Revisit *Hotelling Under Pressure*: Is Oil Production from Existing Wells Immune to Oil Price Variations?*

Yan Wang†, Zheming Wang‡, Yiwei Zhang§

December 7, 2018

Abstract

This paper repeats and extends the empirical work of *Hotelling Under Pressure* (Anderson, Kellogg and Salant, JPE 2018) by data of oil production from the Gulf of Mexico from 1990 to 2007. We show that oil price variations have a significant influence on oil production from existing wells in the short run, contradicting their results. The long-run effect is significant at 20-percent level. Besides, gas price variations also have a significant influence on oil production from existing wells both in the short run and in the long run, which is omitted in their paper.

* We are grateful to Kenneth Hendricks for providing data on oil and gas production in the Gulf of Mexico to support our research. We also thank Yu Ding, Zeyu Li, Chris Taber for helpful comments and suggestions.

† University of Wisconsin- Madison. Email: wang2264@wisc.edu

‡ University of Wisconsin- Madison. Email: zwang2236@wisc.edu

§ University of Wisconsin- Madison. Email: zhang984@wisc.edu

1 Introduction

The production choice of exhaustible resources is one of the intriguing models in economics. The fundamental version is established by Hotelling (1931), who states that a forward-looking resource owner will compare the profits from extraction today with profits of exploitation in the future. Later, by the foundation of OPEC and its great impact on the crude oil market, economists (Stiglitz, 1976; Salant, 1976; Pindyck, 1978; etc.) tend to consider the production of oil as typical monopoly behavior, since oil prices are easily manipulated by large oil providers. Until now, much research has been done on the performance of Hotelling's model on the crude oil market, but few is satisfying (see Krautkraemer, 1998; Slade and Thille, 2009; for reviews). As a result, economists often think exhaustibility not really an issue for historical oil prices (Hamilton, 2009).

Anderson, Kellogg and Salant (JPE, 2018), the authors of *Hotelling under pressure* (HUP), propose a modified version of Hotelling's model on oil production. Their idea is that oil production has intensive margin and extensive margin which conform to different rules. Subject to the geological feature of decreasing reservoir pressures, oil productions from existing wells (intensive margin) decays as oil is extracted and do not respond to oil prices. Drilling activities for new wells (extensive margin), however, is free from the geological pressure constraints and respond strongly to oil prices. These two claims form the critical assumptions for the constrained profit maximization model in the following paragraphs of HUP[1].

1.1 Empirical Results of HUP

The authors briefly justified the two claims by monthly oil production and drilling data from Texas[2] and the West Texas Intermediate (WTI) crude oil futures prices[3] covering 1990-2007.

---

[1] Because this paper is a comparative research on HUP with many citations, I will not put citation symbols for every result from HUP, but I will explicitly and clearly tell which are from HUP.
[2] Drilling data of HUP is from Texas Railroad Commission'(TRRC's) "Drilling permit master" dataset. Lease level production data of HUP is from Texas Railroad Commission'(TRRC's) "Oil and Gas Annuals" dataset.
[3] Crude oil futures price is from New York Mercantile Exchange (NYMEX) price for West Texas Intermediate (WTI) crude oil.

Their main specification is given by:

$$\Delta\log(\mathrm{Y}_t) = \alpha + \beta_0\Delta\log(\mathrm{P}_t) + \beta_1\Delta\log(\mathrm{P}_{t-1}) + \delta_0\Delta\mathrm{R}_t + \delta_1\Delta\mathrm{R}_{t-1} + \eta\cdot\mathrm{T}_t + \varepsilon_t \quad (1)$$

where Y_t could be either average production from existing wells or drilling counts at time t; P_t is WTI futures prices at time t; R_t is the expected increase rate of oil prices, calculated by the percentage difference between the 12-month oil futures price and the front month oil futures price; and T_t is the time trend represents that the pressure-driven production decline curve is hyperbolic rather than exponential. The formula is in first differences because they cannot reject that both $\log(\mathrm{Y}_t)$ and $\log(\mathrm{P}_t)$ are unit root process. For inference, they use Newey-West with four lags.

For oil production from existing wells, $\widehat{\beta_0}$ is 0.083 with a standard error 0.036; $\widehat{\beta_1}$ is -0.083 with a standard error 0.036; $\widehat{\beta_0}+\widehat{\beta_1}$ is 0.0009 with a standard error of 0.034. Similarly, $\widehat{\delta_0}+\widehat{\delta_1}$ is -0.0008 with a test against the null hypothesis that this sum equals zero yields a p-value of 0.171.[1] The results show that oil price changes have neither an economically nor statistically significant effect on production from existing wells.

For drilling activities, they put in a second lag term. The estimates and standard error for $\widehat{\beta_0}'$, $\widehat{\beta_1}'$, $\widehat{\beta_2}'$ is respectively 0.372 (0.153), 0.008 (0.188) and 0.352 (0.165). Summing the coefficients on the current and lagged front month price differences yields an elasticity of drilling with respect to the front month price of 0.732 (with a standard error of 0.201).

1.2 Remarks on Empirical Results of HUP

Though the results seem to affirm the authors' conjectures in HUP, there are some imperfections in their empirical work.

First, their interpretation about the estimates is inaccurate. Note that formula (1) is in first difference. $\widehat{\beta_0}$ and $\widehat{\beta_1}$ are 0.083 and -0.083 means a positive shock of oil price variations in period t will cause a 8.3% positive change on the "speed" of oil production in the first period, and then the "speed" of oil production moves back as before the price

[1] For details, see Appendix A.1 of *Hotelling under pressure*, Table 1.

shock happens in the next period. The accumulated production percentage changes should be integrated from the above periods, which is $(\frac{0.083+0}{2} = 4.15\%)$ by the estimates of HUP. So, our interpretation of the estimates in HUP is: shocks on oil price variation will not affect oil production in the long run (reflected by the return of speed of oil production), but will have a weak short-run impact in the same direction.

Second, the estimates of HUP might be biased for omitted variables. As you might know, wells usually extract oil and gas in the meantime according to the reservoir's deposit. In HUP, they are arguing the effects of oil prices on oil production without considering producers' choice on gas production. Additionally, gas prices are strongly correlated with oil prices. Based on data from 1990 to 2007, $\rho\left[\log(P_{oil}), \log\left(P_{gas}\right)\right] = 0.808$, $\rho\left[\Delta\log(P_{oil}), \Delta\log\left(P_{gas}\right)\right] = 0.149$. It is plausible that the variation of gas prices will also have impacts on production of oil, and make the estimates in HUP biased. We will examine the relationship of oil and gas production in our paper.

Third, although the authors of HUP explained that Texas firms are a small share of the world oil market (1.3% in 2007), the prices they use are WTI oil prices that not only named after Texas, but also emphasize the American (local) crude oil markets, where Texas is a main provider. As a result, we suggest measures be taken to avoid the possible two-way causality that oil production in Texas also affects WTI oil prices. If there is two-way causality, the value of the estimates will be smaller than its true value, because the reverse effect tends to offset the influence by oil price variations (negative feedback) to stabilize the oil market. As our data are from the Gulf of Mexico, we will check the Gulf region for two-way causality, and our results do not necessarily prove whether there is two-way causality in the Texas area.

