inventories, monetary policy responses, storers' expectations of the price of oil and the spot price.

Using this model, we investigated the origins and macroeconomic consequences of several U.S. shocks that are associated with oil price fluctuations, including a total factor productivity shock, a labor productivity shock, a government spending shock, a monetary policy shock, an oil supply shock and a storage demand shock. To quantify the model responses we estimated the model on U.S. data. We identified the relative importance of these shocks for the real price of oil during 1982-2007 as well as for the subsample of 2000-2007. Our estimates suggest that oil demand shocks in the form of total factor productivity shocks and labor productivity shocks are overall the most important drivers of changes in oil prices. When the storage feature is omitted from the model, the estimated contribution of oil supply shocks to oil price fluctuations is amplified considerably, in particular after 2000. Hence, studies that do not consider storage demand shocks are likely to overestimate the role played by oil supply shocks.

Another important finding is that after 2000, the contribution of productivity shocks to the variance of the real price of oil is higher by about 15 percent in the short run, when compared to the whole sample. On the other hand, the contributions of the oil supply shock and the storage demand shock is lower by more than half, compared to the full estimation period. This finding sheds some light on the resilience of the macroeconomic environment to oil price increases at the beginning of the century.

Finally, taking advantage of our general equilibrium model, we show that the presence of speculative oil storers may smooth or intensify the oil price fluctuations depending on the source of the shock. This is in contrast with the classic storage literature which emphasizes the mitigating role of the speculative storage, but in line with the empirical evidence presented in Kilian and Murphy (2010) and Alquist and Kilian (2010).

In the interest of keeping the model tractable, we abstracted from the open economy channels of the transmission of oil price shocks and indeed from the role of foreign shocks and focused on the U.S. oil market. An obvious extension would be to embed our model of storage within a model of the global economy.

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Appendix: Equilibrium Conditions

In what follows, small letters denote percentage deviations of the respective variables from their steady-state levels. Household's maximization of (1) subject to (7) and (8) yields the following (log-linearized) optimality conditions:

$$\begin{aligned}\beta\delta\xi E_t\{i_{t+1}-k_{t+1}\} &= \delta\xi(i_t-k_t)-\frac{\sigma}{1-h}E_t\{\Delta c_{t+1}\}+\frac{\sigma h}{1-h}\Delta c_t+E_t\{\pi_{z,t+1}\} \\ &\quad -E_t\{\pi_{t+1}\}+(1-\beta(1-\delta))E_t\{\widehat{r}^K_{t+1}\} \qquad (27)\end{aligned}$$

$$\left(\frac{\sigma}{1-h}\right)c_t-\frac{\sigma h}{1-h}c_{t-1}+\varphi n_t=\widehat{w}_t \qquad (28)$$

$$E_t\{\Delta c_{t+1}\}=h(\Delta c_t)+\left(\frac{1-h}{\sigma}\right)(r_t-E_t\{\pi_{t+1}\}) \qquad (29)$$

where $\widehat{r}^K_t = r^K_t - p_{z,t}$ is the real rental rate of capital, $\widehat{w}_t = w_t - p_t$ is the real wage, $\log R_t = \log(1+r_t) \approx r_t$ is the nominal interest rate, $\pi_{z,t+1} = p_{z,t+1}-p_{z,t}$ is the non-oil CPI inflation between t and $t+1$, and $\pi_{t+1} = p_{t+1}-p_t$ is the CPI inflation between t and $t+1$. Law of motion for capital in log-linearized form is as follows:

$$k_{t+1}=\delta i_t+(1-\delta)k_t \qquad (30)$$

Oil used in consumption (Equation 5) is log-linearized as:

$$o_{c,t}=-\rho_c\widehat{p_{o,t}}+c_t \qquad (31)$$

where $\widehat{p_{o,t}} = p_{o,t} - p_t$ is the real price of oil.

Firms will minimize $R^K_t K_t + W_t N_t + P_{o,t} O_{y,t}$ subject to (12). Log-linearized F.O.C.s are as follows:

$$\widehat{w}_t+(1/\rho_v)n_t+((1-\rho_v)/\rho_v)a_{2t}=\widehat{r}^K_t+(1/\rho_v)k_t+pr_{z,t} \qquad (32)$$

$$\begin{aligned}o_{y,t} &= y_t-a_{1t}+\rho_y(1-w_{oy})w_{ny}(\widehat{w}_t-a_{2t})+\rho_y(1-w_{oy})(1-w_{ny})\widehat{r}^K_t \\ &\quad -\rho_y(1-w_{oy})\widehat{p_{o,t}}+\rho_y(1-w_{oy})(1-w_{ny})pr_{z,t} \qquad (33)\end{aligned}$$

where $pr_{z,t} = p_{z,t} - p_t$ is the relative price. Equation (33) presents the determinants of the oil used in production.

