Internet Appendix to "Dynamics of Arbitrage"

Louis H. Ederington, Chitru S. Fernando, Kateryna V. Holland, Thomas K. Lee, and Scott C. Linn

A.1. Effect of Omitting Carrying Costs on OLS Estimates of Response of Inventories to Changes in Futures-Spot Spreads

Simplifying the model in equation (7) to a single period and ignoring the operational variables, ΔY, the basic theoretical cash-and-carry arbitrage model is:

(A1) $$\Delta ST = \beta\, (\Delta SP - \Delta SC) + e,$$

where ΔST is the change in oil stocks in storage, ΔSP is the change in the futures-spot spread, and ΔSC is the change in carrying costs, including storage costs and interest costs and net of any convenience yield. For reverse cash-and-carry, *SC* should be replaced by *SSC*, but the analysis is the same. ΔST, ΔSP, and ΔSC are measured as differences from their means to eliminate the intercept so that we can focus on β. To focus on β and simplify the presentation, we ignore other factors incorporated as ΔY in equation (7) of the text. The error term captures any residual random disturbances and is assumed to be independent of both ΔSP and ΔSC.

Suppose that the <u>estimated</u> relation excludes carrying costs, *SC* (again ignoring other contributing factors ΔY) becomes:

(A2) $$\Delta ST = \beta^* \Delta SP + v.$$

The OLS estimate of β^* is $b^* = \sum (\Delta ST^* \Delta SP) / \sum \Delta SP^2$. Substituting for ΔST, i.e., $\Delta ST = \beta\, (\Delta SP - \Delta SC) + e$ in the OLS formula for b^* yields:

(A3) $$b^* = \{\sum [\beta\, (\Delta SP - \Delta SC) + e]\, \Delta SP\} / \sum \Delta SP^2 = \{\sum[\beta \Delta SP^2 - \beta(\Delta SP \Delta SC) + e(\Delta SP)]\} / \sum \Delta SP^2$$

$$= \beta\{1 - [\sum(\Delta SP \Delta SC)/\sum \Delta SP^2]\} + [\sum e(\Delta SP)]/\sum \Delta SP^2 .$$

Under the assumption made above that e is independent of ΔSP,

(A4) $$\text{plim } b^* = \beta \{1-[\text{Cov}(\Delta SP, \Delta SC)/\text{Var}(\Delta SP)].$$

Hence, the bias in b^* depends on the sign of Cov(ΔSP, ΔSC). If carrying costs vary randomly so that Cov(ΔSP, ΔSC) = 0, then plim $b^* = \beta$.

If ΔSP and ΔSC are not independent, one would expect ΔSC to be positively correlated with ΔSP. If the futures-spot spread increases, there should be more buying and storing oil, and shorting futures, and as the demand for storage rises, so should storage costs and, consequently, carrying costs. If Cov(ΔSP, ΔSC)>0, then plim $b^* < \beta$.

In summary, if changes in storage costs net of the convenience yield are independent of changes in the futures-spot spread, then the OLS estimate of the coefficient β^* in equation (A2), which does not account for the change in storage costs, is an unbiased estimate of the coefficient β in the theoretical relation expressed in equation (A1). On the other hand, if changes in net storage costs, ΔSC, are positively correlated with changes in the raw futures-spot spread, ΔSP, as cash-and-carry arbitrage implies, then the OLS estimate of the coefficient β^* in equation (A2) is a downward-biased estimate of β in equation (A1) and, thus, is biased **against** finding evidence of cash-and-carry arbitrage.

A.2. Seasonality Variables

We construct seasonal variables, Z, to control for seasonal patterns in crude oil inventories. First, we define weekly dummy variables as follows: w_1=1 if the observation is the first week in January and 0 otherwise, w_2=1 if the observation is for the second week in January and 0 otherwise, and so forth through w_{52} = 1 the last week in December and 0 otherwise. An estimation with 52 separate dummy variables suffers from high multicollinearity since, if any one dummy variable equals one, all others must equal zero. As a result, the 52 individual coefficients have very high standard errors. Also interpreting 52 coefficients is difficult. To correct this problem, we impose a polynomial form. We then specify five dummy variables, z_k, where z_1 is a zero-degree polynomial of the w_i's, z_2 is a first-degree polynomial, z_3 is a second- degree polynomial, z_4 is a third-degree polynomial, and z_5 a fourth-degree polynomial. Specifically,