At last, the data referred in HUP is panel data, but the authors aggregate along each month to raise a time series model, instead of considering the heterogeneity within each lease, which we think is information loss. For all the reasons above, we hope to repeat the empirical work of HUP by carefully tackling these problems with our oil production data from the Gulf of Mexico[1], and compare our results with theirs.

1.3 Literature Review

Former work has been done studying the supply price elasticity of oil production. Krichene (2005) used worldly oil and gas production data and vector error correction method to show the supply of crude oil had low short-run price elasticity: -0.05 from 1974 to 2004, but natural gas output had a significant effect on the supply of oil, with short-run elasticity estimated at 1.04 from 1974 to 2004. The long-run supply price elasticity, however, was significant and positive: 0.25 from 1974 to 2004. Baumeister and Peersman (2013) showed the oil supply elasticities varied from different demand shocks, and median value for oil supply elasticities fall from 0.3-0.5 before 1983 to less than 0.25 since the late 1980s. Generally speaking, the oil supply price elasticity is deemed to be low in the short run (e.g. Hamilton, 2009; Kilian, 2009).

1.4 Our Work

To repeat the empirical research of HUP, we will use data of offshore oil production in the Gulf of Mexico and the spot oil prices from 1990 to 2007.

First, based on the time-series model in HUP, we use gold prices as an instrumental variable to settle potential two-way causality, that oil production in the Gulf of Mexico may affect oil prices too. Our time series models examine the oil prices effects on both oil production from existing wells and drilling activities for new wells.

Second, except for aggregating panel production data to form time-series data, we build a fixed effect model to control heterogeneity among each lease. A conjecture that if a lease produces more gas, the lease owner will pay more attention on gas price variations, is also tested in the panel model with leases that produce oil and gas simultaneously. In both time-series and panel models, gas prices are included as a controlled variable to settle omitted variables.

We find that oil price variations have a significant influence on oil production from existing wells in the short run, contradicting results of HUP. The long-run effect is

---

[1] Oil production in the Gulf of Mexico is 1.35% of the whole world's oil production in 2006, resembling the ratio of oil production in Texas as the authors of HUP explained.

significant at 20-percent level in all models. Besides, gas price variations also have a significant influence on oil production from existing wells both in the short run and in the long run, which is omitted in their paper. The drilling activities are inelastic to oil price variations, but are sensitive to gas price variations.

Weakness of our paper mainly comes from the structure of data. Selection bias is caused by the fact that the oil productions are recorded as lease-level, not well-level. And without the owner documents for each lease, we cannot clearly verify leases in the Gulf of Mexico are price takers, though oil production of the whole Gulf area only takes a small share of the whole world's oil production. Another weakness is our IV is a macro variable, which cannot be identified as pure exogenous. But our results with IV are reasonable, and results without IV also show the same conclusions.

The plan of the rest of this paper is as follows. In Section 2 we describe the data and explains their difference with HUP's. In Section 3 we set our models and in Section 4 show the empirical results. Section 5 contains concluding remarks.

2 Data

Now that *Hotelling under pressure* is published on JPE, we have access to their merged aggregate data. But we will stick to our data specifying oil production in the Gulf of Mexico, for the following reasons.

First, the authors of HUP only published time-series data after aggregation, without the original panel data, especially without clarification on well completion cases when calculating average production per month[1]. It is of great importance to precisely count how many leases are still able to produce oil, i.e., to differentiate proactive shut-ins with passive shut-ins. The two kinds of 0s (or missing values) in data have different meanings (vaguely described in data). The accurate lease count for average production should include the leases with proactive shut-ins, but exclude those with wells completed. This measurement error is a major concern when we calculate the average production from existing wells with our data[2].

Furthermore, the authors of HUP adjusted oil prices for inflation using CPI[3], but for goods such as crude oil and gas, we will choose PPI for adjustment instead.

Finally, our data contains monthly gas production from each lease and gas prices as controlled variables, by which we can avoid omitted variable bias.

2.1 Crude Oil and Gas Prices

Crude oil price data comes from *Federal Offshore U.S. Gulf Coast Crude Oil First Purchase Price* series collected by the U.S. Energy Information Administration (EIA). It reports domestic crude oil first purchase (spot) prices for the Gulf of Mexico on a monthly basis from 1977 to 2010, in nominal dollars per barrel.

Gas price data comes from the *U.S. Natural Gas Wellhead Price* series. It reports

[1] If they did not consider well completion when calculating average production from existing wells, there are measurement errors in the results of HUP.

[2] We differentiate proactive shut-in with passive shut-in by the following assumption: after we exclude all the leases that used rigs (to drill new wells) in the targeted period, if a lease had reported 0s (or missing values) before a positive production afterwards, these 0s are proactive shut-ins; otherwise they are passive shut-ins.

[3] They use the All Urban, All Goods Less Energy Consumer Price Index (CPI) of the Bureau of Labor Statistics to convert all prices to December 2007 dollars.

wellhead prices on a monthly basis from 1976 to 2009, in nominal dollars per thousand cubic feet. The series are also obtained from EIA's website.

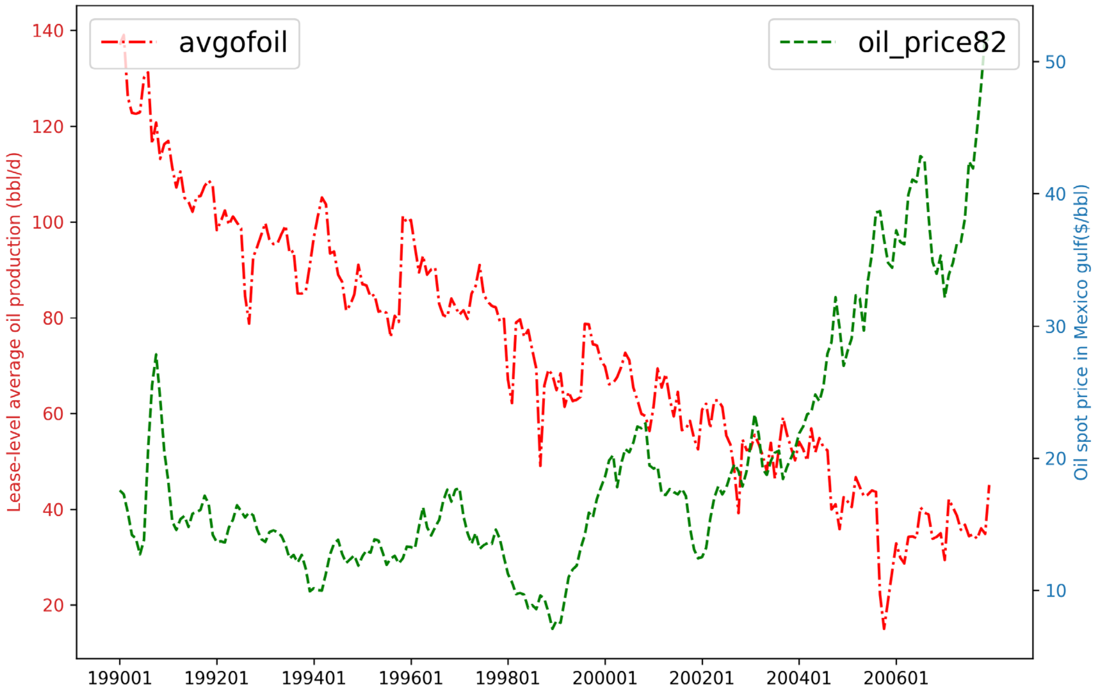
Both prices are adjusted for inflation by the producer price index (PPI) as real \$1982. The PPI index is published by Bureau of Labor Statistics.