The (log-linearized) real marginal cost ($mc_t = mc_t^n - p_{z,t}$) that is faced by the firms is:

$$\begin{aligned} mc_t &= -a_{1t} + (1 - w_{oy})(1 - w_{ny})\widehat{r_t^k} + (1 - w_{oy})w_{ny}(\widehat{w}_t - a_{2t}) \\ &\quad + w_{oy}\widehat{p_{o,t}} - ((1 - w_{oy})w_{ny} + w_{oy})pr_{z,t}. \end{aligned} \tag{34}$$

We assume that firms set prices according to Calvo (1983) framework, in which only a randomly selected fraction $(1 - \theta)$ of the firms can adjust their prices optimally in each period. Thus, θ is the probability that firm i does not change its price in period t. These firms of fraction θ can only adjust the price according to a partial indexation scheme:

$$P_{z,t+k}(i) = \prod_{s=1}^{k} \Pi_{z,t+s-1}^{\varsigma} P_{z,t}(i) \tag{35}$$

where $\Pi_{z,t} = P_{z,t}/P_{z,t-1}$. For firms who do not have chances to reoptimize prices, the prices are adjusted according to past inflation of core goods. ς captures the degree of inflation indexation in the economy.

The firm i who has opportunity to reoptimize the price chooses the price ($\widetilde{P}_{z,t}(i)$) so that it maximizes the stream of profits discounted by $Q_{t,t+k}$:

$$E_t \left\{ \sum_{k=0}^{\infty} \theta^k Q_{t,t+k}(Y_{z,t+k}(i)(\prod_{s=1}^{k} \Pi_{z,t+s-1}^{\varsigma} \widetilde{P}_{z,t}(i) - MC_{t+k}^n) \right\} \tag{36}$$

subject to the demand function faced by the firm:

$$Y_{z,t}(i) = \left(\frac{P_{z,t}(i)}{P_{z,t}} \right)^{-\varepsilon} Y_{z,t} \tag{37}$$

where ε is the elasticity of substitution among the core goods.

Therefore, $\widetilde{P}_{H,t}(i)$ should satisfy the following first order condition:

$$E_t \left\{ \sum_{k=0}^{\infty} \theta^k Q_{t,t+k}(Y_{z,t+k}(i)(\prod_{s=1}^{k} \pi_{z,t+s-1}^{\varsigma} \widetilde{P}_{z,t}(i) - \frac{\varepsilon}{\varepsilon - 1} MC_{t+k}^n) \right\}. \tag{38}$$

Hence, the firms' optimal price setting strategy implies the marginal cost-based (log-linearized) Phillips curve:

$$\pi_{z,t} = \frac{\beta}{1+\beta\varsigma}E_t\left\{\pi_{z,t+1}\right\} + \frac{\varsigma}{1+\beta\varsigma}\pi_{z,t-1} + \frac{(1-\theta)(1-\beta\theta)}{\theta(1+\beta\varsigma)}mc_t. \tag{39}$$

Log-linearization of goods market equilibrium condition around the symmetric steady state gives:

$$y_{z,t} = G_y g_t + I_y i_t + (1 - G_y - I_y)z_t \tag{40}$$

where $z_t = c_t - \rho_c pr_{z,t}$. $G_y = \overline{G}/\overline{Y}_z$ and $I_y = \overline{I}/\overline{Y}_z$ are the steady state shares of government spending and investment in output, where letters with a bar above indicate the steady state levels.

In the oil market, oil supply $(o_{s,t})$ is assumed be exogenous, while oil demand and oil storage are endogenously determined. The (log-linearized) equilibrium conditions are:

$$s_t = \Theta(E_t\{\widehat{p_{o,t+1}}\} - \widehat{p_{o,t}} - E_t\{r_t - \pi_{t+1}\}) + sd_t \tag{41}$$

$$\frac{\overline{O}_y}{\overline{O}_s}o_{y,t} + \frac{\overline{O}_c}{\overline{O}_s}o_{c,t} = o_{s,t} + a\frac{\overline{S}}{\overline{O}_s}s_{t-1} - \frac{\overline{S}}{\overline{O}_s}s_t \tag{42}$$

where $\Theta = \frac{a\beta}{\Psi\overline{S}}$, and the oil supply shock $(o_{s,t})$ and storage demand shock (sd_t) are assumed to follow stationary AR(1) processes.

