price of each intermediate good as given. The bundle  $Y_{Dt}$  is used as input in producing the domestic nonoil consumption good and investment good. A unit of the sectoral output index sells at the price

$$P_{Dt} = \left[ \int_0^1 P_{Dt}(i)^{\frac{1}{\theta_p}} di \right]^{-\theta_p} \tag{12}$$

Similarly, a representative aggregator in the foreign economy combines the differentiated home products  $X_t(i)$  into a single index for foreign imports

$$M_t^* = \left[ \int_0^1 X_t(i)^{\frac{1}{1+\theta_p}} di \right]^{1+\theta_p}, \tag{13}$$

and sells  $M_t^*$  at price  $P_{Mt}^*$

$$P_{Mt}^* = \left[ \int_0^1 P_{Mt}^*(i)^{\frac{1}{\theta_p}} di \right]^{-\theta_p} \tag{14}$$

The bundle  $M_t^*$  is used as input into the production of the foreign nonoil consumption good and investment good.

2.3.3. Production of nonoil consumption, government, and investment goods

The nonoil consumption good  $C_{Nt}$ , the government consumption good  $G_t$ , and the investment good  $I_t$  are produced by perfectly competitive distributors using both aggregates over home and foreign varieties. The production function for the nonoil consumption good  $C_{Nt}$  is given by

$$C_{Nt} = \left( (1 - \omega_{mc}) \frac{\rho_c}{1+\rho_c} C_{Dt}^{\frac{1}{1+\rho_c}} + (\omega_{mc}) \frac{\rho_c}{1+\rho_c} (M_{Ct})^{\frac{1}{1+\rho_c}} \right)^{1+\rho_c}, \tag{15}$$

where  $C_{Dt}$  denotes the quantity of the aggregate over domestically-produced varieties purchased at a price of  $P_{Dt}$ , and used as an input by the representative nonoil consumption distributor. The term  $M_{Ct}$  denotes imports of the aggregate over foreign varieties purchased at a price of  $P_{Mt}$ . The Lagrangian multiplier from the cost minimization problem for the distributors determines the price of the nonoil consumption good,  $P_{CNt}$ .

The production of the government consumption good  $G_t$  is identical to the production of the nonoil consumption good. Thus, its price is  $P_{CNt}$ .

Finally, the production function for investment goods is isomorphic to that given in Equation (15), though allowing for possible differences in the import intensity of investment goods (determined by  $\omega_{mi}$ , akin to  $\omega_{mc}$  in Equation (15)), and the degree of substitutability between nonoil imports and domestically-produced goods in producing investment goods (determined by  $\rho_i$ ). The import preference shock  $\mu_{Mt}$  also affects investment imports. The inputs are denoted by  $I_{Dt}$  and  $M_{It}$ . Thus,

$$Y_{Dt} = C_{Dt} + G_{Dt} + I_{Dt}, \tag{16}$$

$$M_{Dt} = M_{Ct} + M_{Gt} + M_{It}. \quad (17)$$

The Lagrangian from the problem that investment distributors face determines the price of new investment goods,  $P_{It}$ , that appears in the household's budget constraint.<sup>9</sup>

#### 2.3.4. Production of final consumption good

The consumption basket  $C_t$  that enters the household's budget constraint is produced by perfectly competitive consumption distributors. The form of the production function mirrors the preferences of households over consumption of nonoil goods and oil. These distributors purchase a nonoil consumption good  $C_{Nt}$  and oil services  $O_{Ct}$  as inputs in perfectly competitive input markets, and produce a composite consumption good according to a CES production function

$$C_t = \left( (1 - \omega_{oc}) \frac{\rho_o}{1+\rho_o} C_{Nt}^{\frac{1}{1+\rho_o}} + \omega_{oc} \frac{\rho_o}{1+\rho_o} \left( \frac{O_{Ct}}{\mu_{OCt}} \right)^{\frac{1}{1+\rho_o}} \right)^{1+\rho_o}, \quad (18)$$

where the quasi-share parameter  $\omega_{oc}$  determines the importance of oil purchases in the household's composite consumption bundle, and the parameter  $\rho_o$  determines the long-run price elasticity of demand for oil. This shock could capture changes in oil demand coming from external factors, such as unusually cold winters, or a shift towards consuming goods that are more energy intensive.

Consumption distributors choose their inputs  $C_{Nt}$  and  $O_{Ct}$  to minimize the costs of producing the consumption bundle, taking as given input prices  $P_{CNt}$  and  $P_{Ot}$ , respectively. The Lagrangian multiplier from this cost-minimization problem determines the price of the consumption bundle charged to households, i.e.,  $P_{Ct}$  in the household's budget constraint given in Equation (2). The inclusion of oil inputs in the consumption bundle allows us to distinguish between headline or overall consumer prices,  $P_{Ct}$ , and a measure of core prices that excludes the influence of the oil input in consumption. Conveniently, this core measure is defined as  $P_{CNt}$ .

#### 2.4. The oil market

Each period the home and foreign countries are endowed with exogenous supplies of oil  $Y_{Ot}$  and  $Y_{Ot}^*$ , respectively. The two endowments are governed by distinct stochastic processes. The oil price  $P_{Ot}$  adjusts endogenously to clear the world oil market

$$Y_{Ot} + \frac{1}{\zeta} Y_{Ot}^* = O_{Yt} + O_{Ct} + \frac{1}{\zeta} (O_{Yt}^* + O_{Ct}^*). \quad (19)$$

To clear the oil market, the sum of home and foreign oil production must equal the sum of home and foreign oil consumption by firms and households. Because all variables are expressed in per capita terms, foreign variables are scaled by the relative population size of the home country  $1/\zeta$ , in Equation (19).

#### 2.5. Monetary and fiscal policy

Monetary policy follows an interest rate reaction function as suggested by Taylor (1993). However, when policy rates reach zero, we assume that no further actions are taken by the central bank. The notional rate that is dictated by the interest rate reaction function is denoted by  $i_t^{not}$ , whereas the effective rate is denoted by  $i_t$ . The two differ only if the notional rate turns negative

<sup>9</sup> As discussed in Erceg et al. (2006), our trade specification implies that the activity variable driving (nonoil) import and export demand can be regarded as a weighted average of consumption and investment, with the latter receiving a large weight consistent with the high weight of investment goods in U.S. trade. The paper also provides empirical support in favor of this specification over a specification in which the real activity variable driving trade is total absorption. See also Engel and Wang (2008).

$$i_t^{not} = \bar{i} + \gamma_i \left( i_{t-1}^{not} - \bar{i} \right) + (1 - \gamma_i) \left( \pi_t + \gamma_\pi (\pi_t - \bar{\pi}) + \frac{\gamma_y}{4} y_t^{gap} \right), \quad (20)$$

as the effective policy interest rate satisfies

$$i_t = \max \left( 0, i_t^{not} \right). \quad (21)$$

The terms  $\bar{i}$  and  $\bar{\pi}$  are the steady-state values for the nominal interest rate and core inflation, respectively. The inflation rate  $\pi_t$  is expressed as the logarithmic percentage change of the price level so that  $\pi_t = \log(P_{CNI}/P_{CNI-1})$ . The term  $y_t^{gap}$  denotes the output gap, given by the log difference between actual and potential output. Potential output is defined to be the level of output that would prevail in a model without nominal price and wage rigidities but otherwise identical to the one with rigidities.<sup>10</sup> Notice that the coefficient  $\gamma_y$  is divided by four as the rule is expressed in terms of quarterly inflation and interest rates. The lagged interest rate in the rule and the associated parameter  $\gamma_i$  allow for interest rate smoothing.

Government purchases are a constant fraction of output  $\bar{g}$  and they fall exclusively on the domestically-produced varieties. These purchases make no direct contribution to household utility. To finance its purchases, the government imposes a lump-sum tax on households that is adjusted so that the government's budget is balanced every period.

The government finances its purchases  $P_{CNI}G_t$ , and the subsidies to firms and employment agencies through lump-sum taxes. Given complete reliance on lump-sum taxes to finance outlays, the additional assumption that the government budget is balanced each period implies no loss of generality.

## 2.6. Resource constraints for nonoil goods, and net foreign assets

The resource constraint for the nonoil goods sector of the home economy can be written as

$$Y_t = C_{Dt} + I_{Dt} + G_{Dt} + \frac{1}{\zeta} M_t^* + \phi_{It}, \quad (22)$$

where  $M_t^*$  denotes foreign imports – again expressed in per capita terms, which accounts for the population scaling factor  $1/\zeta$ . The term  $\phi_{It}$  denotes the resources that are lost due to costs of adjusting investment.

The evolution of net foreign assets can be expressed as

$$e_t P_{Bt}^* B_{Ft+1} = e_t B_{Ft} + e_t P_{Mt} \frac{1}{\zeta} M_t^* - P_{Mt} M_t + P_{Ot} (Y_{Ot} - O_{Yt} - O_{Ct}). \quad (23)$$

This expression can be derived by combining the budget constraint for households, the government budget constraint, and the definition of firm profits.