2.2 Crude Oil and Gas Production in the Gulf of Mexico

Oil and gas production data comes from *Oil and Gas Operations Reports – Part A (OGOR-A)* compiled by Bureau of Ocean Energy Management (BOEM). They report monthly oil and gas production data per lease (each lease may contain multiple wells) from 1947 to 2010. The number of productive leases[1] is 3,548 from 1990 to 2007, and 534 after we drop leases that drilled new wells. Considering well completion, the number of leases producing oil drop from 355 in Jan 1990, to 68 in Dec 2007.

Our data on oil and gas production have the same features such as lease-level, monthly records as HUP's, which facilitate us to compare our results with theirs.

Figure 1: Crude oil prices and production from existing wells in Gulf of Mexico



Notes: This figure presents spot crude oil prices and daily average lease-level production from leases on which there was no rig activity (so that all production comes from pre-existing wells). All prices are real \$1982. See text for details.

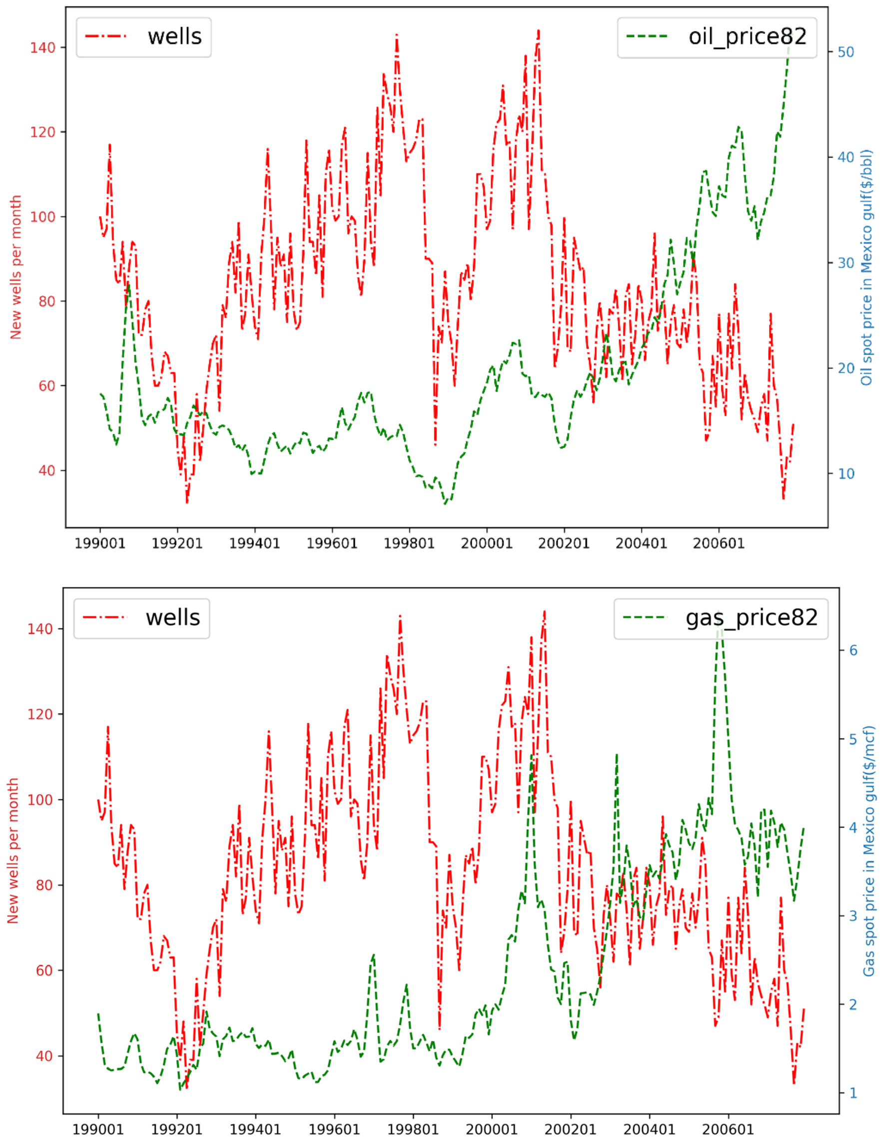
[1] Productive leases have positive production records for at least one month during all time.

Figure 1 confirms that the average oil production from existing wells decays as HUP claims as well as the geological feature predicts, but it is still unclear whether the average oil production from existing wells does not respond to oil price variations.

2.3 Drilling Activity in the Gulf of Mexico

Drilling data is from *The US Department of Interior's Minerals Management Service (MMS) boreholes data*. The total number of new wells drilled from 1990 to 2007 is 18,086, with an average of 83.7 per month.

Figure 2: Crude oil, gas prices and drilling of new wells in the Gulf of Mexico

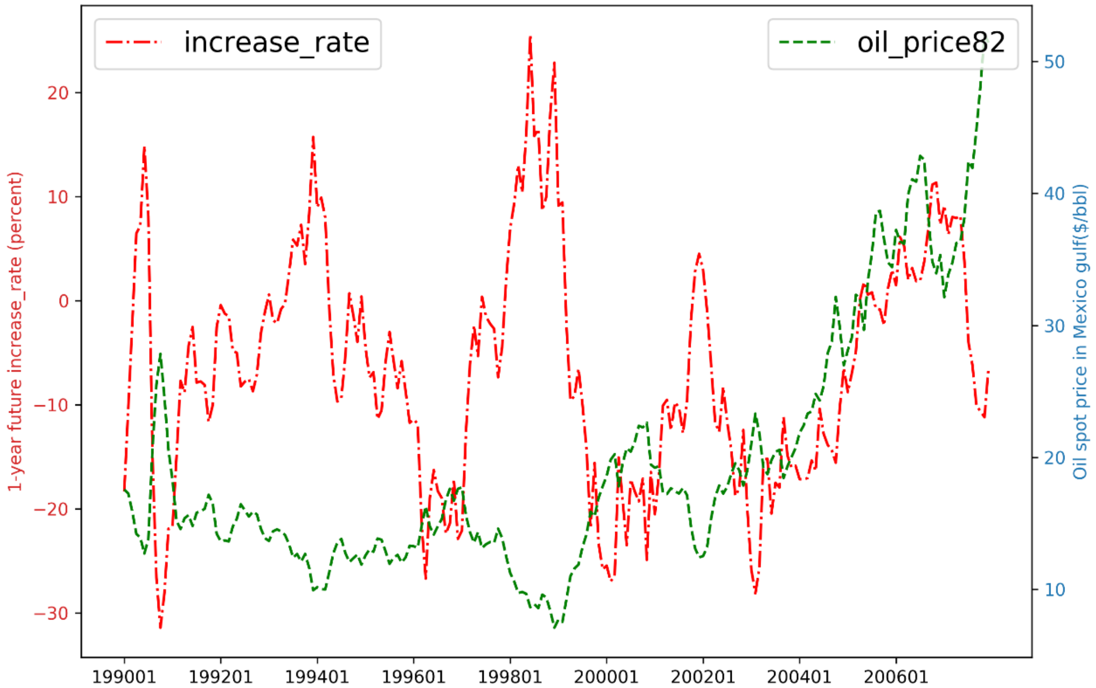


Notes: This figure shows the total number of new wells drilled across all leases in our dataset, comparing with spot oil prices and gas prices. All prices are real $1982. See text for details.