Notice that at steady state, $\kappa + \psi\overline{S} = a\beta - 1 < 0$, $\frac{\overline{O}_y}{\overline{O}_s} = \left(1 + \frac{(1-G_y-I_y)w_{oc}}{w_{oy}(1-w_{oc})}\right)^{-1}(1 + (a-1)\frac{\overline{S}}{\overline{O}_s})$, and $\frac{\overline{O}_c}{\overline{O}_s} = \frac{(1-G_y-I_y)w_{oc}}{w_{oy}(1-w_{oc})}\frac{\overline{O}_y}{\overline{O}_s}$.

Table 1. Calibrated parameters

$\beta = 0.99$	Discount factor
$\delta = 0.025$	Depreciation rate
$I_y = 0.2$	Share of investment spending in output
$G_y = 0.18$	Share of government spending in output
$\omega_{ny} = 0.66$	Share of labor in value added
$\omega_{oc} = 0.023$	Share of oil in consumption
$\omega_{oy} = 0.028$	Share of oil in production
$S/O_s = 0.61$	Ratio of oil stocks to quarterly oil supply
$1 - a = 0.01$	Oil waste

Table 2. Prior distributions and posterior estimates (sample period: 1982Q1-2007Q4)

					benchmark			no storage		
		prior distribution			posterior distribution			posterior distribution		
		type	mean	st.dev.	mean	5%	95%	mean	5%	95%
standard deviation of the innovations										
ε_{tfp}	total factor prod.	inverse gamma	2	2	0.52	0.45	0.58	0.45	0.39	0.51
ε_{l}	labor productivity	inverse gamma	2	2	2.22	1.53	2.92	2.07	1.55	2.58
ε_{g}	govern. spending	inverse gamma	2	2	2.61	2.15	3.00	3.65	2.73	4.47
ε_{mp}	monetary policy	inverse gamma	2	2	0.66	0.52	0.81	0.52	0.30	0.72
ε_{os}	oil supply	inverse gamma	2	2	1.04	0.92	1.16	0.36	0.30	0.41
ε_{sd}	storage demand	inverse gamma	2	2	4.62	2.80	6.33	-	-	-
persistence of the exogenous processes										
ρ_{tfp}	total factor prod.	beta	0.5	0.2	0.80	0.74	0.87	0.83	0.78	0.88
ρ_{l}	labor productivity	beta	0.5	0.2	0.95	0.91	0.99	0.96	0.93	0.98
ρ_{g}	govern. spending	beta	0.5	0.2	0.64	0.54	0.74	0.83	0.77	0.89
ρ_{mp}	monetary policy	beta	0.5	0.2	0.36	0.29	0.43	0.16	0.06	0.26
ρ_{os}	oil supply	beta	0.5	0.2	0.53	0.42	0.64	0.95	0.91	0.99
ρ_{sd}	storage demand	beta	0.5	0.2	0.94	0.90	0.98	-	-	-
structural parameters										
κ	convenience yield	normal	-0.03	0.05	-0.04	-0.05	-0.03	-	-	-
ρ_{v}	elasticity:capital/labor	gamma	0.5	0.1	0.05	0.03	0.08	0.05	0.03	0.07
ρ_{c}	elasticity:core/oil	gamma	0.4	0.1	0.66	0.40	0.89	1.16	0.93	1.39
ρ_{y}	elasticity:va/oil	gamma	0.4	0.1	0.55	0.37	0.72	0.61	0.52	0.69
θ	Calvo parameter	beta	0.5	0.15	0.38	0.28	0.48	0.26	0.18	0.34
ς	price indexation	beta	0.5	0.15	0.32	0.13	0.49	0.26	0.07	0.44
h	habit persistence	beta	0.6	0.1	0.27	0.15	0.38	0.1	0.03	0.16
σ	inv.el. of int.subst. cons.	normal	1	0.1	0.93	0.76	1.08	1.04	0.91	1.18
φ	inv.el. of labor supply	gamma	1	0.25	0.95	0.58	1.27	0.87	0.47	1.19
ϕ_{π}	response to inflation	gamma	1.5	0.5	3.30	2.78	3.82	3.72	3.01	4.44
ϕ_{y}	response to output	gamma	0.5	0.05	0.37	0.29	0.45	0.24	0.16	0.32
ϕ_{r}	int.rate persistence	beta	0.6	0.1	0.52	0.41	0.62	0.64	0.50	0.79