$z_1 = w_1 + w_2 + w_3 + \cdots + w_{52}$ (picked up by the intercept)

$$z_2 = w_1 + 2 \cdot w_2 + 3 \cdot w_3 + \cdots + 52 \cdot w_{52}$$

$$z_3 = w_1 + 2^2 \cdot w_2 + 3^2 \cdot w_3 + \cdots + 52^2 \cdot w_{52}$$

$$z_4 = w_1 + 2^3 \cdot w_2 + 3^3 \cdot w_3 + \cdots + 52^3 \cdot w_{52}$$

$$z_5 = w_1 + 2^4 \cdot w_2 + 3^4 \cdot w_3 + \cdots + 52^4 \cdot w_{52}$$

The seasonal inventory pattern over 52 weeks of the year implied by z variable coefficient estimates is graphed in Figure A.1 (a) for total U.S. stocks and in Figure A.1 (b) for Cushing. Crude oil inventory levels are graphed in red and presented on the left axis, while the changes are graphed in blue and presented on the right axis.

***** Insert Figures A.1 (a) and A.1 (b) about here*****

Figures A.1 (a) and A.1 (b) show similar seasonal patterns for crude oil inventories. Specifically, crude oil inventories tend to increase from the beginning of the year until about mid-May (week 20–22). Then a period of withdrawals follows, bringing inventory levels lower through the end of September or so (week 40–42). The seasonal build-up in crude inventories resumes from mid-October onwards with a brief withdrawal period around the holiday season at the end of December and the beginning of January. Note that while the year ending inventory level in Figure 1(a) (total U.S.) is approximately the same as the level at the beginning of the year, it is considerably higher in Figure 1(b) (Cushing). This is because Cushing inventories increased sharply over the data period while inventories in the rest of the United States did not change substantially.

A.3. Inventories and Operational Factors

Since Table 2 indicates that price spreads influence inventories mainly at Cushing, we examine here how other factors, mainly operating factors, influence inventories at Cushing and other storage districts. Results for all PADD districts (1, and 3–5) are presented in Table A.1. Results for Cushing and PADD2 (excluding Cushing) are replicated from Table 2 and presented in Table A.1 for comparison. While Table 3 in the paper presents evidence on the influence of spread on inventories in all PADD districts, the focus of Table A.1 is on the influence of operational factors on inventories. As such, future spread estimates are presented as a cumulative of the 10 past and contemporaneous spreads for brevity. Likewise for brevity, we present *F*-statistics for the seasonal *Z* variables as a group and not individual coefficients.

*****Insert Table A.1 about here*****

Inventory changes in most PADD districts are a negative function of recent changes in refinery inputs (which is what we would expect if the changes were partially unexpected) and a positive function of the change in refinery inputs over the coming week (which is what we expect if refinery demand is partially anticipated). Similarly, inventory changes are a positive function of recent changes in imports and a negative function of imports over the coming week. Also, changes in U.S. oil production influence inventories but only in PADD1 and PADD2 excluding Cushing. Overall, Table A.1 indicates that over the 2004–2015 period, inventories outside of Cushing responded strongly to operating factors but Cushing inventories did not. Interestingly, seasonal patterns are strongest for PADD3 (Gulf Coast) and weakest for PADD1 (East Coast).

A.4. Spread Index Creation

We form *Index_ΔSP* as a linear function of the 10 ΔSP variables where each is weighted by its coefficient from Model 1 in Table 2. Specifically, *Index* Δ*SP* = 380.21*Δ*SP*(fut-spot) + 222.19*

ΔSP(fut-spot)(-1) + 501.03* ΔSP(fut-spot)(-2) + …..+277.63* ΔSP(fut-fut)(-9). To confirm that the index was created correctly, we re-estimate Model 1 in Table 2 replacing the 10 contemporaneous and lagged spread variables with *Index* ΔSP and verify that its coefficient is 1.0 and the other coefficients are unchanged.