2.4 Expected Increase Rate on Crude Oil Futures Price

The expected increase rate of oil futures prices is from the published data of HUP, since we did not find free access to 12 months WTI future prices. As said before, it is calculated by the percentage difference between 12 months WTI futures prices and front month WTI futures price. The origin of the data from *New York Mercantile Exchange (NYMEX) price for West Texas Intermediate (WTI) crude oil*.

Figure 3: Oil prices and expected increase rate of oil prices



Notes: This figure shows spot oil prices and the expected increase rate of oil prices, calculated by the percentage change in futures prices between the 12-month futures price and the front month price, for each month of the sample. All prices are real \$1982. See text for details.

The lack of expected increase rate data unfortunately sets constraints to our research in two ways. First, our research is confined in the period from 1990 to 2007 as HUP is. Second, lack of data for expected increase rate of gas prices may put our results for gas markets in risk of omitted variables[1], if the expected increase rate for gas prices is a crucial signal for producers, and it is correlated with current gas price (a plausible guess is they are negatively correlated given the relationship on oil counterparts:

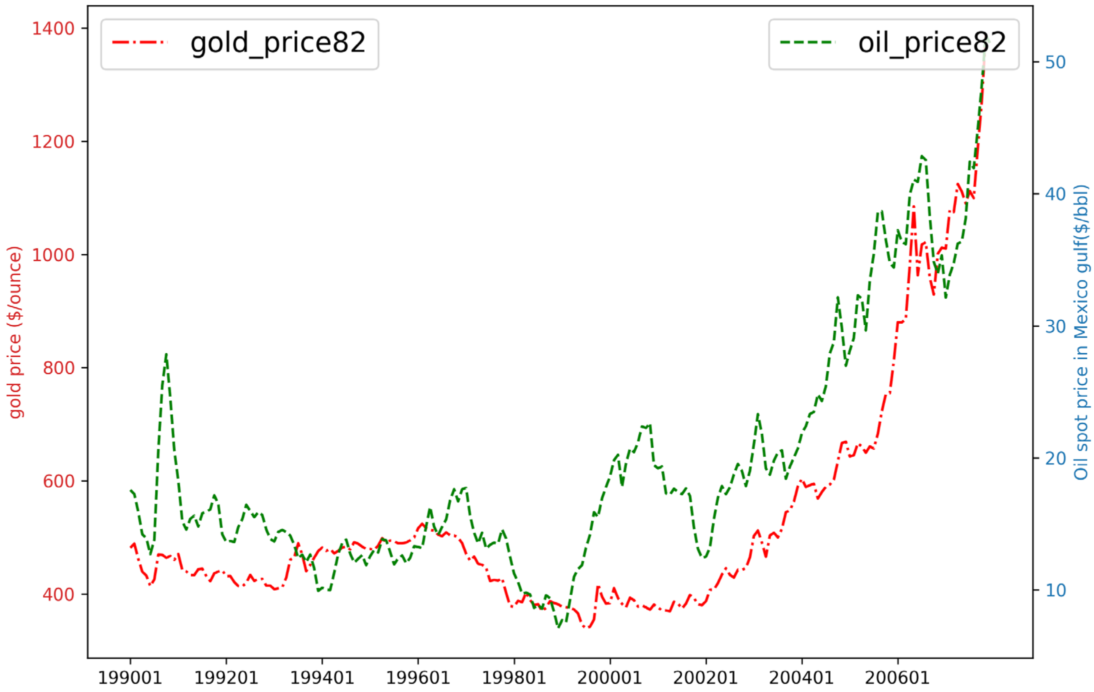
[1] The omitted expected increase rate of gas prices is probably not important for oil production, since in Section 4, we identify the impact of expected increase rate of oil prices on oil production is already very weak.

$\rho[\log(P_{oil}), R_{oil}] = -0.2147$ based on our data). This is the reason we do not show the results for the gas market in the Gulf of Mexico.

2.5 Gold Price

In the following passage, we will use gold prices as an instrumental variable for oil prices[1]. The gold prices are monthly data compiled by the London Bullion Market Association (LMBA), in nominal dollars per ounce. They are also adjusted for inflation in the same way with oil and gas prices.

Figure 4: Oil prices and gold prices



Notes: This figure presents gold prices and spot oil prices. All prices are real $1982. See text for details.

[1] The reasons that the gold price is a good instrumental variable are in Section 3.1

3 Methods

3.1 Time Series Model

Our main specification is modified from HUP's appendix A.1, adding the omitted variable gas prices and a hurricane seasonal variable. The results of time series model fits best to compare with HUP's. Imagine the production of oil is determined by:

$$\Delta \log(\mathrm{Y}_t) = \alpha + \beta_0 \Delta \log(\mathrm{P}_t) + \beta_1 \Delta \log(\mathrm{P}_{t-1}) + \delta_0 \Delta \mathrm{R}_t + \delta_1 \Delta \mathrm{R}_{t-1} + \gamma_0 \Delta \log(\mathrm{G}_t) + \gamma_1 \Delta \log(\mathrm{G}_{t-1}) + \eta \cdot \mathrm{T} + \mu \cdot \mathrm{S}_t + \varepsilon_t \quad (2)$$

Where Y_t is either average oil production from existing wells each month, or the number of new wells drilled; P_t is the oil price; R_t is the expected increase rate of oil prices, defined by the percentage difference between the 12-month oil futures price and the front month oil futures price ; G_t is the gas price; T_t is the time trend or a controlled variable for each year; and S_t represents the Atlantic hurricane season which is defined from June 1st to November 30th each year, by U.S. National Hurricane Centre. The constant α in formula (2) represents production decay speed of existing wells given other factors fixed. One lag is added for minimization of the AIC criterion. Removing this lag or adding additional lags does not qualitatively change the results. $\widehat{\beta_0}$ and $\widehat{\beta_1}$ show the short-run oil price effects, while $\widehat{\beta_0} + \widehat{\beta_1}$ identifies the long-run oil price effect, as explained in Section 1.2.

Table 1: DF-GLS unit-root tests

	Before first difference		After first difference	
Variables	Trend	No trend	Trend	No trend
Average oil production	-5.283***	-0.591	-10.486***	-11.006***
New wells drilled	-3.166**	-2.461**	-12.650***	-12.480***
Oil prices	-1.287	-0.512	-9.496***	-8.652***
Increase rate of oil prices	-2.751*	-2.180**	-6.734***	-3.762***
Gas prices	-2.829*	-1.750*	-8.197***	-4.701***
Gold prices	0.367	2.122	-10.779***	-10.609***

Notes: All variables are monthly from 1990 to 2007, and transformed by log function as depicted in formula (2). The number of lags used in the test was 1.

* Significant at 10-percent level.

** Significant at 5-percent level.

*** Significant at 1-percent level.

Formula (2) is in first difference given the results of DF-GLS unit-root test (Elliott, Rothenberg and Stock, 1996). Table 1 shows we cannot reject that oil production, oil prices and gold prices are unit-root processes for no trends.

For inference, we use Newey-West with 4 lags. The choice of 4 lags is based on the fact that the sample size is 214 from 1990 to 2007, and for direct comparison with HUP's results with 4 lags.