Table 3. Variance decomposition (sample period: 1982Q1-2007Q4)

		benchmark						no storage				
	quarter	ε_{tfp}	ε_{l}	ε_{g}	ε_{mp}	ε_{os}	ε_{sd}	ε_{tfp}	ε_{l}	ε_{g}	ε_{mp}	ε_{os}
real price of oil	4	32.49	28.37	9.73	3.48	14.87	11.06	25.25	24.76	11.07	2.89	36.03
	8	24.06	47.15	5.88	2.16	12.74	8.01	18.01	38.69	8.95	1.54	32.82
	12	17.99	60.72	4.12	1.54	9.91	5.73	13.12	50.47	6.95	1.03	28.44
	50	6.02	87.04	1.30	0.49	3.26	1.89	3.50	83.32	2.05	0.25	10.87
storage growth	4	2.27	0.17	6.38	1.78	78.57	10.83	-	-	-	-	-
	8	2.23	0.24	3.19	1.76	77.49	12.10	-	-	-	-	-
	12	2.18	0.27	6.12	1.74	77.80	11.90	-	-	-	-	-
	50	2.11	0.30	6.00	1.70	76.92	12.98	-	-	-	-	-

Table 4. Variance decomposition (sample period: 2000Q1-2007Q4)

		benchmark						no storage				
	quarter	ε_{tfp}	ε_{l}	ε_{g}	ε_{mp}	ε_{os}	ε_{sd}	ε_{tfp}	ε_{l}	ε_{g}	ε_{mp}	ε_{os}
real price of oil	4	51.73	23.88	4.92	6.29	5.65	3.52	51.91	13.00	9.77	1.83	23.50
	8	39.38	43.29	3.10	6.71	4.92	2.59	44.76	27.18	8.08	1.09	18.89
	12	29.80	57.48	2.20	4.84	3.83	1.85	36.70	41.23	6.48	0.78	14.80
	50	9.49	86.84	0.66	1.45	1.18	0.59	12.49	80.50	2.19	0.23	4.59
storage growth	4	17.65	0.10	12.87	2.66	62.84	3.88	-	-	-	-	-
	8	18.04	0.12	12.67	2.74	62.21	4.22	-	-	-	-	-
	12	17.95	0.14	12.59	2.80	62.34	4.18	-	-	-	-	-
	50	17.74	0.18	12.47	2.81	62.08	4.72	-	-	-	-	-