## 3. Solution method and calibration

The model is log-linearized around its non-stochastic steady state. We abstract from the other non-linearities since these are not the focus of the current paper. Accordingly, as in Eggertsson and Woodford (2003), Adam and Billi (2006, 2007), Christiano et al. (2009), and Woodford (2011), the zero lower bound constraint on nominal interest rate is the only non-linearity preserved.

The number of state variables in the model precludes the use of global solution methods employed in Adam and Billi (2006, 2007). The piecewise linear method in Eggertsson and Woodford (2003) and Jung et al. (2005), or the shooting algorithm that builds on Fair and Taylor (1983) outlined in

<sup>10</sup> Technically, we construct potential output by augmenting the model with nominal rigidities with a shadow potential model. Both models start from the same initial conditions and are affected by the same disturbances. Capital stocks, like other endogenous variables are not assumed to be equalized across models.

Bodenstein et al. (2009) would be viable alternatives. Instead, while numerically equivalent, we find it computationally expedient to adapt the approach proposed by Svensson and Laséen (2009).

Svensson and Laséen (2009) noted that under the zero bound constraint, monetary policy can simply be interpreted as being too tight. Then the effects of any stochastic disturbance can be traced through the model by making sure that if the disturbance implies negative nominal policy rates, anticipated monetary policy shocks return policy rates to zero. For our linearized model subject to the zero lower bound constraint, this approach produces the same solution as a forward shooting algorithm, or as a piece-wise linear method. However, the computation time for our model is cut drastically. Appendix A describes in detail our implementation of the insights in Svensson and Laséen (2009).

The model is calibrated at a quarterly frequency. The parameter values for the home economy under our benchmark calibration are listed in Table 1. Parameters for the foreign economy are identical except for the parameters determining the intensity of oil use, the capital share of production, and the trade shares. The latter are determined by the assumption that trade is balanced in the steady state and that the relative population size,  $\zeta$ , is scaled so that the home economy accounts for one third of world GDP.

The parameter  $\sigma$  is set equal to 1. We set  $\chi = 10$ , implying a Frisch elasticity of labor supply of 0.2. The utility parameter  $\chi_0$  is set so that employment comprises one third of the household's time endowment. In line with Smets and Wouters (2007), the real rigidities affecting consumption,  $\phi_c$ , and investment,  $\phi_i$ , are 0.7 and 3, respectively.

The depreciation rate of capital  $\delta = 0.03$  is consistent with an annual depreciation rate of 12 percent. We set the government share of output to 18 percent, and adjust the capital share parameter  $\omega_k = 0.28$ , so that the investment share of output equals an empirically-realistic value of 20 percent.

Nominal rigidities in prices and wages have an average duration of four quarters, determined by the parameters  $\xi_p = 0.75$  and  $\xi_w = 0.75$ . Export price rigidities have a shorter duration of 2 quarters, as implied by the parameter  $\xi_{px} = 0.5$ . As noted above, monetary policy follows the Taylor rule, aside from

**Table 1**  
Benchmark calibration.

Parameter	Used to determine	Parameter	Used to determine
Parameters common across countries			
$\beta = 0.99$	Discount factor	$\sigma = 1.5$	Intertemporal consumption elasticity
$\chi = 10$	Labor supply elasticity (0.2)	$N_{ss} = 0.33$	Steady state labor share to fix $\chi_0$
$\kappa = 0.8$	Habit persistence	$\phi_i = 3$	Investment adj. cost
$\delta = 0.025$	Depreciation rate of capital	$\phi_c = 0.7$	Consumption habits
$\rho_o = -1.6$	Oil sub. elasticity (0.4)	$\rho_c = \rho_i = 13$	Cons./inv. import sub. elasticity (1.1)
$\xi_p = 0.75$	Prob. of not adjusting price	$\xi_w = 0.75$	Prob. of not adjusting wage
$\iota_p = 0.5$	Lagged price indexation	$\iota_w = 0.5$	Lagged wage indexation
$\xi_{px} = 0.5$	Prob. of not adjusting export price	$g = 0.18$	Steady state gov. cons. share of GDP
$\iota_{px} = 0.5$	Lagged export price indexation	$\omega_k = 0.28$	Parameter on K in value added
$\gamma_i = 0.8$	Mon. policy weight on lagged interest rate	$\gamma_\pi = 0.5$	Mon. policy weight on inflation
$\gamma_y = 0.5$	Mon. policy weight on output gap		
Parameters not common across countries			
$\omega_{oy} = 0.028$	Weight on oil in production (home)	$\omega_{oy}^* = 0.057$	Weight on oil in production (foreign)
$\omega_{oc} = 0.023$	Weight on oil in consumption (home)	$\omega_{oc}^* = 0.041$	Weight on oil in consumption (foreign)
$\omega_{mc} = 0.068$	Weight on imports in consumption (home)	$\omega_{mc}^* = 0.039$	Weight on imports in consumption (foreign)
$\omega_{mi} = 0.40$	Weight on imports in investment (home)	$\omega_{mi}^* = 0.25$	Weight on imports in investment (foreign)
Parameters specific to home country			
$\zeta = 1/2$	Relative size of home country	$\frac{Y_{Oss}^1}{O_{Yss}^1 + O_{Css}^1} = 0.3$	Steady state ratio oil prod. to cons. (home)
$\phi_b = 0.0001$	Curvature of bond intermed. cost		

allowing for interest rate smoothing and taking account of the zero lower bound constraint. Thus, the parameter  $\gamma_\pi$  on the inflation gap is 0.5 and the parameter  $\gamma_y$  on the output gap is also 0.5; we set the smoothing parameter  $\gamma_i$  to 0.8. The steady state real interest rate is set to 4% per year ( $\beta = 0.99$ ). Given steady state inflation  $\bar{\pi}$  equal to zero, the implied steady state nominal interest rate is 4 percent.

The calibration of the parameters  $\omega_{oy}$  and  $\omega_{oc}$  is informed by the overall oil share of output, and the end-use ratios of oil in consumption and production. Based on data from the Energy Information Administration of the U.S. Department of Energy for 2008, the overall oil share of the domestic economy is set to 4.2 percent. We use data over the period 1998–2008 from the U.S. Input Output Use Tables compiled by the Bureau of Economic Analysis to apportion oil use to intermediate production and final consumption. Based on this data, we set the steady state ratio of oil used by firms to oil used for final consumption to be 1.86. The oil imports of the home country are set to 70 percent of total demand in the steady state, implying that one third of oil demand is satisfied by domestic production. This estimate is based on 2008 data from the National Income and Product Accounts (NIPA). In the foreign block, the overall oil share is set to 8.2 percent. The oil endowment abroad is 9.5 percent of foreign GDP, based on oil supply data from the Energy Information Administration.

Turning to the parameters determining trade flows,  $\omega_{mc}$  is chosen to match the estimated average share of imports in total U.S. consumption of about 7 percent using NIPA data, while the parameter  $\omega_{mi}$  is chosen to match the average share of imports in total U.S. investment of about 40 percent. This calibration implies a ratio of nonoil goods imports relative to GDP for the home country of about 12 percent. Given that trade is balanced in steady state, and that the oil import share for the home country is 3 percent of GDP, the goods export share is 15 percent of GDP.

The parameters governing the elasticity of substitution for oil,  $\rho_o$ , the elasticity of substitution between domestic and foreign goods,  $\rho_c = \rho_i$ , are chosen in line with those obtained from the moment matching exercise in Bodenstein et al. (2011). More specifically, we set  $\rho_o$  to obtain an oil price elasticity of 0.4, and  $\rho_c = \rho_i$  to obtain a trade elasticity of 1.1.

The model in Bodenstein et al. (2011) differs from ours with respect to the presence of nominal rigidities. However, in their moment matching exercise Bodenstein et al. (2011) focus on medium term frequencies rather than business cycle frequencies implying little bearing of nominal rigidities for the estimates.

#### 4. Oil demand shocks

Our analysis focuses on the effects of oil shocks against the backdrop of an initial severe recession in the home country. The initial recession is generated by a preference shock,  $\nu_{ct}$ , that follows an autoregressive process with persistence parameter equal to 0.9. The shock reduces the home country's marginal utility of consumption. As a result of the shock, monetary policy attempts to stimulate the economy by lowering rates, but the policy rate reaches the zero lower bound, which is expected to bind for 10 quarters at the point in which the additional oil shock strikes. As the initial consumption shock occurs exclusively in the home country, the foreign economy has latitude to offset much of the contractionary spillover impact by reducing its policy rate. Further details about the recession that generates the initial conditions are given in Appendix B.

Figs. 1 and 2 consider the effect of an oil demand shock abroad against the severe domestic recession. Following Bodenstein et al. (2011), the oil demand shock has a persistent growth component and a level error correction component. The process governing the shock is:

$$\mu_{OYt} = \left(1 + \rho_{\mu_{OY}}^1 + \rho_{\mu_{OY}}^2\right) \mu_{OYt-1} - \rho_{\mu_{OY}}^2 \mu_{OYt-2}.$$

We set  $\rho_{\mu_{OY}}^1 = 0.5$  and  $\rho_{\mu_{OY}}^2 = 0.02$ . Furthermore, there is perfect correlation between  $\mu_{OYt}$  and  $\mu_{OCt}$ , respectively the demand shock for oil in production, and the demand shock for oil in consumption.<sup>11</sup> As shown in Fig. 1, the price of oil deflated by the price of the domestic nonoil good rises for one year, then

<sup>11</sup> In our model the unconditional behavior of oil prices reflects a variety of shocks and their propagation mechanisms. Accordingly, the finding that a simple unit root process provides a good fit for the behavior of oil prices in the postwar period does not imply that all structural shocks affecting the oil market should themselves be governed by unit root processes.