As mentioned above, we use gold prices variations as the instrumental variable[1] to settle potential two-way causality, that the oil production in Gulf area may affect oil prices too. Gold prices are correlated with oil price because they are both commodities and denominated in dollars[2]. The correlation between gold prices and oil prices can be seen in Figure 4. Sujit and Kumar (2011) use daily data from Jan 1998 to June 2011 showed that fluctuations in gold prices are largely dependent on gold itself rather than oil and other indices; but gold price fluctuation affects the WTI index. So we can take gold prices as exogenous to the oil market.

3.2 Fixed Effect Model

In this part we will only focus on oil production as the dependent variable. The fixed effect model has three main advantages comparing with the time-series model.

First, with panel data, we can control the heterogeneity of each lease. Because we are investigating oil production, it is reasonable that all the leases are different by their positions, the oil deposit underneath, the age of wells and so on. We can control the individual-specific, time-invariant effects of all the leases. Particularly, with panel data, we can test the conjecture that if a lease produces more gas, the lease owner will pay more attention on gas price variations, by the samples that produce oil and gas simultaneously.

Second, because of an inherent defect in our data that the production records are in lease-level, not well-level, when we look into oil production from existing wells, we

[1] Precisely speaking, we use Δlog(gold prices) as instruments for Δlog(oil prices).

[2] We first try US Dollar Index as the instrument variable, but it is too weak to identify oil price effects. Then we turn to gold prices which is in form of prices, instead of an index.

need to exclude samples of all the leases that drilled new wells in the targeted period. This method leads to selection bias that our estimates only account for production of leases which do not drill wells. The longer the targeted period is, the more leases will be excluded, and the severer the selection problem will be. So, there is a selection trade-off between time and leases. When relaxing the selection problem on leases by shortening targeted period, the sample size will shrink in time-series model. But this will not necessarily affect the sample size of panel model because for each month we will have more leases producing, thus more production observations.

Third, the data we have is unbalanced, because not all leases have oil production during all time. This means in the panel model, the price effects in each month are weighted by the number of productive leases in each month[1]. Therefore, the results should be more accurate comparing with the time-series model where the price effects are equally weighted in each month, no matter how many leases are producing.

There is one disadvantage with panel model as well, that the instrumental variable we use in time series models become too weak to identify price effects, because most of the independent variables in the model only vary across t, not across i. A consolation is that now we are discussing oil production from each lease, not from the whole Gulf area, so the possibility of two-way causality is rare[2]. And if several leases have market power, it should also be controlled by the fixed effect.

The fixed effect model is:

$$\begin{aligned}\Delta\log(\mathrm{Y}_{i,t}) = {} & \alpha + \beta_0\Delta\log(\mathrm{P}_{i,t}) + \beta_1\Delta\log(\mathrm{P}_{i,t-1}) + \theta_0\Delta\mathrm{R}_{i,t} + \theta_1\Delta\mathrm{R}_{i,t-1} \\ & + \gamma_0\Delta\log(\mathrm{G}_{i,t}) + \gamma_1\Delta\log(\mathrm{G}_{i,t-1}) + \mu\cdot\mathrm{S}_{i,t} + \delta_i + \pi_t + \varepsilon_{i,t} \quad (3)\end{aligned}$$

Most settings of the model follow from the time series model, including all the variables, except that $\mathrm{Y}_{i,t}$ now varies both across i and t. The fixed effect for lease i is added in the panel model. Because most of our independent variables only vary across t, we cannot control the fixed effect of each month, so we will roughly control the fixed effect

[1] Recall that from 1990 to 2007, except the leases which drilled new wells, the number of productive leases drop from 355 in Jan 1990, to 68 in Dec 2007, due to well completion.

[2] Unfortunately, our data do not show whether some leases have the same owner, to collect market power.

of time by each year.

With monthly data from 1990 to 2007, our data forms an unbalanced long panel. Considering possible problems with group-wise heteroskedasticity, autocorrelation within panel and cross-sectional correlation, we will report results of the fixed effect model by two estimation techniques: OLS with panel-corrected standard error[1], and FGLS assuming $\varepsilon_{i,t}$ is an AR(1) process by Prais-Winsten regression.

One important thing that needs to be carefully attended to is the 0s in production data. By our previous assumption and data cleaning process, the remaining 0s are all proactive shut-ins, representing any amount of production yields expected profit less than 0. Because we transform the production by logarithm function before regression, there cannot be any 0s. We adopted two methods to solve the problem. First, we just drop all the entries with 0 productions. The problem with this method is more selection bias that the results do not support situations right before or after shut-ins. Another method is to replace each 0 with a small enough number. The problem now is subjectivity in the choice of the small enough number. To best illustrate the results comprehensively, we will show results both with dropping 0s and replacing every 0 with 0.01, 0.1, 0.5.

Some may argue the numbers we choose are too large to interpret results as the meaning of percentage change by log functions. Note that we want to show whether the coefficients are 0s that oil production does not respond to oil prices. With larger numbers the estimates get closer to 0. So if we can prove the price effects exist with larger numbers, they should be more salient with smaller numbers. Besides, if the number gets too small, the estimates will be influenced too much by the choices just before or after shut-ins, which is not what we want.

Additionally, in the method we drop all 0 productions, we can make sure the remaining leases are not pure gas producers with no oil production, so we can test the conjecture that if an oil producer produces more gas, he will pay more attention on gas price variations. The model is:

[1] OLS with panel-corrected standard error will take into account group-wise heteroskedasticity and cross-sectional correlation.

$$\Delta\log(\mathrm{Y}_{i,t}) = \alpha + \beta_0\Delta\log(\mathrm{P}_{i,t}) + \beta_1\Delta\log(\mathrm{P}_{i,t-1}) + \delta_0\Delta\mathrm{R}_{i,t} + \delta_1\Delta\mathrm{R}_{i,t-1} + \gamma_0\Delta\log(\mathrm{G}_{i,t})\log(\mathrm{Q}_{i,t}) + \gamma_1\Delta\log(\mathrm{G}_{i,t-1})\log(\mathrm{Q}_{i,t-1}) + \mu\cdot\mathrm{S}_{i,t} + \delta_i + \pi_t + \varepsilon_{i,t} \quad (4)$$

$\mathrm{Q}_{i,t}$ the gas production from lease i on time t. The only difference between formula (3) and (4) is we put a weight function[1] on $\Delta\log(\mathrm{G}_{i,t})$. A key assumption here is log gas production is exogenous for a given lease. This is not far from reality because the log function really scales the fluctuation of gas production in a small interval for a short period[2].

At last, we relax the selection problem on leases by repeat the fixed effect OLS model from formula (3) for every two years from 1990 to 2007. Because now N is much larger than T, we will only report results by OLS, without using OLS with panel-corrected standard error or FGLS.

[1] Note that all gas productions are greater than or equal to 1 (we also drop 0 gas production entries), so there is no case $\log(\mathrm{Q}_{i,t})$ is negative so that gas prices will take a negative effect.

[2] Based on data from 1990 to 2007, mean of $\log(\mathrm{Q}_{i,t})$ is 7.24 with within standard deviation 1.03 for an average of 60.3 months.

4 Results

4.1 Time Series Model

Table 2 shows our main results of the time series model (formula (2)). Column (1) to (4) are price effects on average oil production from existing wells, (5) to (8) are on drilling activities for new wells. For a comprehensive comparison, column (1), (2), (5), (6) are similar to HUP's specification, without considering the impact of gas price variations, which column (3), (4), (7), (8) includes. In the even columns, oil prices are instrumented by gold prices.