A.5. Arbitrage Effects on Prices in Particular Periods

One additional issue we consider is whether arbitrage was stabilizing or destabilizing in particular periods, such as during the sharp run-up in oil prices in 2007–2008 or during the financial crisis. Accordingly, we take a closer look at weeks when C&C arbitrage did not tend to stabilize prices. Table A.2 presents the number of weeks each year where estimated arbitrage inventories tended to increase (thus reducing supply) when oil prices were relatively high and the number of weeks where inventories tended to decrease when prices were relatively low. We use equation (8) to identify relatively high or low prices with spot prices j=2 weeks before and after date t.

*****Insert Table A.2 about here*****

No consistent seasonal patterns are documented for periods when C&C arbitrage did not tend to stabilize prices. Weeks with destabilizing additions to arbitrage inventories are somewhat higher than average in 2005, 2006, 2008, 2012, and 2015. However, the null that destabilizing additions do not differ by year cannot be rejected at the 10% level using chi-square tests. Weeks with destabilizing withdrawals are somewhat higher in 2007, 2010, 2011, 2013, and 2017 but again the null that these do not differ by year cannot be rejected at the 10% level. In summary, we find no significant evidence that cash-and-carry arbitrage tended to be destabilizing in any particular periods. The cases where arbitrage leads to oil coming off the market when prices are relatively high and on the market when prices are relatively low are spread over our data period, not concentrated in any particular subperiod.

A.6. Results of Robustness Checks

We check the robustness of our results by exploring several alternative regression specifications. First, it is important to confirm that our results are not driven by the large increases in crude oil storage capacity at Cushing, Oklahoma that occurred over our data period (see Figure A.2). Accordingly, we re-estimate the Cushing regression in Table 2 measuring storage changes in percentage changes, as opposed to barrel changes. For consistency, we use percentage changes for refinery inputs, imports, and production as well. Second, we control for crude oil flows between PADDs. Since we find that the major inter-PADD flows are between PADD2 (Midwest) and PADD3 (Gulf Coast), which confirms what we've learned from EIA personnel, we add the lagged changes in PADD3 stocks and PADD3 imports as controls expecting positive coefficients for both.

Finally, we control for possible persistent changes to crude oil inventories caused by forces not captured by our regression specification. In 2012 inventories at Cushing rose as oil flowed in from the Bakken shale field and other fields newly equipped for fracking production but could not leave, as the available pipelines were configured to flow from the Gulf to Cushing and not the reverse. This problem was largely resolved as flows were reversed on the Seaway pipeline in May 2012 and new pipelines were completed. Dating this phenomenon is difficult because there were no sharp time demarcations, but in a rough attempt to control for the impact of this transport bottleneck, we include a zero-one dummy for 2012 observations.[1] Finally, to improve efficiency and impose some structure on spread coefficients, we re-estimate our main regressions expressing

[1] In unreported results, we repeat our analysis by limiting our sample to periods immediately before and after the 2012 pipeline constraints (as in Gilje and Taillard (2017)) and verify that the relationship between storage and spreads remains significant in both periods.

the spread lags in a polynomial distributed lag (PDL) model where the lagged spreads follow a fourth degree polynomial. Models 1–4 in Table A.3 present results using percentage changes, controlling for PADD3 flows, including the 2012 dummy, and using the PDL structure respectively.

*****Insert Table A.3 about here*****

Our results remain: inventories at Cushing are a function of current and past spreads. The Model 1 results indicate that over a 10-week period an increase in the spread of $1 results in an increase in storage levels at Cushing of over 10%. Model 2 shows that both PADD3 imports and stocks have the expected sign but the change in imports is only significant at the 10% level and the change in stocks is insignificant.[2] Model 3 confirms the relationship between inventories and spreads after controlling for Bakken-related crude inventory inflows. Model 4 shows that imposing the structure with the PDL spread does not change our main results.

Several other robustness checks are available upon request but our main results remain unchanged. Specifically, we: (1) estimate the models with winsorized variables to control for outliers, (2) add lagged changes in operational variables to reduce the influence of asynchronous reporting, (3) estimate the regressions with monthly seasonal dummies in contrast to the weekly dummy variable measures, (4) add year dummies, (5) estimate our model(s) with Intercontinental Exchange (ICE) WTI European futures prices, and (6) estimate our model(s) without forward-looking variables or future data in the independent variable set. Our results are robust to these specification changes.