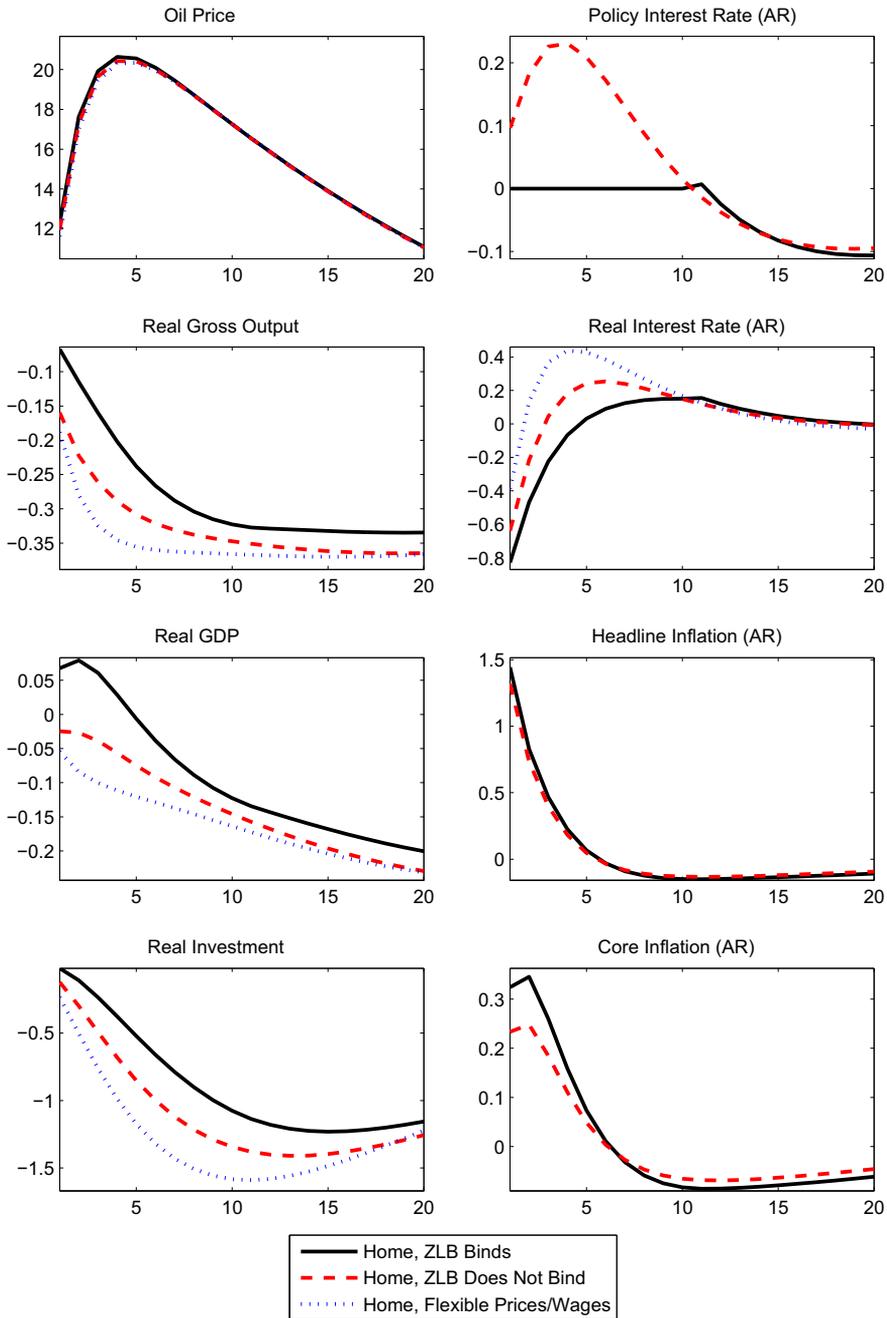


Fig. 1. An oil demand shock at the zero lower bound.

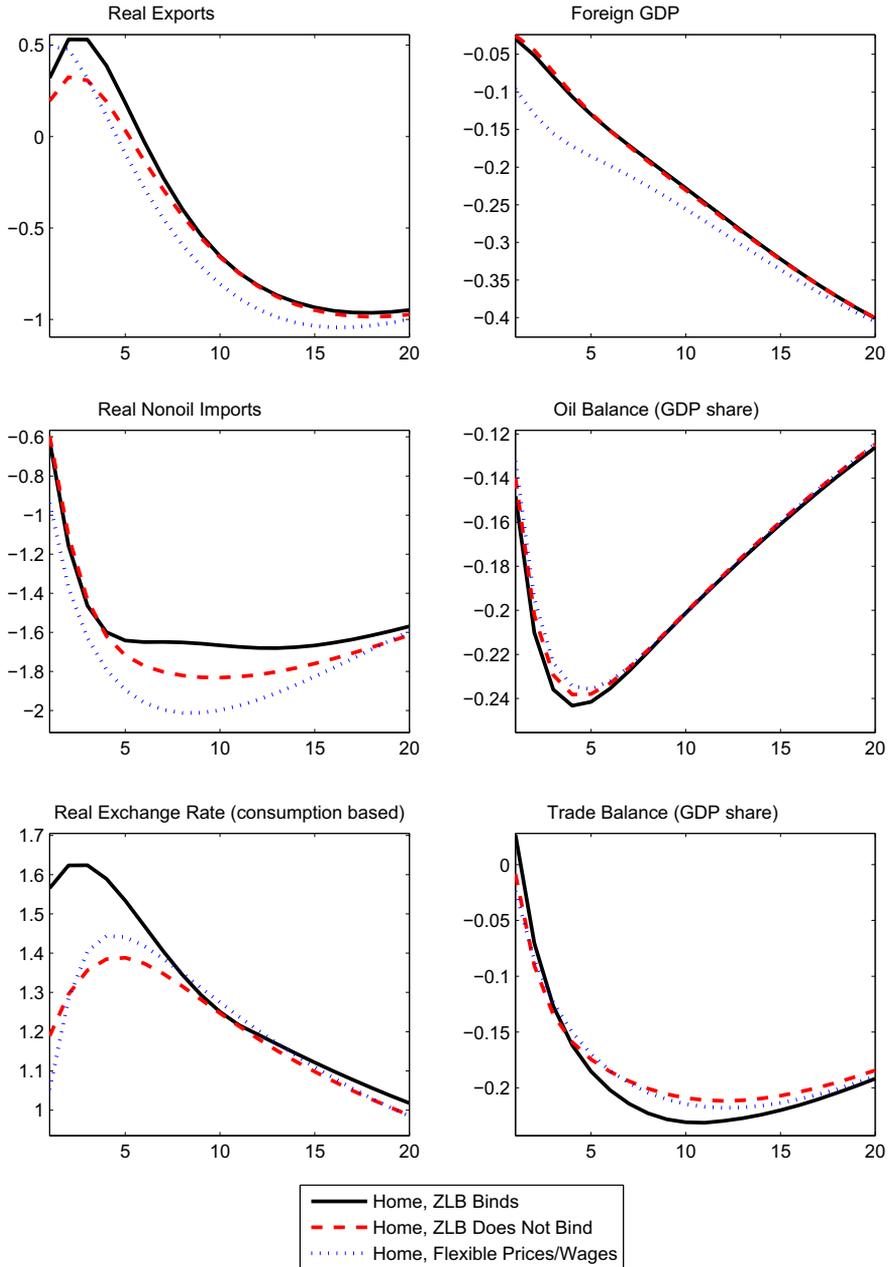


Fig. 2. An oil demand shock at the zero lower bound: trade flows.

slowly declines. All the responses shown are presented in deviation from the path implied by the initial severe recession. Each panel in the figure shows three lines: the response to the shock against the background of the severe recession, the solid lines; the response to the shocks in normal times when the zero lower bound does not bind, the dashed lines; and the response to the shock in an economy

with flexible prices and wages, the dotted lines. The shock is unchanged for the three cases shown and the relative price of oil shows negligible differences across the cases.

Characterizing the optimal response exactly is no small task in the presence of the zero lower bound. The task is made more challenging by the open economy dimension and oil trade.<sup>12</sup> The form of the interest rate reaction function, our modified Taylor rule, implies that there are quantitatively small differences between the effects of the shock with and without nominal rigidities, as long as the zero lower bound is not enforced, or equivalently in a linear setting, as long as the zero lower bound does not bind. We interpret the proximity of such responses, the dashed and the dotted lines in Fig. 1, as heuristic evidence that the monetary policy rule for an oil demand shock away from the zero lower bound.