Figure 1. Impulse responses to a one standard deviation positive TFP shock

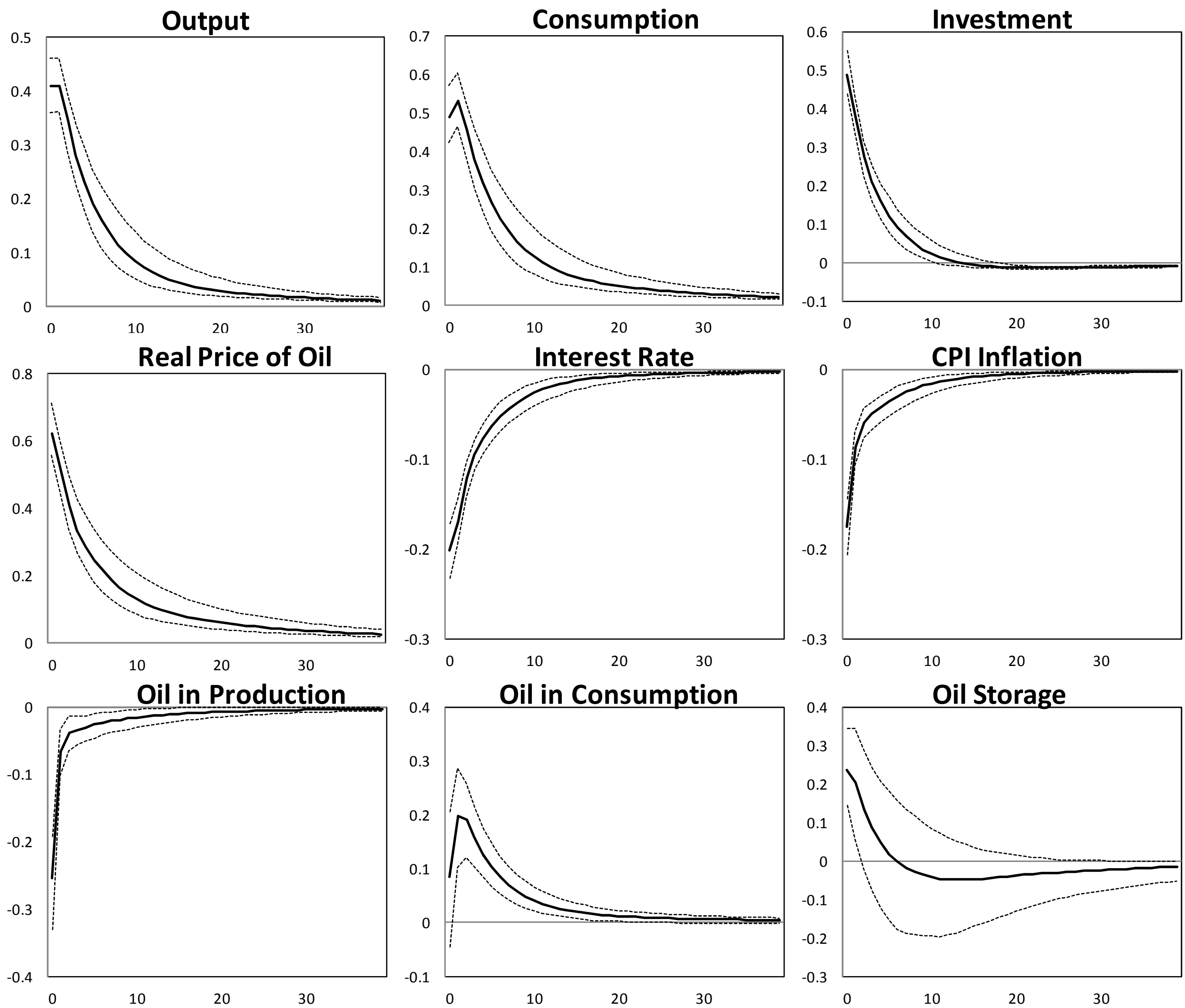

Figure 2. Impulse responses to a one standard deviation positive labor productivity shock