Table 2: First-differenced regressions of oil production and drilling on oil prices

Variables	Δ log(production)				Δ log(drillings)			
	OLS	IV	OLS	IV	OLS	IV	OLS	IV
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Δ log(oil prices)	0.564*	2.036	0.602*	2.181	-0.320	1.968	-0.191	1.274
	(0.319)	(1.359)	(0.317)	(1.395)	(0.354)	(2.764)	(0.361)	(2.886)
Lagged Δ log(oil prices)	-0.329	-0.724	-0.362	-0.794*	0.659	0.012	0.507	0.084
	(0.309)	(0.448)	(0.287)	(0.468)	(0.431)	(0.834)	(0.415)	(0.882)
Δ (increase rate)	0.009*	0.029	0.010**	0.032	-0.004	0.027	-0.001	0.019
	(0.005)	(0.018)	(0.004)	(0.019)	(0.004)	(0.038)	(0.005)	(0.040)
Lagged Δ (increase rate)	-0.003	-0.004	-0.002	-0.004	0.008	0.005	0.007	0.006
	(0.003)	(0.004)	(0.003)	(0.004)	(0.005)	(0.007)	(0.006)	(0.006)
Δ log(gas prices)			0.072	0.107			0.318**	0.371**
			(0.121)	(0.120)			(0.127)	(0.152)
Lagged Δ log(gas prices)			0.065	0.122*			0.032	0.099
			(0.058)	(0.073)			(0.128)	(0.181)
Hurricane season	-0.037***	-0.046***	-0.037***	-0.046***	-0.034	-0.028	-0.042**	-0.041**
	(0.013)	(0.015)	(0.014)	(0.016)	(0.020)	(0.024)	(0.020)	(0.021)
Time trend	0.004*	0.007**	0.003	0.006				
	(0.002)	(0.004)	(0.003)	(0.004)				
Constant	-0.010	-0.021	-0.001	-0.006	0.008	0.020	0.019	0.030
	(0.023)	(0.039)	(0.023)	(0.038)	(0.024)	(0.057)	(0.025)	(0.041)
Observations	214	214	214	214	214	214	214	214
R^2	0.082	-0.132	0.091	-0.151	0.029	-0.156	0.062	-0.011

Note: All variables are monthly from 1990 to 2007, and defined in formula (2). Production is the average oil production from existing wells. Drilling is the number of new wells drilled. Increase rate is the expected increase rate of oil prices. All prices are in real $1982. For column (2), (4), (6), (8), oil prices are instrumented by gold prices. The fixed effects of each year are omitted in the table. All standard errors in parentheses are Newey-West with 4 lags. R^2 for 2SLS are centered R^2.

* Significant at 10-percent level.

** Significant at 5-percent level.

*** Significant at 1-percent level.

In column (1), we find that oil price changes have a significant influence on average oil production from existing wells, that a 10 percent change in current oil price variations will lead to a 5.6 percent change in oil production variations. When we add the omitted variable gas price in column (3), the oil price effect become slightly stronger. Meanwhile, the expected increase rate of oil prices has a statistically significant but economically weak influence on average oil productions. When the oil prices are instrumented by gold prices in column (2) and (4), the oil price effects become much larger. This result confirms the existence of two-way causality which offsets the oil price effects, and shows the real oil price effects might be much larger than expected, though the estimates are only significant at 15-percent level. One more thing to notice is that gas price variations also have a significant effect on the oil production in column (4). All the results confirm that the short-run oil or gas price effects on oil production and drilling activities are not negligible.

For the long-run oil price effects on average oil production, $\widehat{\beta_0} + \widehat{\beta_1}$ is 0.240 with a standard error of 0.196 in column (3), and 1.387 with a standard error of 1.020 in column (4). An interesting result is gas price variations probably also take effects on oil production in the long run. $\widehat{\gamma_0} + \widehat{\gamma_1}$ is 0.137 with a standard error of 0.124 in column (3), and 0.228 with a standard error of 0.142 in column (4). The gas price effects show the importance of adding gas prices as controlled variables.

For drilling activities for new wells, the estimates of short-run and long-run oil price effects are all non-significant, but the gas price effects are significant both in the short run and the long run. $\widehat{\gamma_0} + \widehat{\gamma_1}$ is 0.350 with a standard error of 0.158 in column (7), and 0.470 with a standard error of 0.266 in column (8). A possible explanation of this result is most of the new wells drilled in this period aim for gas production, instead of oil production[1].

In conclusion, for drilling activities, our results are consistent with HUP's

[1] We find that data from HUP can distinguish wells drilled for oil production or gas production or for both, so they select oil wells to research in the other paper (Kellogg, 2014). This may explain why the oil price effects are significant for drilling in HUP. But this leads to a new problem that wells for both oil and gas, or even wells for gas may also produce oil, thus could affect the oil market too and should not be ignored.

considering the new wells are mainly gas wells. For oil production, the short-run oil price effects are statistically significant, as HUP's, but are much larger. And the long-run oil price effects probably exists, which we will verify again in the next section with panel data.

4.2 Fixed Effect Model

Table 3 shows the results of fixed effect models (formula (3)) when we replace 0s in the oil production by a small number (0.01, 0.1, 0.5). Because we have a long panel, we take both OLS and FGLS Prais-Winsten regression for each constant.

Table 3: Fixed effect regressions of oil production on oil prices (replace 0s)

	Δ log(production)					
	C=0.01		C=0.1		C=0.5	
Variables	OLS (1)	FGLS (2)	OLS (3)	FGLS (4)	OLS (5)	FGLS (6)
Δ log(oil prices)	0.506* (0.306)	0.545* (0.298)	0.393* (0.208)	0.424** (0.204)	0.315* (0.164)	0.343** (0.158)
Lagged Δ log(oil prices)	-0.087 (0.300)	-0.109 (0.294)	-0.073 (0.206)	-0.103 (0.203)	-0.064 (0.163)	-0.106 (0.157)
Δ (increase rate)	0.005 (0.005)	0.006 (0.005)	0.004 (0.003)	0.005 (0.003)	0.004 (0.003)	0.005* (0.003)
Lagged Δ (increase rate)	0.000 (0.005)	0.000 (0.004)	0.001 (0.003)	0.000 (0.003)	0.001 (0.003)	0.000 (0.002)
Δ log(gas prices)	0.041 (0.102)	0.020 (0.099)	0.066 (0.073)	0.058 (0.071)	0.083 (0.059)	0.086 (0.056)
Lagged Δ log(gas prices)	0.187* (0.098)	0.205** (0.096)	0.123* (0.070)	0.128* (0.068)	0.078 (0.056)	0.072 (0.054)
Hurricane season	-0.035* (0.021)	-0.037* (0.018)	-0.020 (0.015)	-0.022* (0.013)	-0.009 (0.012)	-0.012 (0.010)
Constant	0.143 (0.152)	0.147 (0.124)	0.090 (0.117)	0.095 (0.095)	0.053 (0.094)	0.060 (0.074)
Observations	37,061	37,061	37,061	37,061	37,061	37,061
Time	214	214	214	214	214	214
Leases	397	397	397	397	397	397
R^2	0.004	0.006	0.004	0.006	0.004	0.005

Note: This table show results when we replace 0s in oil productions with a small number. Here the small numbers are 0.01, 0.1, 0.5. All variables are monthly from 1990 to 2007, and defined in the formula (3). Production is the average oil production from existing wells. Increase rate is the expected increase rate of oil prices. All prices are in real $1982. The fixed effects of each year or each lease are omitted in the table. OLS standard errors are panel-corrected standard error, considering group-wise heteroskedasticity and cross-sectional correlation. FGLS assumes $\varepsilon_{i,t}$ is an AR(1) process by Prais-Winsten regression.