Furthermore, at the zero lower bound, the rule chosen has features that align it with the optimal policy for special cases of our model. Jung et al., 2005, Eggertsson and Woodford (2003), Adam and Billi (2006, 2007) derive the optimal policy under the zero bound constraint in a closed economy in models that do not consider oil trade. As argued in Eggertsson and Woodford (2004), a credible commitment to lower rates regarding future policy can largely mitigate the distortions created by the zero bound. In our model, this feature of the optimal policy is partly captured by the smoothing term in the rule.

In all of the cases shown, the persistent rise in the price of oil induces a fall in home oil demand. Both households and firms substitute away from the more costly oil input. The decline in oil use has effects on gross nonoil output, the expenditure components, and the real interest rate that resemble those of a highly persistent decline in productivity. Lower oil use leads to a fall in the current and future marginal product of capital, causing investment and gross output to fall. In the long term the capital stock also falls. Consumption contracts due to a reduction in household income.

The measure of gross output shown in the figure corresponds to  $Y_{Dt}$ , defined in Equation (11). As the production technology involves the use of oil inputs that are partly imported, the definition of GDP involves netting out the imported oil inputs used in production from gross output. When oil prices rise, oil imports are reduced disproportionately relative the fall in oil demand. The reduction in oil imports accounts for the cushioning of the GDP response relative to the fall in gross output.

Strikingly, the imposition of the zero lower bound can generate persistent qualitative differences in the response of real GDP and gross output relative to the unconstrained case. At the zero lower bound, GDP rises for 5 quarters. Similarly the response of gross output is cushioned. Eventually, GDP does fall, but the contraction is mitigated. In the simulation that enforces the zero bound, GDP remains above its unconstrained level for years past the end of the liquidity trap.

As policy rates are constrained, and as the oil shock generates a persistent increase in inflation, the short-term real interest rate falls more, cushioning the fall of investment. The cushioning of the investment props up the capital stock in such a way as to introduce a persistent wedge between real (nonoil) gross output at the zero bound relative to its counterpart in normal times. Due to the presence of consumption habits and investment adjustment costs, as well as to the phasing in of the oil shock, gross output only falls gradually. In this setting, the difference between gross output and GDP is a wedge implied by the presence of imported oil inputs in production. The initial fall in gross output happens to be small enough that the contraction in oil imports brought about by higher oil prices translates into a boost to GDP.

The implications of the oil demand shock for the external sector are shown in Fig. 2. Since the home country's nonoil balance must improve enough to offset the long-run deterioration in the oil balance, the exchange rate depreciates. The depreciation leads to an expansion of nonoil exports and to a contraction of nonoil imports.

#### 4.1. Alternative policy rules and interest rate sensitivity

We consider sensitivity analysis for the specification of monetary policy with respect to two important dimensions: the interest rate smoothing and the measure of inflation included in the rule.

<sup>12</sup> For a comprehensive review of the issues involved in characterizing optimal monetary policy in an open economy setting see Corsetti et al. (2010). Bodenstein et al., 2010 consider the optimization of simple rules away from the zero lower bound.

The panels in the left column of Fig. 3 report responses to the same foreign demand shock as considered in the benchmark experiment described above. However, the monetary policy rule used in this case excludes the lagged interest rate term by setting  $\gamma_i$  to zero, (see Equation (20)). For ease of comparison, the panels in the right column of Fig. 3 reproduce the benchmark results.<sup>13</sup>

Away from the lower bound, the rule that excludes the smoothing term pushes up the policy interest rate on impact. However, after the initial rise, policy rates are reduced quickly. With forward-looking behavior as in our model, the entire expected path for policy rates is relevant in the determination of consumption and investment. Accordingly, a measure of longer-term interest rates, such as the expected real rate on a 5-year bond reported in Fig. 3, captures more effectively the current and future stance of monetary policy. Based on that longer-term measure, one can see that omitting the smoothing term from the rule clearly lowers the persistence of the increase in real rates and explains why the rule without the smoothing term is a little more inflationary.

At the zero lower bound, the higher inflation response associated with the rule without smoothing translates into a further cushioning the effects of the oil demand shock. On impact, the rise in GDP is more than doubled relative to the benchmark case. Moreover, the wedge between the response of GDP at the zero bound and its counterpart away from the zero bound is also enhanced quantitatively.

The particular inflation measure included in the rule is also important. Our benchmark rule responds to current core inflation (the inflation for the price of the consumption basket with the oil component stripped out). A number of central banks characterize their policies as focusing on a forecast of future headline inflation. As discussed by Bodenstein et al. (2008), such rules can be less effective in controlling inflation. When faced with temporary increases in the price of oil, rules that incorporate a forecast of headline inflation can look past the peak inflation response and lower rates in anticipation of the expected decline in oil prices.

The responses shown in the left panels of Fig. 4 build on the previous sensitivity exercise by not only doing away with the smoothing term in the monetary policy rule, but also substituting the current core inflation measure with the forecast of next period headline inflation rate. For ease of comparison the panels in the right column of the figure report the effects of the same foreign oil demand shock for the case in which the only modification to the rule involves the exclusion of the smoothing term and the rule responds to current core inflation.

As shown in the bottom panels of Fig. 4, the rule that responds to the one-step-ahead forecast of headline inflation implies a larger inflation response. At the zero bound, more inflation translates into a bigger fall in the real interest rate. Investment and consumption still fall, but are propped up relative to their response under the rules considered previously. Moreover, the fall in net real rates enhances the exchange rate depreciation. The consequent boost to net exports leads to a temporary expansion in gross output. Under this alternative rule, at the zero bound real GDP rises close to 0.3 percent on impact, while it drops almost 0.1 percent in normal times.

#### 4.2. Alternative preferences

In this section we present sensitivity of our benchmark results with respect to the specification of preferences. We consider two distinct alternatives and compare each case against the benchmark case. Under one alternative, consumption habits are excluded. Under the other alternative, preferences are additively separable in consumption and leisure.

By incorporating consumption habits, the benchmark calibration constrains the sensitivity of the economy to interest rate movements, the key transmission channel for the zero lower bound. The left panels of Fig. 5 report the response to the foreign oil demand shock for a calibration of the model that excludes consumption habits. For ease of comparison, the panels in the right column replicate the responses for the baseline calibration with consumption habits.

As in normal times the benchmark policy rule implies a rise in the longer-term real interest rates such as the 5-year rate shown in the figure, the decline in private absorption is amplified by the

<sup>13</sup> As changes in calibration affect the expected duration of the liquidity trap, we varied the size of the consumption shock that generates the initial severe recession in order to equalize the expected duration of the liquidity trap across calibrations.

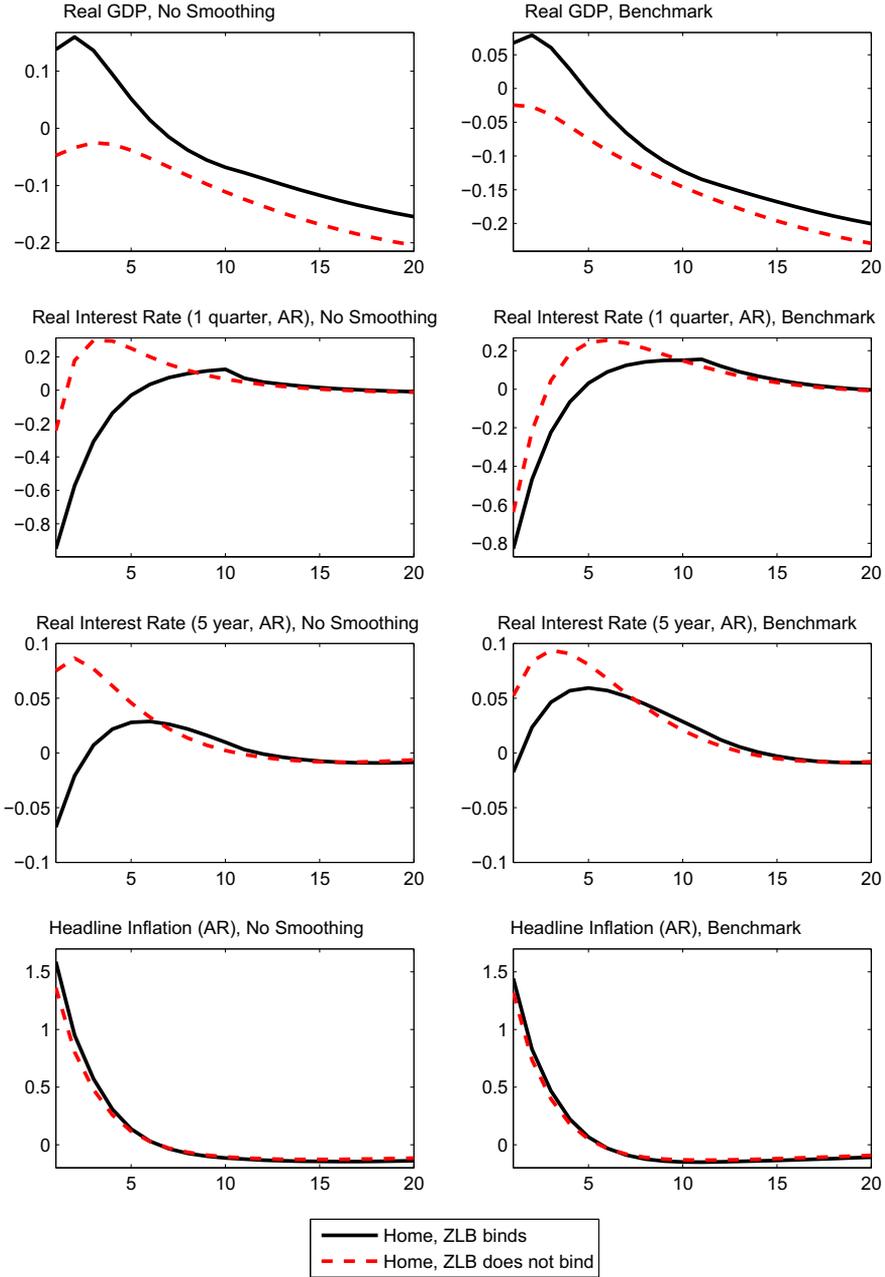


Fig. 3. An oil demand shock at the zero lower bound: monetary policy rule with No Smoothing.