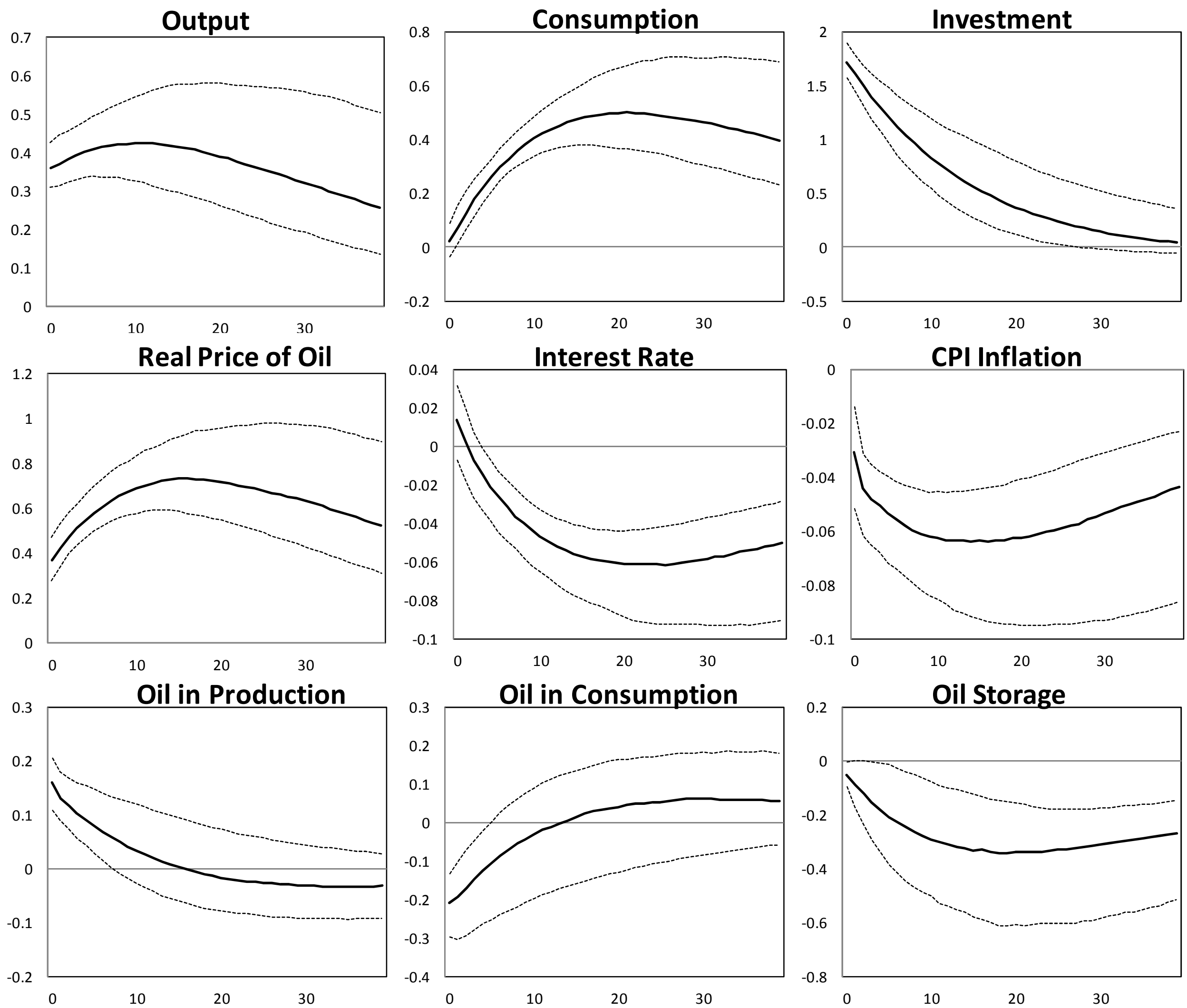

Figure 3. Impulse responses to a one standard deviation negative oil supply shock