[2] Since the changes in PADD3 stocks and imports are correlated, we also estimated regressions with them individually. The results are unchanged. The change in PADD3 stocks is insignificant and the change in PADD3 imports is significant at the 10% level but not at the 5% level.

Since our main independent variables are time-matched spot-futures and futures-futures spreads, not time series returns, our results are not subject to the contract expiration issues related to the "roll yield" discussed in Bessembinder (2018) and Bessembinder, Carrion, Tuttle, and Venkataraman (2016). However, it is possible that close to expiration the prices of the nearby contract are impacted by traders closing position before expiration. To ensure that our results are not impacted by such trading, we identify all dates in our sample that fall on contract expiration dates or any three days preceding contract expiration. Removal of these observations does not impact the results.

References

Bessembinder, H. “The 'Roll Yield' Myth.” *Financial Analysts Journal*, 74 (2018), 41-53.

Bessembinder, H.; A. Carrion; L. Tuttle; and K. Venkataraman. “Liquidity, Resiliency and Market Quality around Predictable Trades: Theory and Evidence,” *Journal of Financial Economics,* 121 (2016), 142–166.

Gilje, E.P., and J.P. Taillard. “Does Hedging Affect Firm Value? Evidence from a Natural Experiment.” *Review of Financial Studies,* 12 (2017), 4083–4132.

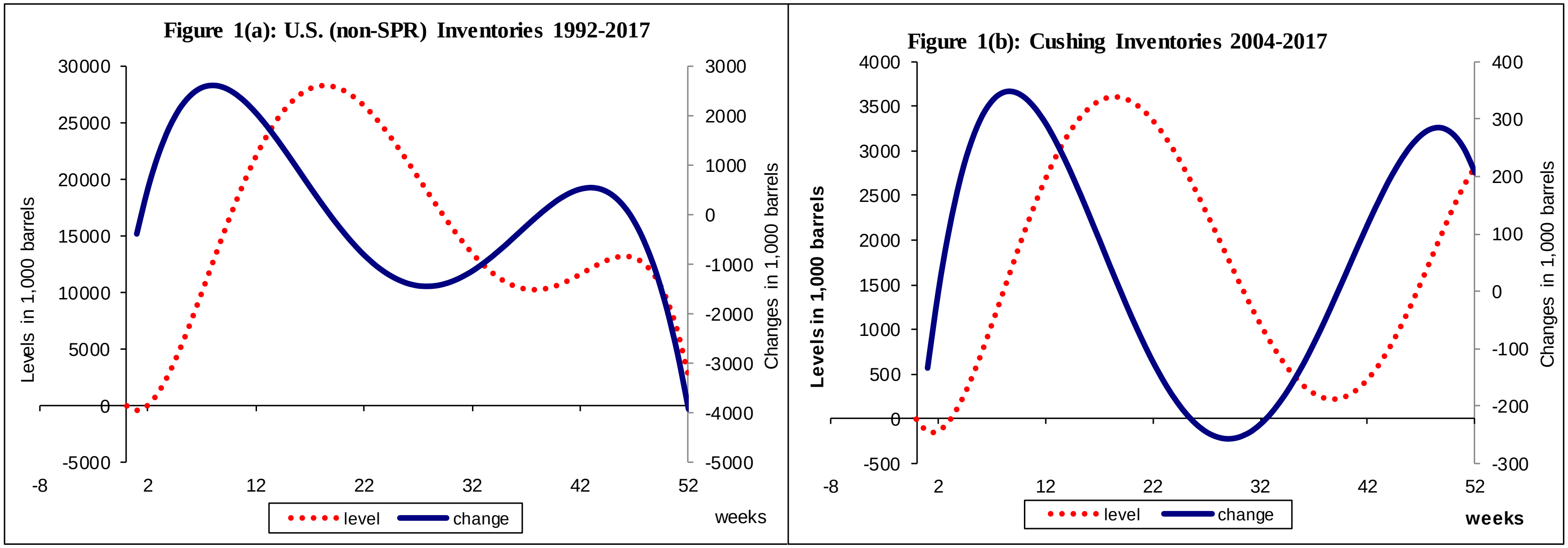

Figure A.1. Seasonal Patterns in Crude Oil Inventory Levels and Changes
This figure presents estimated seasonal patterns in crude oil inventories as implied by the weekly polynomial form estimation described in the text. Both inventory levels and changes are presented. Figure 1(a) plots the U.S. (non-SPR) inventories over the 1992–2017 period; Figure 1(b) plots Cushing, Oklahoma inventories over the 2004–2017 period.