exclusion of habits. However, a higher degree of interest rate sensitivity implies that at the zero lower bound, lower real rates can generate a larger wedge relative to the unconstrained responses.

Fig. 6 compares the effects of an oil demand shock under two preference specifications. The right panels in the figure reproduce the results from the benchmark model with preferences that follow

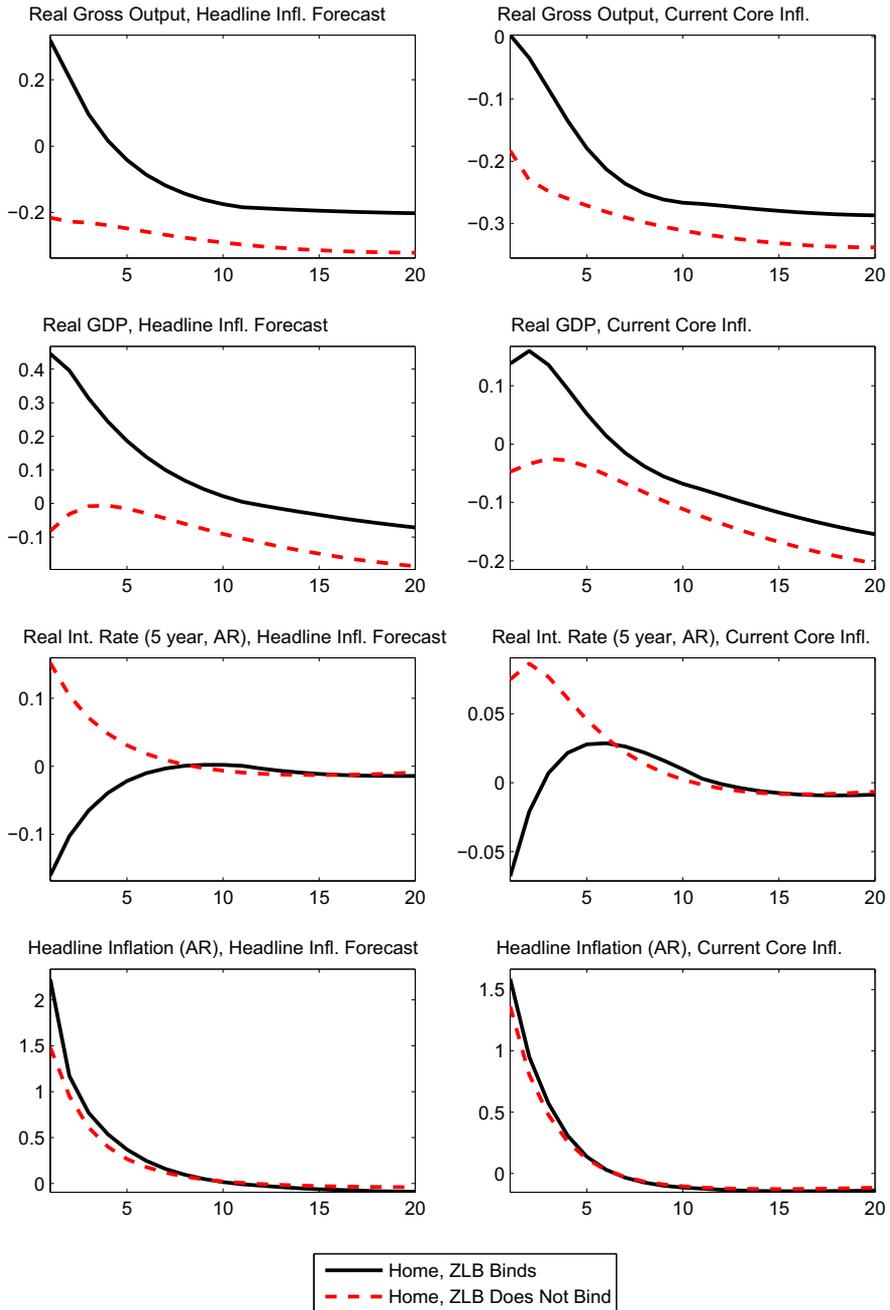


Fig. 4. An oil demand shock at the zero lower bound: monetary policy rule responds to a forecast of headline inflation.

those in Greenwood et al. (1988). The left panels in Fig. 6 show responses from a model with the commonly used specification of additively separable preferences over consumption and leisure. Under this alternative, the utility functional is

$$\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j \left[ \frac{1}{1-\sigma} \left( C_{t+j} - \phi_c \frac{C_{t+j-1}^A}{\zeta} \right)^{1-\sigma} + \frac{\chi_0}{1-\chi} (1 - N_{t+j})^{1-\chi} + V \left( \frac{MB_{t+j+1}}{P_{t+j}} \right) \right].$$

Under the alternative, we left the function  $V$  unchanged relative to the benchmark specification. Also unchanged are the values chosen for the parameters  $\sigma, \phi_c, \zeta$ , and  $\chi$ . We calibrated the value for the parameter  $\chi_0$  so that employment comprises one-third of the household’s time endowment as for the benchmark preferences.

The additively separable preferences let the marginal utility of consumption influence labor supply, while this influence is suppressed by the benchmark specification. As shocks that push up the price of

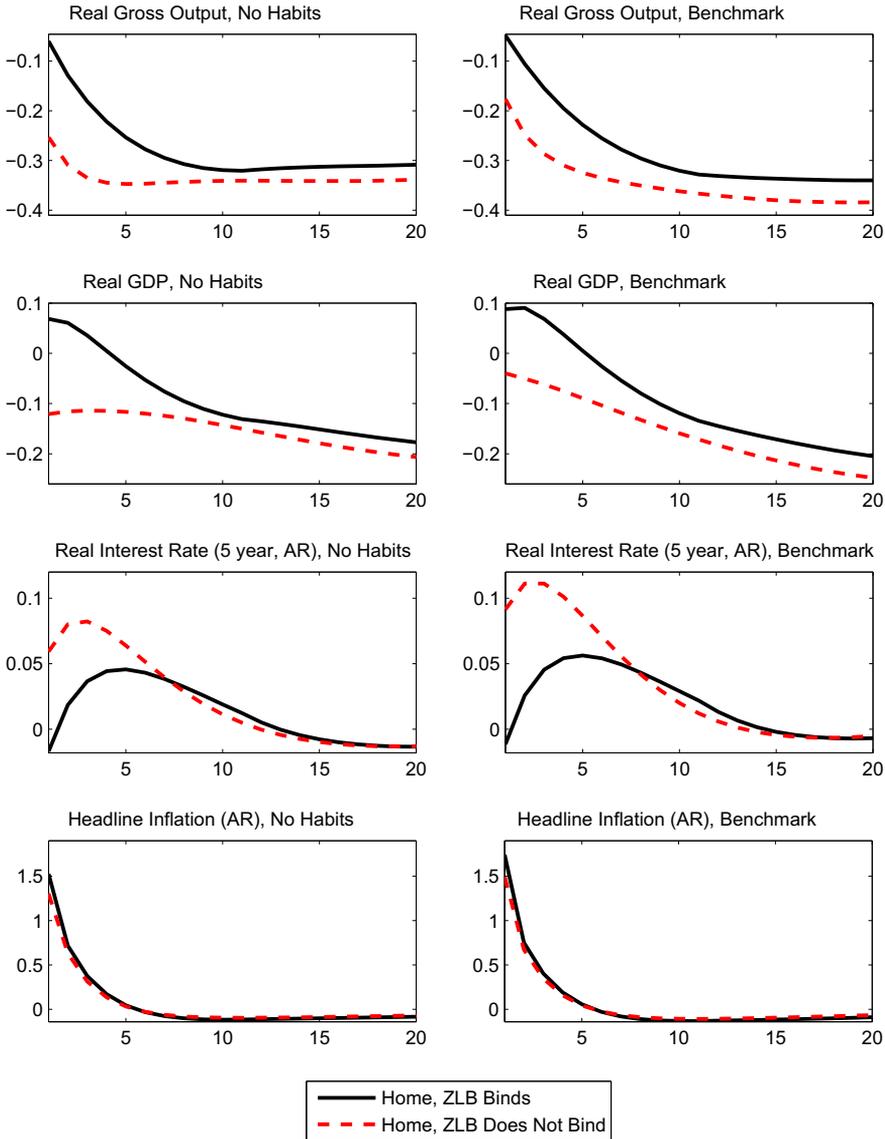


Fig. 5. An oil demand shock at the zero lower bound: no Habit persistence.