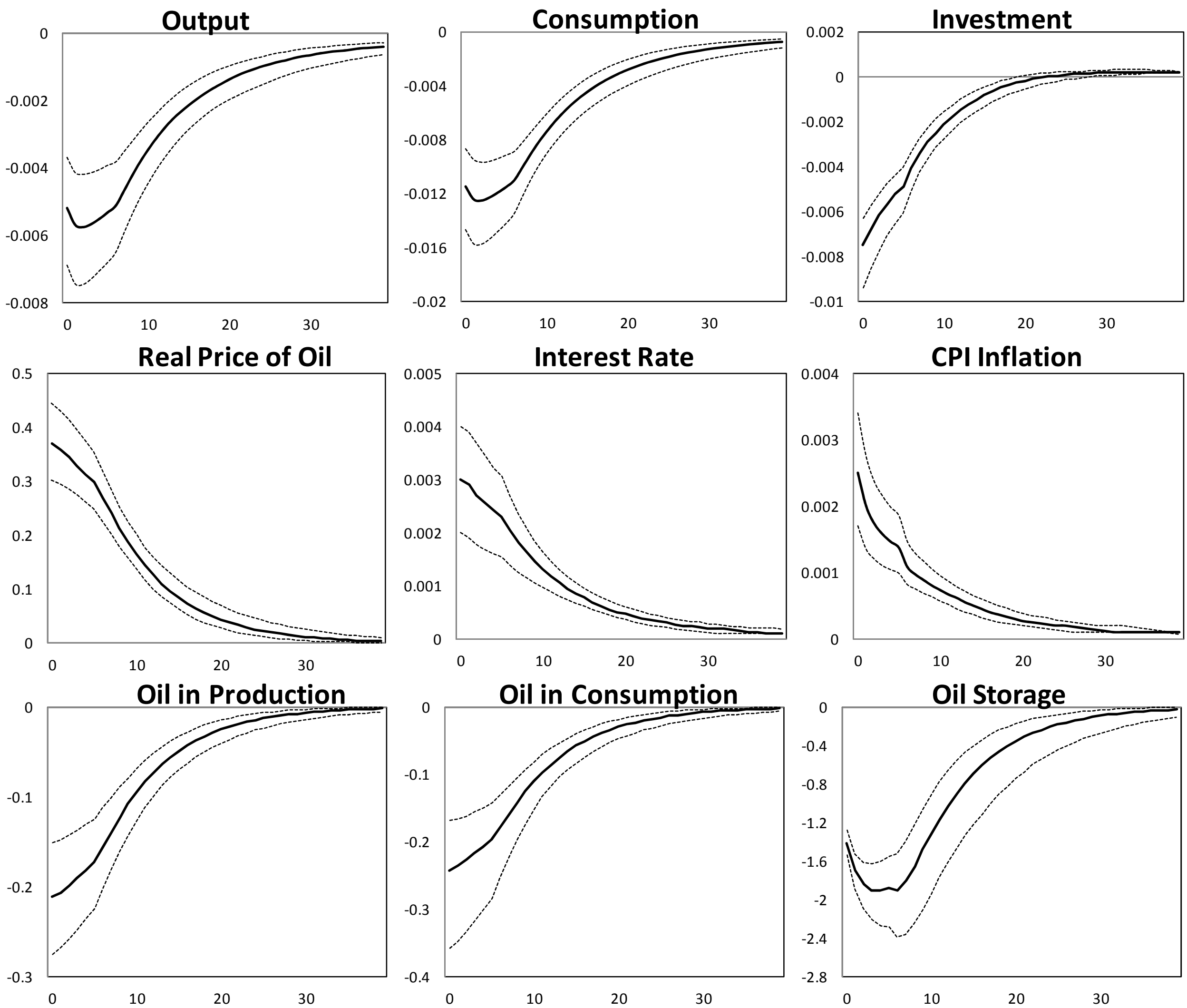

Figure 4. Impulse responses to a one standard deviation storage demand shock

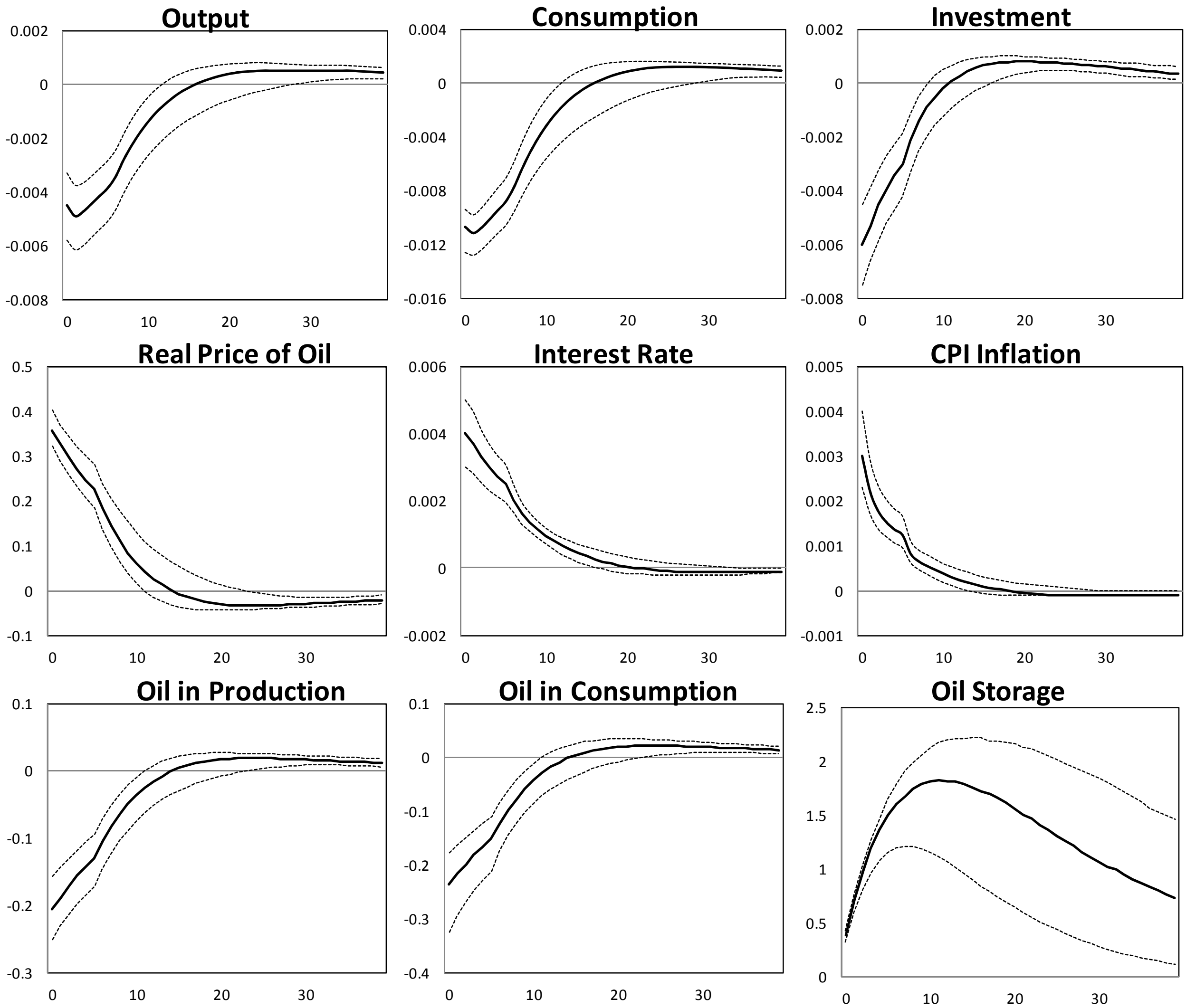

Figure 5. Impulse responses to a one standard deviation positive TFP shock with and without storage