* Significant at 10-percent level.

** Significant at 5-percent level.

In the fixed effect model, the estimated oil price effects are smaller than those in the time series models. A plausible explanation is with panel data, we can control the lease fixed effects of large oil producers, whereas in the time series models large producers have great influence when calculating the average oil production. So if large producers are more sensitive to oil price variations, the estimates from time series models will be larger. That said, we can see all the columns in table 3 confirms the existence of short-run oil price effects. This result is consistent with our findings in the time series model. The long-run oil price effects are only significant at 20-percent levels, but the long-run gas price effects are significant at 10-percent levels in all six columns. Note that $\widehat{\gamma_0} + \widehat{\gamma_1}$ are more significant than $\widehat{\beta_0} + \widehat{\beta_1}$ because for gas price effects, $\widehat{\gamma_0}$ and $\widehat{\gamma_1}$ are both positive; but for oil price effects, $\widehat{\beta_0}$ is positive while $\widehat{\beta_1}$ is negative[1]. This difference suggests for oil production, the long-run oil price effect is smaller than the short-run, but the long-run gas price effect is larger than the short-run.

Comparing the results in table 3 by different substitute constants, we find as the constant gets larger, the oil price effects gets stronger but less significant, while the gas price effects are stronger and more significant. This result suggests oil price effects and gas price effects may not be both precisely identified in a single model of ours. The real price effects are more close to the situation when the constant is small, but the real oil price effects are more close to the situation when the constant is large. Results of OLS and FGLS only have a small difference, so our results are robust.

The fixed effect model is also used to test the conjecture that if an oil producer produces more gas, he will pay more attention on gas price variations. Table 4 shows our result by data drop all the zero oil or gas production entries in a single month from 1990 to 2007. In column (1) and (2) we use evenly weighted gas prices as controlled variables. And in column (3) and (4) we use production-weighted gas prices as controlled variables, where the weight is calculated by $\Delta\log(\text{gas production}_{i,t})$ (as formula (4)). The results are also estimated by OLS and FGLS as in table 3.

[1] Estimated results of HUP have the same sign for oil price effects.

Table 4: Fixed effect regressions of oil production on oil prices (remove 0s)

Variables	Δ log(production)			
	Gas prices		Weighted gas prices	
	OLS	FGLS	OLS	FGLS
	(1)	(2)	(3)	(4)
Δ log(oil prices)	0.284	0.250	0.298	0.269
	(0.213)	(0.189)	(0.212)	(0.188)
Lagged Δ log(oil prices)	-0.141	-0.143	-0.145	-0.152
	(0.207)	(0.185)	(0.206)	(0.184)
Δ (increase rate)	0.003	0.003	0.003	0.003
	(0.003)	(0.003)	(0.003)	(0.003)
Lagged Δ (increase rate)	0.001	0.000	0.001	0.000
	(0.003)	(0.003)	(0.003)	(0.003)
Δ log(gas prices)	0.164^{**}	0.170^{***}		
	(0.066)	(0.061)		
Lagged Δ log(gas prices)	0.075	0.051		
	(0.063)	(0.058)		
Weighted Δ log(gas prices)			0.023^{**}	0.024^{***}
			(0.009)	(0.009)
Lagged Weighted Δ log(gas prices)			0.013	0.010
			(0.009)	(0.008)
Hurricane season	0.011	0.005	0.010	0.004
	(0.014)	(0.011)	(0.014)	(0.011)
Constant	-0.004	0.011	-0.004	0.011
	(0.043)	(0.034)	(0.043)	(0.034)
Observations	20,584	20,584	20,584	20,584
Time	214	214	214	214
Leases	397	397	397	397
R^2	0.011	0.014	0.011	0.014

Note: This table show results when we remove entries with 0s in oil or gas productions. All variables are monthly from 1990 to 2007. Column (1) and (2) are based on the formula (3). Column (3) and (4) are based on formula (4). Production is the average oil production from existing wells. Increase rate is the expected increase rate of oil prices. All prices are in real $1982. The fixed effects of each year or each lease are omitted in the table. OLS standard errors are panel-corrected standard error, considering group-wise heteroskedasticity and cross-sectional correlation. FGLS assumes $\varepsilon_{i,t}$ is an AR(1) process by Prais-Winsten regression.

* Significant at 10-percent level.

** Significant at 5-percent level.

*** Significant at 1-percent level.

After we drop all zero oil or gas production entries in a single month, the oil price effect become less significant, but the gas price effect is significant in all four columns. This might because the ratio of productive leases aiming for gas production increases. The result again confirms gas price effect on oil production is not negligible.

Because the estimates of gas price effects are equally significant between column (1) and (3), or column (2) and (4), we cannot directly reject the conjecture that oil producers think about gas price effects based on the amount of gas production. One explanation is the producers are a mixed group of the two kinds. Another possibility is there is a better weight function that will exceed both of ours.

4.3 Selection bias

Due to the inherent defect of our data that is not well-level, there is a selection-bias trade-off between time and number of leases when we calculate the average oil production from existing wells. All the average oil productions above are based on 399 productive leases that did not drilled new wells, whereas the total number of productive leases from 1990 to 2007 are 3548. In order to avoid the selection bias on oil production, Table 5 shows the OLS results[1] of formula (3) for every two years from 1990 to 2007, so that in each period, we can include more leases that did not drilled new wells.

Table 5: Fixed effect regressions of oil production on oil prices (every two years)

	Δ log(production)								
Variables	1990-91	1992-93	1994-95	1996-97	1998-99	2000-01	2002-03	2004-05	2006-07
Δ log(oil prices)	-0.940*** (0.230)	1.481*** (0.492)	-1.460*** (0.546)	0.128 (0.652)	0.209 (0.238)	-0.159 (0.237)	2.017*** (0.355)	2.388*** (0.267)	0.653*** (0.235)
Lagged Δ log(oil prices)	0.309* (0.182)	1.548*** (0.532)	1.979*** (0.492)	0.241 (0.621)	-0.320 (0.281)	0.825** (0.332)	-0.167 (0.216)	-1.021*** (0.174)	-0.102 (0.250)
Δ (increase rate)	-0.018*** (0.004)	0.031*** (0.010)	-0.030*** (0.008)	-0.001 (0.011)	0.003 (0.004)	-0.001 (0.003)	0.032*** (0.005)	0.110*** (0.005)	0.007 (0.005)
Lagged Δ (increase rate)	0.004 (0.003)	0.030*** (0.011)	0.033*** (0.008)	0.003 (0.008)	-0.003 (0.003)	0.015*** (0.004)	0.016*** (0.004)	-0.002 (0.005)	-0.004 (0.005)
Δ log(gas prices)	0.948*** (0.161)	0.014 (0.088)	0.504*** (0.119)	-0.103 (0.081)	0.385*** (0.126)	0.081 (0.082)	0.377*** (0.075)	-3.399*** (0.155)	-0.009 (0.103)
Lagged Δ log(gas prices)	-0.525*** (0.162)	-0.181* (0.105)	-0.297** (0.124)	-0.042 (0.074)	0.124 (0.105)	0.066 (0.072)	0.288*** (0.069)	0.492* (0.296)	-0.170* (0.092)
Hurricane season	-0.025 (0.021)	-0.025* (0.015)	0.008 (0.014)	-0.029* (0.015)	-0.015 (0.013)	-0.035** (0.015)	-0.024 (0.015)	-0.011 (0.024)	-0.052*** (0.016)
Constant	-0.020 (0.013)	-0.013 (0.012)	-0.047*** (0.013)	-0.019 (0.015)	-0.038*** (0.012)	-0.052*** (0.015)	-0.038*** (0.014)	-0.154*** (0.018)	0.074*** (0.013)
Observations	21,944	22,365	19,832	18,884	22,369	20,539	24,587	25,271	26,854
Time	22	22	22	22	22	22	22	22	22
Leases included	1082	1110	985	937	1114	1022	1224	1245	1324
All productive leases	1775	1780	1855	1944	1999	2067	2128	2128	2333
R^2	0.003	0.002	0.003	0.001	0.001	0.002	0.004	0.006	0.001