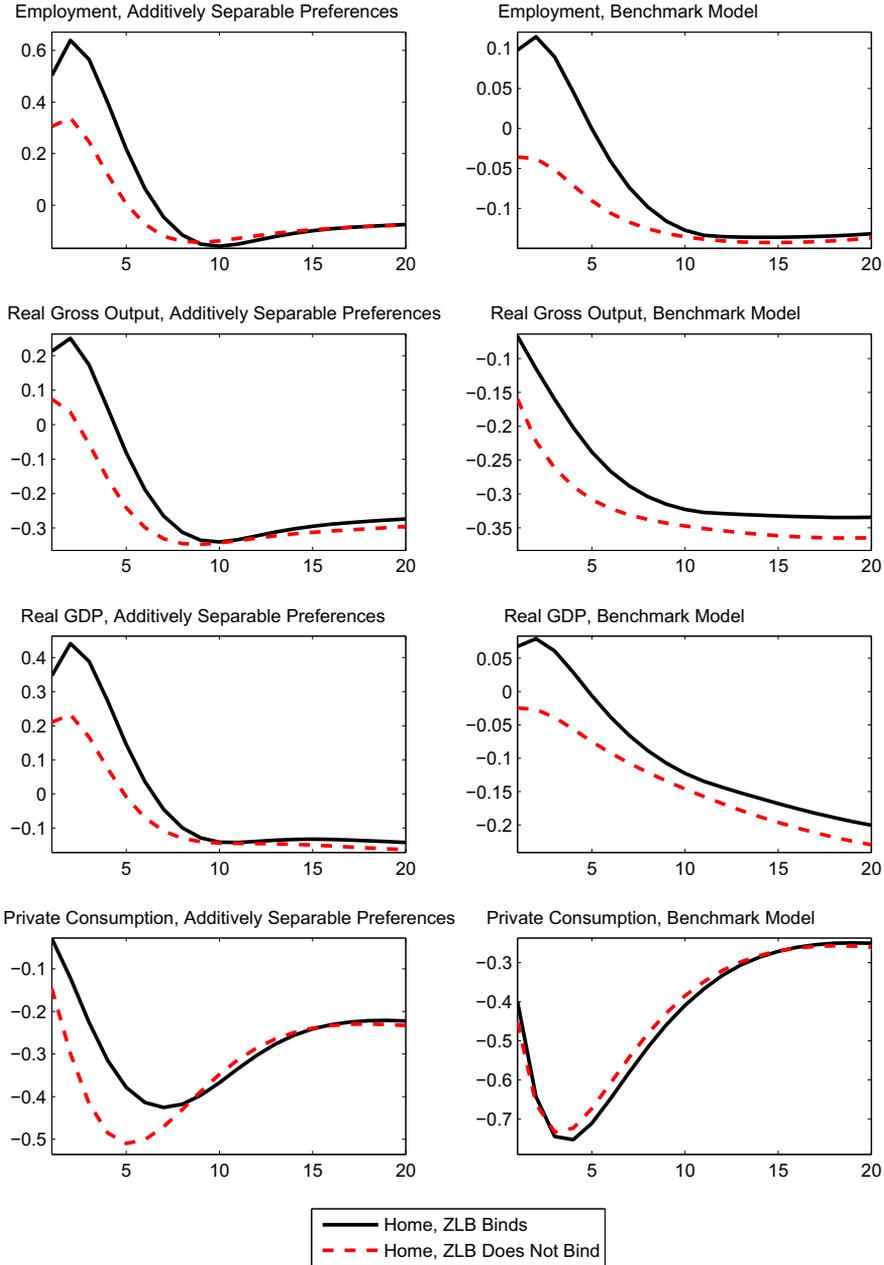


Fig. 6. An oil demand shock at the zero lower bound: alternative preferences.

oil compress consumption for the home oil-importing country, the marginal utility of consumption increases and stimulates labor supply. Fig. 6 shows an expansion in labor supply both in normal times and at the zero lower bound for the alternative preferences. Under additively separable preferences, an increase in the price of oil can lead to such an increase in labor supply that gross output and GDP expand even when the economy is not in a liquidity trap. By contrast, in the benchmark model it is the

liquidity trap that initially reverses the sign for the response of GDP. However, under both types of preference, the zero lower bound cushions the eventual contraction of economic activity.<sup>14</sup>

## 5. Alternative shocks

We consider two alternative sources of fluctuations. We focus on oil supply contraction as an example of shocks that lead to a front-loaded increase in oil prices. As such, the headline inflation spurt is not long-lived enough to cushion the contractionary effects of the oil price increase at the zero lower bound. To provide an even starker contrast the oil demand shock considered above, we show the effects of an increase in government spending. As previously emphasized in the literature, in that case, inflation and output move in the same direction. Then, the stimulative effect on GDP of increases in government spending is enhanced at the zero lower bound on policy rates.

### 5.1. A contraction in oil supply

Following Bodenstein et al. (2011), we assume that oil supply in each country follows a process close to a unit-root.<sup>15</sup> Fig. 7 shows the domestic response to a foreign oil supply shock both when the economy is mired in a liquidity trap and in normal times. For ease of comparison, we also show the responses to an oil demand shock. The contraction in foreign oil supply is sized to match the peak of the oil demand shock discussed earlier. However, in contrast to the oil demand shock, the supply shock does not lead to a protracted rise in inflation. Apart from the initial period, headline inflation is close to zero. Thus, the real interest rate is little changed at the zero bound and the shock has similar effects at the zero bound and in normal times.

Abstracting from monetary policy consideration at the zero lower bound, our model with nominal rigidities displays responses similar to the flexible price economy in Bodenstein et al. (2011). The nearly permanent foreign supply contraction leads to a persistent fall in domestic activity, and a persistent deterioration of the home country's oil balance that is mostly offset by an improvement in the nonoil trade balance. The latter is brought about by a persistent depreciation of the home country's real exchange rate.

If the oil supply shock lead to a period of increasing oil prices similar to the oil demand shock and thus to protracted inflation, the oil supply shock would be compressed in the same manner. However, as argued in Bodenstein et al. (2011) oil supply and demand shocks differ along exactly this dimension: oil supply shocks are near unit-root processes, but oil demand shocks are best described as AR(2) processes.<sup>16</sup>

### 5.2. An increase in government spending

An expanding literature has analyzed the effects of government spending shocks at the zero lower bound. This literature has emphasized that the effects of these shocks are *amplified* when policy rates do not respond. In line with Christiano et al. (2009), Fig. 8 considers an exogenous increase in government spending entirely financed by lump-sum taxes. The process for government spending  $G_t$  is assumed to be:

$$G_t = (1 - \rho_g) \bar{G} + \rho_g G_{t-1} + \varepsilon_{G,t},$$

where  $\rho_g = 0.95$ ,  $\bar{G}$  is the steady state level of government spending and  $\varepsilon_{G,t}$  is an exogenous innovation, chosen to deliver an initial increase in government spending equal to 1% of steady state GDP. As found

<sup>14</sup> The large influence of wealth effect on labor supply with additively separable preferences is well understood. For instance, see Jaimovich and Rebelo (2009).

<sup>15</sup> To be specific, the AR(1) coefficient for home and foreign oil supply is set at 0.99.

<sup>16</sup> Our finding, that the transmission of highly persistent oil shocks hardly differs when they occur against the backdrop of a large recession compared to normal times does not depend on our assumption of incomplete financial markets. If international financial markets were complete, the domestic country could smooth the effects of the oil shock by running a persistent trade deficit. However, a near unit-root shock to oil supply would still imply a very short-lived increase in inflation.