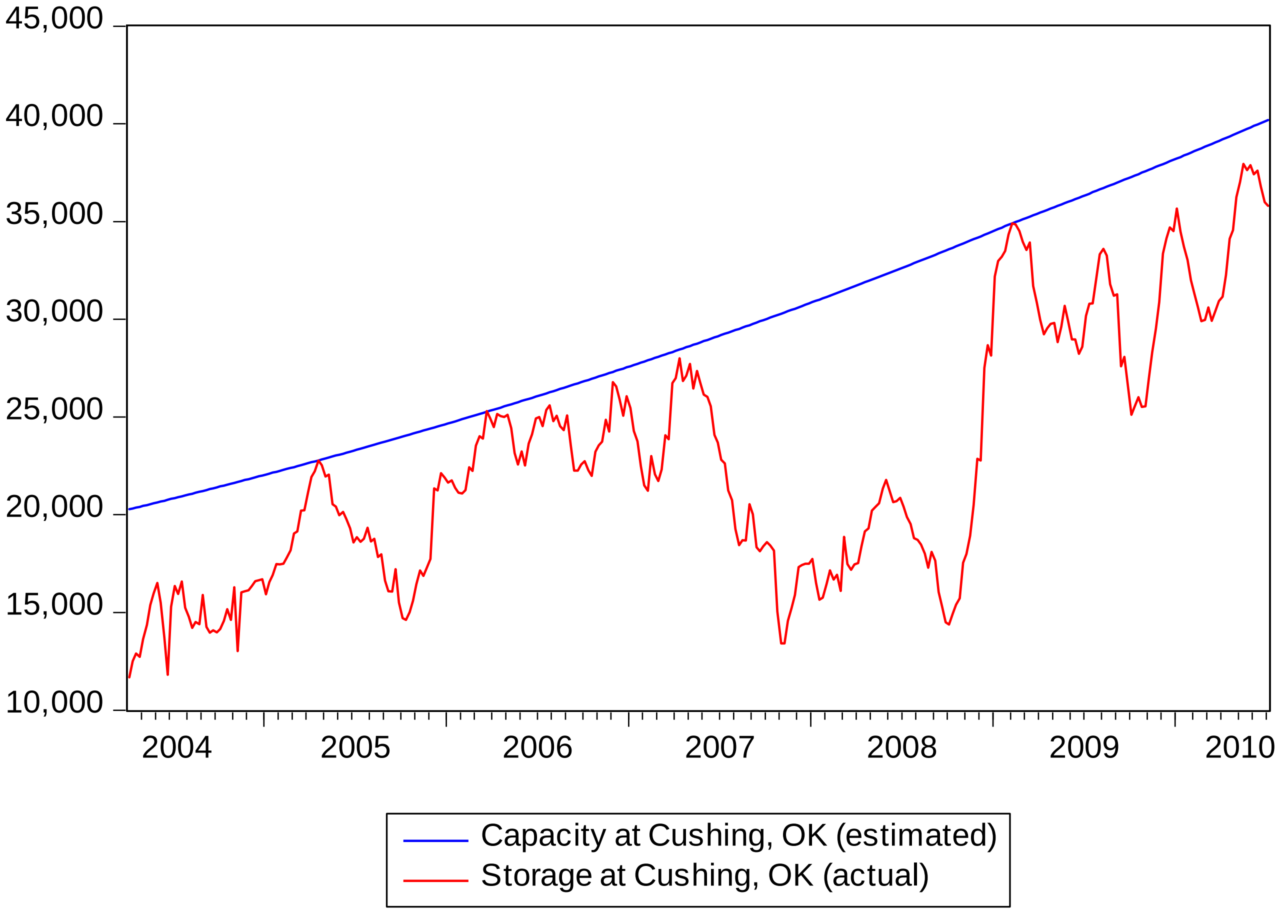

Figure A.2. Estimated Storage Capacity at Cushing (April 2004–October 2010)

This figure presents the actual weekly crude oil storage and estimated effective crude oil capacity from April 2004 to October 2010 at Cushing, Oklahoma, which is the NYMEX physical settlement point for the crude oil WTI futures contract. Crude oil storage data is collected from the U.S. Energy Information Administration (EIA). The estimated capacity proxy is described in Section VI.B. After October 2010 actual EIA capacity numbers are made publicly available and are used in analysis after October 2010.