Note: This table show results when we replace 0s in oil productions with 0.25. All variables

[1] From above results we know the OLS coefficients are close to FGLS coefficients.

are monthly from 1990 to 2007, and defined in the formula (3). Production is the average oil production from existing wells. Increase rate is the expected increase rate of oil prices. Leases included is the number of productive leases without drilling activities in the period. All productive leases is the number of productive leases in the period. All prices are in real \$1982. The fixed effects of each year or each lease are omitted in the table. OLS standard errors in parentheses are cluster-robust.

* Significant at 10-percent level.

** Significant at 5-percent level.

*** Significant at 1-percent level.

Each period now contains around half of productive leases, but selection on time appears to be a problem. The estimated oil and gas price effects fluctuates drastically and significantly among all periods, and are usually quite different from results of table 3 and 4, though the ratio of productive leases are almost fixed. This result proves that the oil market is unstable in the short run, probably be strongly affected by non-price factors. It also gives us a warning shot that theoretical models describing oil producers' behavior only based on oil and gas prices might probably fail in the short run. It also shows that behaviors of producers that do not want to drill new wells (maybe because their fields are already well developed) might be largely different from other leases.

Meanwhile, results of table 5 confirms the existence of oil and gas price effect in the short run in almost all periods (except only in 1996-1997 there is no significant estimates for price effect), which contradicts HUP's assumption that oil production does not respond to oil prices.

5 Conclusion

As a comparative research on *Hotelling under pressure*, our paper differs from HUP mainly by the following aspects. First, we add an omitted variable to describe the variation of gas prices, which proves to be an important signal for oil producers too. Second, the data we use are from the Gulf of Mexico, and variables representing oil production and price variations are carefully calculated. Third, oil prices are instrumented by gold prices in the time series model to avoid potential two-way causality in the Gulf area. Fourth, we use a fixed effect model to examine the results in the time series models, and test the conjecture that if a lease produces more gas, the lease owner will pay more attention on gas price variations. Finally, selection bias on oil production from existing wells is relaxed by repetition of our main model for every two years from 1990 to 2007 with panel data.

Some of our conclusions are consistent with HUP's, by evidence from the Gulf of Mexico. Drilling activities prove to be sensitive to gas price variations (instead of oil price variations in HUP). The variations of expected increase rate of oil prices have economically weak influences on oil production.

Other conclusions are different from HUP's. Oil price variations prove to have a significant influence on variations of oil production in the short run. The coefficients for current oil price effects are estimated above 0.2 with all models by data from 1990 to 2007, much larger than 0.083 in HUP. The estimated long-run oil price effects are significant at 20-percent level.

Some of our conclusions are not touched on in HUP. By instrumental variable, we show there is indeed two-way causality of oil markets in the Gulf area. Gas prices (and possibly conditions on the gas market) is not negligible for study of oil markets, since gas price effects on oil production are significant both in the short run and in the long run. Oil producers probably value gas prices variations based on gas production of their leases. At last, unfortunately, oil and gas price effects for oil production estimated in a long period fail to describe to the oil market in the short run.

Future work should focus on three directions based on our paper. First, models account for both oil and gas markets should be considered. An exemplary model is Krichene (2005). Second, methods to weaken selection bias should be taken, no matter by econometric models or by more precise data. Third, more influence factors of oil market or oil producers' behavior could be included, for example a measurement for financial risks of the whole world in each period.

Reference

Anderson, S. T., Kellogg, R., and Salant, S. W. (2018). Hotelling under pressure. *Journal of Political Economy*, *126*(3), 984-1026.

Baumeister, C., & Peersman, G. (2013). The role of time-varying price elasticities in accounting for volatility changes in the crude oil market. *Journal of Applied Econometrics*, 28(7), 1087-1109.

Beck, N. L., and J. N. Katz. (1995). What to do (and not to do) with time-series cross-section data. *American Political Science Review*, 89: 634–647.

Elliott, G., Rothenberg, T. J., & Stock, J. H. (1996). Efficient Tests for an Autoregressive Unit Root. *Econometrica*, 64(4), 813-836.

Hamilton, J. D. (2009). Understanding crude oil prices. *The Energy Journal*, 30(2), 179-207.

Hendricks, K., and Porter, R. (2014). Auctioning resource rights. *Annual Review of Resource Economics*, 6(1), 175-190.

Hotelling, H. (1931). The economics of exhaustible resources. *Journal of Political Economy*, 39(2), 137-175.

Kellogg, R. (2014). The effect of uncertainty on investment: Evidence from Texas oil drilling. *American Economic Review*, 104(6), 1698-1734.

Kilian, L. (2009). Not all oil price shocks are alike: Disentangling demand and supply shocks in the crude oil market. *American Economic Review*, 99(3), 1053-69.

Krautkraemer, J. A. (1998). Nonrenewable resource scarcity. *Journal of Economic literature*, 36(4), 2065-2107.

Krichene, M. N. (2005). *A simultaneous equation model for world crude oil and natural gas markets* (No. 5-32). International Monetary Fund.

Newey, W. K., and West, K. D. (1987). A simple, positive semi-definite, heteroskedasticity and autocorrelation consistent covariance matrix. *Econometrica*, 55.3: 703-708.

Pindyck, R. S. (1978). The optimal exploration and production of nonrenewable resources. *Journal of Political Economy*, 86(5), 841-861.

Prais, S. J., & Winsten, C. B. (1954). *Trend estimators and serial correlation* (Vol. 383, pp. 1-26). Chicago: Cowles Commission discussion paper.

Salant, S. W. (1976). Exhaustible resources and industrial structure: A Nash-Cournot approach to the world oil market. *Journal of Political Economy*, 84(5), 1079-1093.

Slade, M. E., & Thille, H. (2009). Whither Hotelling: tests of the theory of exhaustible resources. *Annual Review of Resource Economics*, 1(1), 239-260.

Stiglitz, J. E. (1976). Monopoly and the rate of extraction of exhaustible resources. *The American Economic Review*, 66(4), 655-661.

Sujit, K. S., & Kumar, B. R. (2011). Study on dynamic relationship among gold price, oil price, exchange rate and stock market returns. *International journal of applied business and economic research*, 9(2), 145-165.