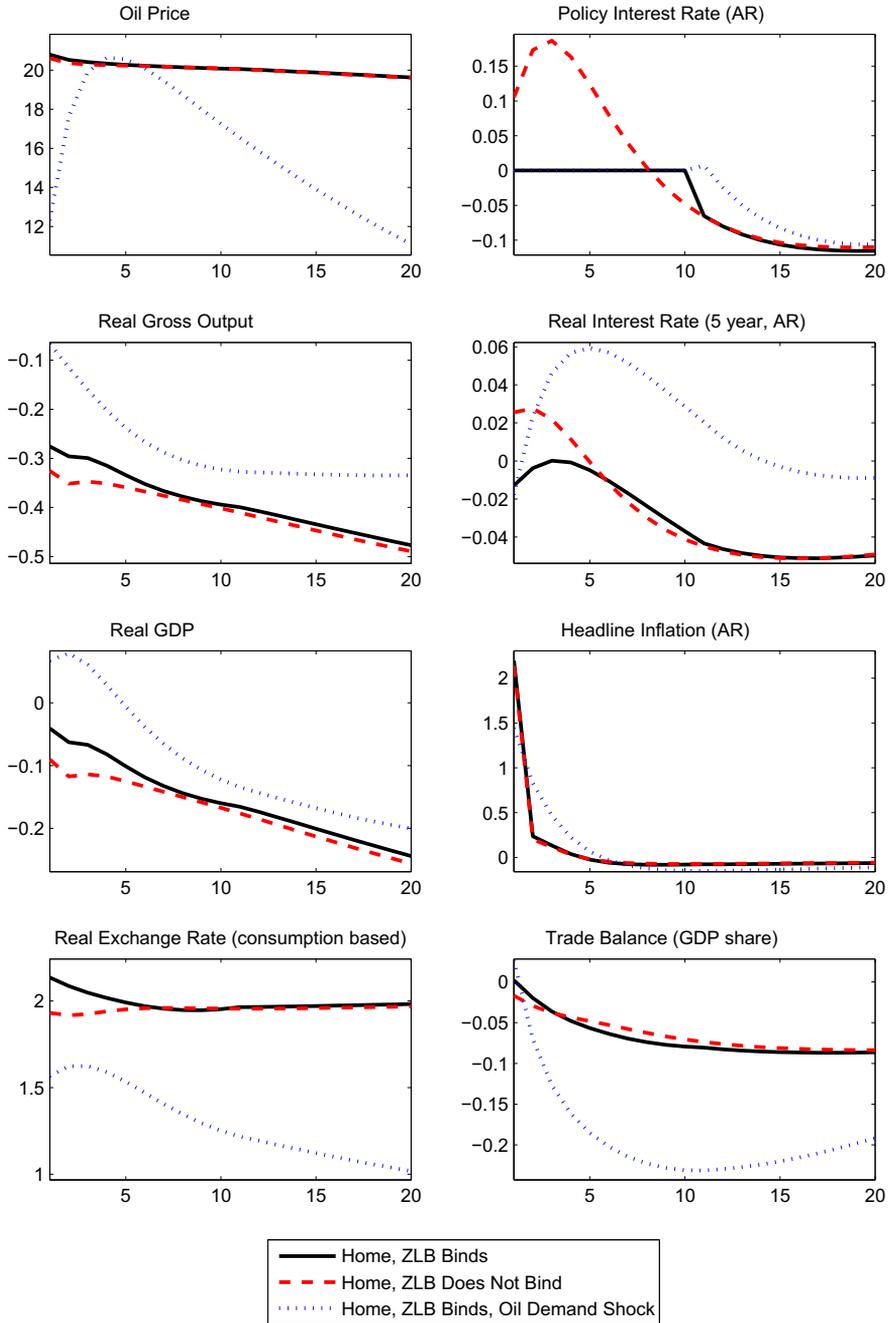


Fig. 7. An oil supply shock at the zero lower bound.

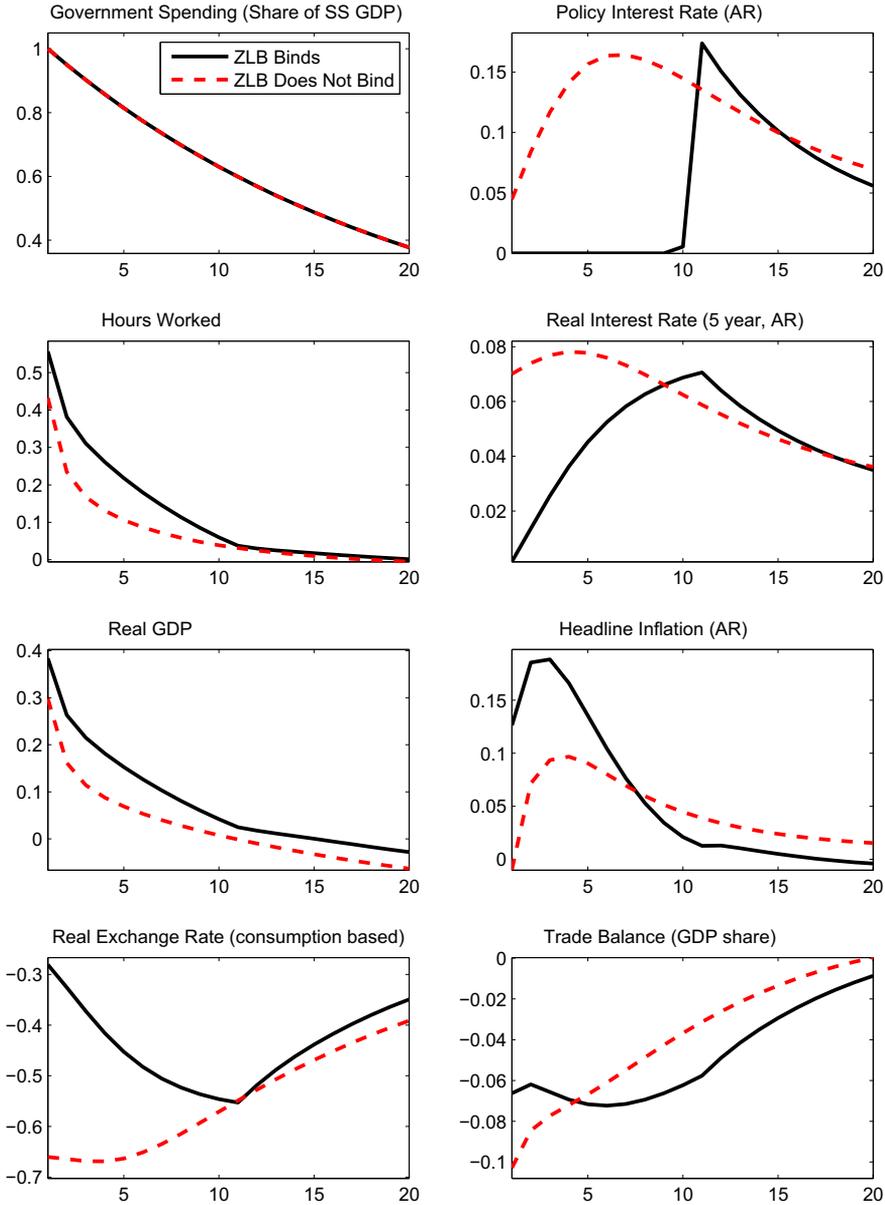


Fig. 8. A government spending shock at the zero lower bound.

in the related literature, it is also the case in our model that the zero lower bound increases the government spending GDP multiplier. In normal times, monetary policy offsets the stimulative effects of the shock by raising interest rates. However, if the ZLB has been reached because the economy is mired in a deep recession, policy rates remain unvaried and the higher inflation induces a fall in real rates. These lower real rates in turn *crowd in* investment, amplifying the effects of the government spending shock. On impact, GDP rises by 0.4%, 25% more than the 0.3% increase away from the ZLB. After one quarter, it is 60% larger, rising 0.26% instead of 0.16%.

## 6. Conclusion

When monetary policy has latitude to adjust policy rates, nominal rigidities do not imply large departures in the transmission of oil shocks from a model with flexible prices and wages. However, even for rules that are close-to-optimal, at the zero lower bound the transmission of oil shocks can be substantially different.

The discussion of the consequences of a liquidity trap has recently focused on the amplification of demand shocks. Such shocks typically move inflation and output in the same direction. By contrast, oil shocks move inflation and output in opposite directions so that their effects on activity are cushioned in a liquidity trap. The cushioning is larger for shocks that imply a persistent bout of inflation especially under policy rules that do not imply an aggressive response to inflation away from the zero lower bound. Examples of such rules include rules with no interest rate smoothing and rules that respond to a forecast of future headline inflation.

### Appendix A. Numerical implementation

Svensson and Laséen (2009) suggested a method for obtaining simulations with arbitrary restrictions on the path of the nominal interest rate in a linear model with perfect foresight. A desired path for the nominal interest rate can be implemented through a sequence of anticipated monetary policy shocks in the interest rate reaction function of the policy maker.

Consider the policy rule for the notional policy rate and the definition of the effective interest rate in Equations (20) And (21), which we repeat below for convenience:

$$i_t^{not} = \bar{i} + \gamma_i(i_{t-1}^{not} - \bar{i}) + (1 - \gamma_i) \left( \pi_t + \gamma_\pi(\pi_t - \bar{\pi}) + \frac{\gamma_y}{4} y_t^{gap} \right)$$

$$i_t = \max(0, i_t^{not})$$

Repurposing the method outlined in Svensson and Laséen (2009) to implement the zero lower bound constraint implies replacing the max operator in the definition of the effective rate with:

$$i_t = i_t^{not} + m_t, \tag{24}$$

where  $m_t$  is the current monetary policy shock. The current shock is itself linked to past shocks in the following fashion:

$$m_t = m_{t-1}^1 + \varepsilon_{mt}$$

$$m_t^1 = m_{t-1}^2 + \varepsilon_{m^1 t}$$

$$\vdots$$

$$m_t^n = m_{t-1}^{n+1} + \varepsilon_{m^n t}$$

$$m_t^{n+1} = \varepsilon_{m^{n+1} t}.$$

Notice that this shock structure has the convenient property that  $E_t m_{t+i} = m_t^i$ .