Table A.1. Inventories and Operational Factors for PADD1-5 and Cushing, Oklahoma

Weekly changes in crude oil storage for PADD1-5 and Cushing are regressed on the current and five lagged values of the futures-spot spread and the futures-futures spread lagged from six to nine weeks as in Table 2, but individual coefficients are suppressed and only shown cumulatively. PADD2 (no Cushing) and Cushing results are replicated from Table 2 for convenience. Current week changes in refinery inputs, imports, and U.S production are included to proxy for the impact of unforeseen changes in crude oil supply and demand and one-week lead values of these variables to proxy for inventory changes to meet expected future changes in supply and demand. The refinery input and import figures are PADD specific. The seasonal *Z* variables are included but not shown individually; instead the *F*-stat for test of the null that all four *Z* variable coefficients equal zero is reported. The *p*-values shown in parentheses are based on Newey-West standard errors. ***, **, and * designate coefficients significantly different from zero at the 0.01, 0.05, and 0.10 levels, respectively, in two-tailed tests. The regressions are estimated using weekly data from 4/9/2004 to 12/29/2017 and there are 717 observations.

	PADD 1	PADD2 (no Cushing)	Cushing	PADD3	PADD4	PADD5
10 spreads cumulative	274.77	-105.64	3,618.03***	-409.58	-76.44	540.47
	(0.36)	(0.817)	(0.000)	(0.767)	(0.629)	(0.309)
ΔRefinery input	0.002	-0.032***	-0.007	-0.036***	-0.042***	-0.038***
	(0.881)	(0.003)	(0.388)	(0.000)	(0)	(0.008)
ΔRefinery input(+1)	0.018*	0.012	0.013	0.045***	0.022*	0.021
	(0.095)	(0.261)	(0.13)	(0.000)	(0.075)	(0.146)
ΔImports	0.022***	0.02***	0.006	0.04***	0.01*	0.028***
	(0.000)	(0.000)	(0.234)	(0.000)	(0.058)	(0.000)
ΔImports(+1)	-0.012***	-0.006	0.000	-0.039***	0.001	-0.012**
	(0.001)	(0.322)	(0.99)	(0.000)	(0.89)	(0.019)
ΔUS production	0.007	0.007	0.005	0.038*	0.002*	0.011
	(0.308)	(0.351)	(0.244)	(0.065)	(0.076)	(0.194)
ΔUS production(+1)	0.005	0.014***	-0.007**	-0.01	0.006***	-0.008
	(0.314)	(0.009)	(0.031)	(0.563)	(0.001)	(0.217)
ΔSpot Price	7.589	-15.88	9.85	-25.45	-1.78	-8.68
	(0.992)	(0.202)	(0.443)	(0.403)	(0.665)	(0.595)
F-stat for seasonal variables (*Z*)	1.926	3.657***	3.796***	22.895***	5.745***	14.198***
	(0.103)	(0.006)	(0.004)	(0.000)	(0.000)	(0.000)
Intercept	139.56	-209.8	-295.22	557.79	-100.77	-826.82***
	(0.339)	(0.315)	(0.26)	(0.39)	(0.199)	(0.000)
Adjusted R^2	0.178	0.052	0.156	0.388	0.060	0.150

Table A.2. Cash-and-Carry Arbitrage-Related Inventory Changes when Not Price Stabilizing

The table presents a sum of the number of weeks each year when forecasted cash-and-carry arbitrage-related inventory changes at Cushing, Oklahoma would not have been price stabilizing. Column A presents weeks when oil was forecasted to go into storage during the period of relatively high prices. Column B presents weeks when oil was forecasted to come out of storage during the period of relatively low prices. The relative price level during the week of the forecasted storage changes as compared to j=2 weeks surrounding it (before and after). The data is weekly from 4/9/2004 to 12/29/2017.