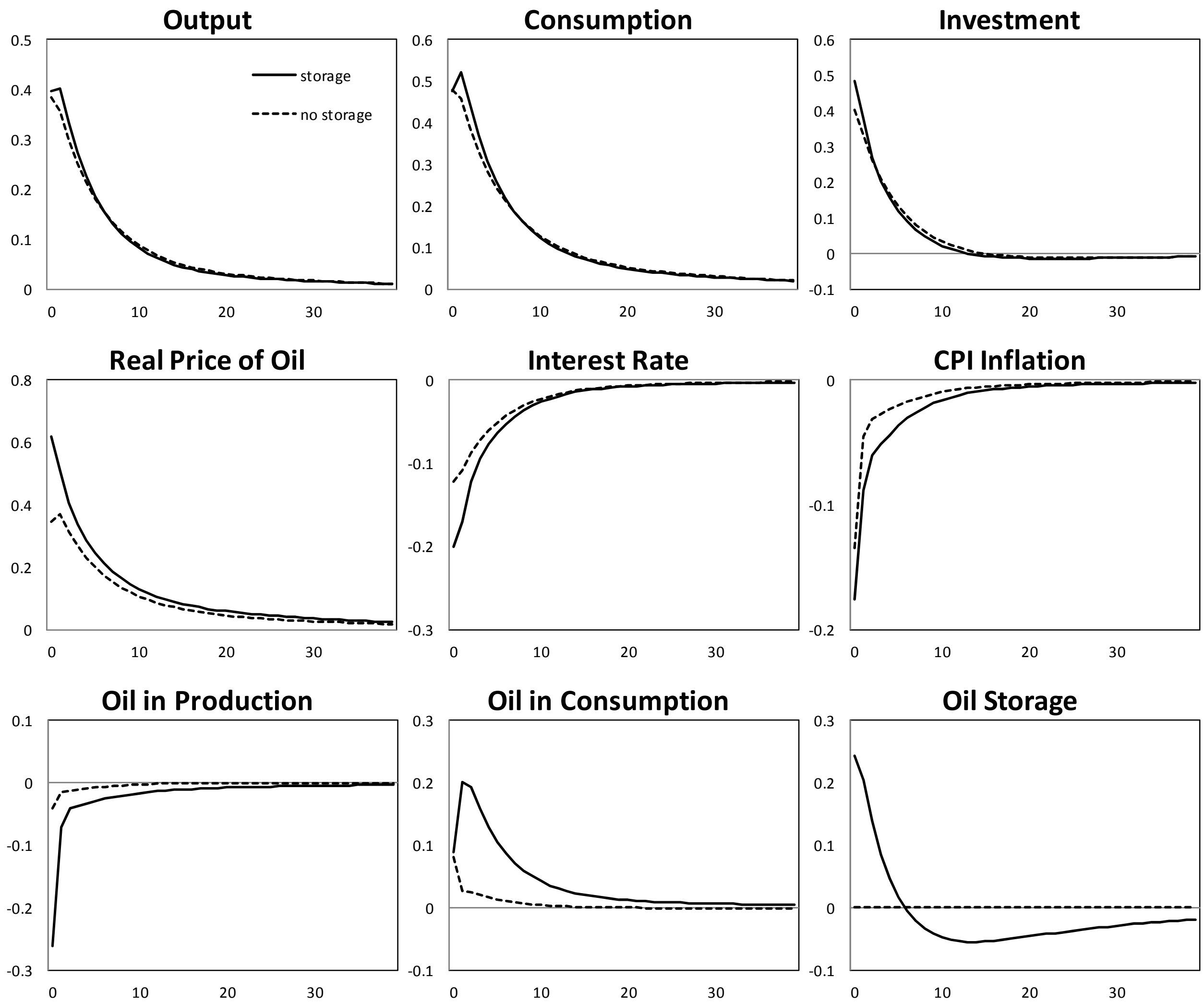

Figure 6. Impulse responses to a one standard deviation positive labor productivity shock with and without storage