Following Anderson and Moore (1985), the linear approximation to the decision rule for our model in the neighborhood of its non-stochastic steady state can be represented as:

$$X_t = AX_{t-1},$$

where  $X_t$  is a vector of all the variables in the model expressed in deviation from the steady state. Equation (A) implies that

$$E_t X_{t+k} = A^{k+1} X_{t-1}$$

for all  $k \in \mathbb{N}$ . Let  $A_{[i]}^{k+1}$  denote the row of the matrix  $A^{k+1}$  that corresponds to the effective policy interest rate  $i$ . We can then trace the expected path for the notional interest rate using the following equation:

$$\begin{pmatrix} i_t \\ E_t i_{t+1} \\ \vdots \\ E_t i_{t+n} \end{pmatrix} = \begin{bmatrix} A_{[i]} \\ A_{[i]}^2 \\ \vdots \\ A_{[i]}^{n+1} \end{bmatrix} X_{t-1}. \tag{25}$$

The last equation suggests that we can use the predetermined values for the monetary policy shocks described above,  $m_{t-1}^1, \dots, m_{t-1}^{n+1}$ , to achieve any desired expected path for the effective interest rate. Denoting  $A_{[i]}^{k+1[m]}$  the columns of row vector  $A_{[i]}^{k+1}$  that correspond to the shocks  $m_{t-1}^1, \dots, m_{t-1}^{n+1}$  we can obtain:

$$\begin{pmatrix} i_t \\ E_t i_{t+1} \\ \vdots \\ E_t i_{t+n} \end{pmatrix} = B \begin{pmatrix} m_{t-1}^1 \\ m_{t-1}^2 \\ \vdots \\ m_{t-1}^{n+1} \end{pmatrix}, \tag{26}$$

and where  $B$  is a square matrix given by

$$B = \begin{bmatrix} A_{[i]}^{1[m]} \\ A_{[i]}^{2[m]} \\ \vdots \\ A_{[i]}^{n+1[m]} \end{bmatrix} \tag{27}$$

Accordingly, we can invert the system of equation above to find the predetermined values for  $m_{t-1}^1, \dots, m_{t-1}^{n+1}$  that will achieve a desired expected path for the effective interest rate (equivalently, we could back out the relevant innovations  $\varepsilon_{mt}, \dots, \varepsilon_{mt}^n$ ).

Implementing the zero lower bound involves constraining the effective rate to remain at zero in those periods when the notional interest rate falls below zero and otherwise equating the effective and notional rates. We can endogenize the duration of the liquidity trap contingent on the realization of particular shocks with the following algorithm:

- 1 Guess duration of the liquidity trap based on periods in which the “unconstrained” decision rule in equation (A) implies a negative value for the potential interest rate  $i^{not}$  in response to the shocks.
- 2 Based on Equation (26), choose a sequence of foreseen monetary policy shocks to enforce the zero lower bound constraint. Only those periods for which the constraint is enforced need to be considered in (26).
- 3 Revise the duration of liquidity trap given the sequence of monetary policy shocks (if in any period  $i^{not} > i$  do not enforce the zero lower bound for that period).
- 4 Repeat steps 2 and 3 above until no revision to the periods in which to enforce the zero lower bound constraint is necessary.

Relative to the algorithm described by Jung et al. (2005), this algorithm has several advantages: 1) it deals naturally with cases in which the zero lower bound constraint binds only after a number of periods from the shock’s impact; 2) the extension to multicountry models simply requires stacking the paths for the effective policy rates across countries in Equation (26); 3) for models with a large number of state variables, the inversion Equation (26) is faster than the inversion of the entire decision rule required by the method in Jung et al. (2005).

**Appendix B. Baseline simulation**

Fig. 9 shows the response to the consumption shock that generates the initial conditions for the benchmark simulation of an oil demand shock, shown in Figs. 1 and 2, and for the oil supply and technology shocks shown in Figs. 7 and 8. As parameter changes can affect the expected duration of the zero lower bound, to make the simulations comparable, we changed the size of the underlying

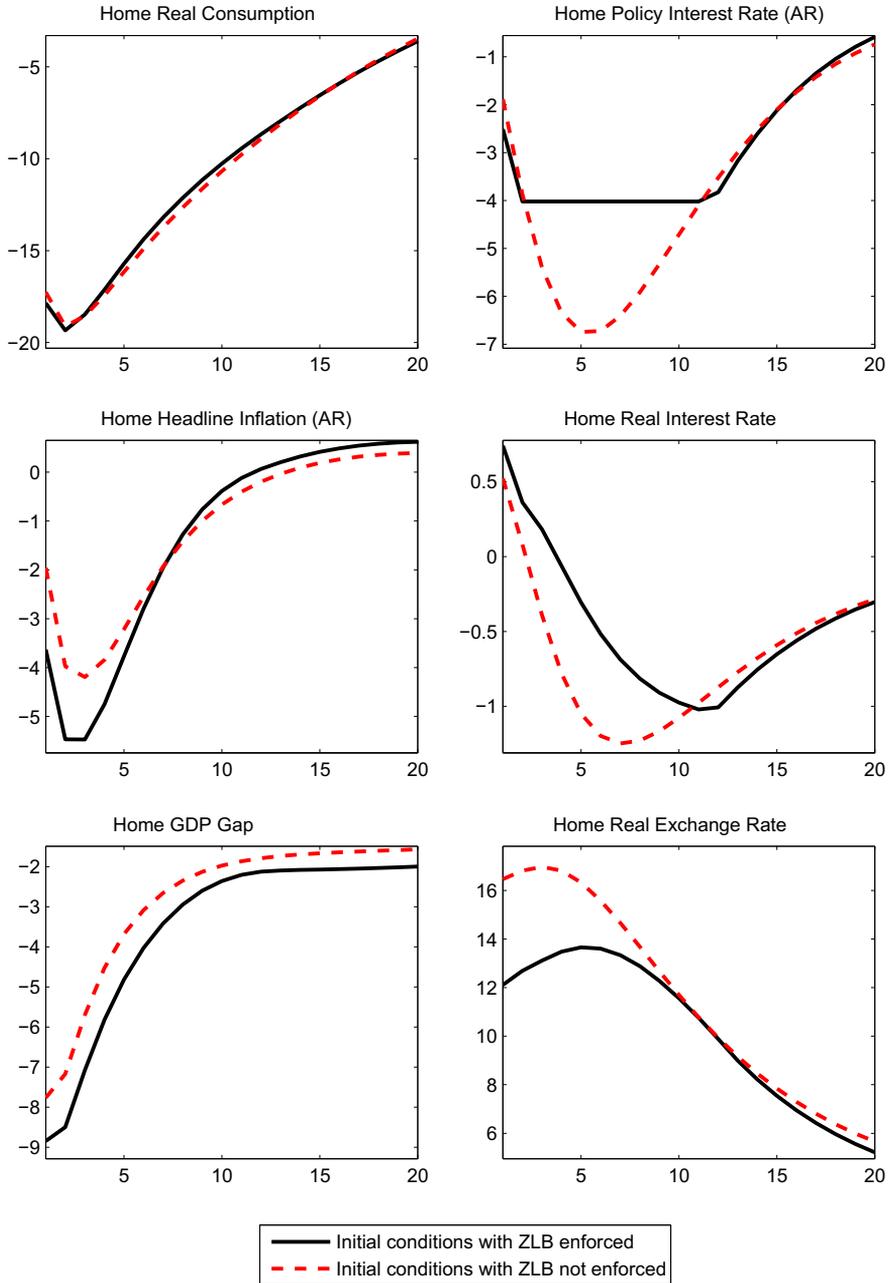


Fig. 9. A severe domestic recession that takes the home economy to the zero lower bound on policy rates.

preference shock so as to keep the duration of the liquidity trap unchanged. In all cases, the preference shock  $v_{ct}$  affects the home country only. Home consumption declines sharply, as does inflation. The economy's output falls below its potential level in the absence of sticky prices and wages. Home policy rates are cut gradually because of the smoothing term in the benchmark rule. However, after one quarter, the nominal policy rate reaches its lower bound indicated by a fall to  $-4\%$  in the figure. The drop in inflation and the size of the output gap shown in Fig. 9 might seem outside relative to the recent U.S. experience. Our benchmark model implies little inflation persistence, but the addition of real rigidities such as variable price markups considered as sensitivity analysis, and lagged indexation would reduce the drop in inflation in Fig. 9 to a magnitude in line with the recent experience. These features would also cushion the movement in the output gap. However, these additional complications would imply little change in our simulation results for the effects of oil shocks. The increased inflation persistence would compensate for the smaller initial change in influencing longer term real interest rates that affect the response of consumption and investment in our model. Accordingly, we decided to omit such features from the discussion. All of the simulations presented in the main body of the paper start in the first period of the liquidity trap, so that agents expect the trap to last 10 quarters in the absence of additional shocks, but are surprised by one more shock.

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