	Weeks with high relative prices and forecasted storage additions	Weeks with low relative prices and forecasted storage withdrawals
2004	13	6
2005	14	9
2006	17	8
2007	7	15
2008	14	10
2009	10	11
2010	10	14
2011	11	16
2012	16	12
2013	8	14
2014	11	11
2015	16	7
2016	13	13
2017	4	21
Total	164	167

Table A.3. Robustness Checks

We present results for variations of Table 2 regressions. In Model 1 the dependent variable is the percentage change in Cushing stocks; the refinery inputs, imports, and production variables are also changed to percentage change terms. In Model 2, the lagged change in PADD3 stocks and inputs is added. In Model 3, a dummy variable to denote observations in 2012 is added to the Cushing regression. In Model 4, spread changes are presented in a polynomial distributed lag (PDL) format. Regressions are estimated with weekly data from 4/9/2004 to 12/29/2017.

	Percentage change		PADD3 changes		2012 dummy		Cushing with PDL	
	Coeff.	*p*-val.	Coeff.	*p*-val.	Coeff.	*p*-val.	Coeff.	*p*-val.
ΔSP(fut-spot)	0.015***	0.000	378.335***	0.000	380.093***	0.000	329.624***	0.000
ΔSP(fut-spot)(-1)	0.009**	0.023	227.287**	0.04	220.539**	0.049	384.923***	0.000
ΔSP(fut-spot)(-2)	0.018***	0.000	516.06***	0.000	498.46***	0.000	412.077***	0.000
ΔSP(fut-spot)(-3)	0.016***	0.000	476.274***	0.000	472.672***	0.000	414.536***	0.000
ΔSP(fut-spot)(-4)	0.01***	0.000	334.435***	0.000	327.783***	0.000	395.752***	0.000
ΔSP(fut-spot)(-5)	0.01***	0.001	309.016***	0.000	308.262***	0.000	359.177***	0.000
ΔSP(fut-fut)(-6)	0.013***	0.006	479.204***	0.001	486.162***	0.001	308.26***	0.000
ΔSP(fut-fut)(-7)	0.005	0.236	170.81	0.209	163.782	0.237	246.454***	0.000
ΔSP(fut-fut)(-8)	0.013**	0.02	475.314***	0.001	456.469***	0.001	177.211***	0.002
ΔSP(fut-fut)(-9)	0.009*	0.079	278.911**	0.037	272.863**	0.041	103.98*	0.069
ΔPDL_1							395.752***	0.000
ΔPDL_2							-28.255	0.224
ΔPDL_3							-8.896**	0.022
ΔPDL_4							0.575	0.624
ΔRefinery input	-0.008	0.311	-0.007	0.37	-0.007	0.404	-0.006	0.461
ΔRefinery input(+1)	0.006	0.446	0.012	0.133	0.013	0.121	0.008	0.35
ΔImports	0.003	0.159	0.005	0.306	0.006	0.244	0.005	0.269
ΔImports(+1)	0.000	0.987	0.000	0.992	0.000	0.975	-0.001	0.86
ΔUS production	0.019**	0.013	0.004	0.288	0.004	0.301	0.003	0.524
ΔUS production(+1)	-0.01	0.127	-0.007**	0.038	-0.008**	0.023	-0.006*	0.094
ΔPADD3 stocks(-1)			0.003**	0.045				
ΔPADD3 imports(-1)			0.000	0.824				
2012 dummy					335.257**	0.026		
Z2	0.608***	0.003	175.65**	0.01	174.435***	0.009	173.538**	0.011
Z3	-0.05***	0.002	-15.062***	0.004	-14.962***	0.004	-15.073***	0.005
Z4	0.001***	0.004	0.418***	0.006	0.415***	0.005	0.422***	0.006
Z5 (x.01)	-0.001***	0.009	-0.365**	0.01	-0.361***	0.01	-0.371***	0.01
ΔSpot price	0.07	0.157	11.579	0.365	10.222	0.419	11.373	0.422
Intercept	-1.211	0.132	-292.412	0.271	-314.457	0.237	-275.787	0.3
Cumulative -all spreads	0.119***	0.000	3,646***	0.000	3,587***	0.000		0.000
Cum. - 6 futures - spot	0.079***	0.000	2,241***	0.000	2,208***	0.000		
Cum. - 4 futures - futures	0.004***	0.001	1,404***	0.000	1,379***	0.001		
Adjusted R^2	0.126		0.157		0.162		0.142	