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# Information, Price Levels and Price Volatility of Oil, Natural Gas, and Petroleum Product Futures Price [†]


Investigators: Scott C. Linn*, Louis H. Ederington*, Chitru S. Fernando*, Scott B. Guernsey**, Thomas K. Lee***

*Price College of Business
University of Oklahoma
307 West Brooks, Norman, OK 73019 USA

** Cambridge Endowment for Research in Finance (CERF)
Cambridge Judge Business School
Trumpington Street
Cambridge CB2 1AG, UK

*** Office of Energy Markets and Financial Analysis
U.S. Energy Information Administration
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585 USA


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## Executive Summary

This paper investigates how unexpected information about factors related to supply and demand fundamentals influences both the level of crude oil, natural gas, gasoline and distillate (heating oil) futures prices and the volatility of those prices. The report reviews the empirical evidence on how announcements about inventories (including changes in the amount of oil held in the Strategic Petroleum Reserve), macroeconomic variables, and monetary policy influence short-term changes and volatility in the price levels for crude oil, natural gas, gasoline, and distillate futures. Our focus is on how prices respond to information that was unexpected. In addition to our review of the evidence, the study presents empirical results regarding the speed of adjustment of prices to the release of information and the general relations between futures price changes and unexpected information for the four announcement categories. The reviews and empirical analyses focus largely on information released by departments or agencies of the U.S. government and futures prices for contracts traded in the United States. The empirical analyses utilize intraday price observations and daily price observations for the period from May 1999 through June 2017. The time periods examined vary based upon the availability of data related to the specific announcements.

1. **A review of the literature that has examined the relation between announcements of unexpected information in the categories we address and energy price changes indicates the following:**
    a. The front month futures prices of crude oil, gasoline, distillate and natural gas respond inversely to unexpected news about changes in inventories of these commodities as

revealed in the Weekly Petroleum Status Report and the Weekly Natural Gas Storage Report issued by the U.S. Energy Information Administration and that cross-product effects are also observed. The response is immediate. Volatility spikes at the time inventory reports are released but then reverts, and is increasing in the absolute value of the surprise.

b. The release of the majority of reports announcing levels and changes in macroeconomic variables (excluding announcements about monetary policy), generally have little impact on energy futures prices at the time of the announcement. However, these prices do respond to unexpected news about a select number of economic variables, including U.S. Employees on Nonfarm Payrolls Month-to-Month Change. Further, when the response is measured at the daily frequency there is virtually no statistically significant relation identified between price responses and unexpected (surprises) about the macroeconomic factors. There is some evidence that unexpected macroeconomic news may move prices at the time of the announcement in environments characterized by monetary policy uncertainty, but whether those same announcements impact prices at the daily frequency is unknown.

c. There is evidence that futures prices respond inversely to market-based surprises about the target federal funds rate at the time press releases are issued following meetings of the Federal Reserve Open Market Committee. These results are consistent with the hypothesis that there are numerous channels through which changes in monetary policy could influence oil prices. However, there is no evidence that the impact of target surprises impacts price changes at the daily frequency, and that the intraday response is driven by press releases following special meetings.

d. Since the inception of the Strategic Petroleum Reserve there have been times at which crude oil was being added to the Reserve and times at which crude was being extracted. The frequency of these events has not been large. With that caveat in mind, the extant evidence suggests that announcements of increases or decreases in oil to be stored has no impact on crude oil futures prices. The number of studies which have directly investigated this relation are however very limited.

**2. The empirical analysis presented in this report largely confirms the results identified in the extant literature but also provides new perspectives on the intraday versus daily price responses to unexpected news, and especially on the relation between announcements regarding changes in the SPR and energy futures price changes.**

a. The report presents evidence that oil, natural gas, gasoline, and distillate futures prices respond inversely not only to information about unexpected changes in the product's own inventory, but that there are cross-product effects as well. Specifically, on the day the WPSR is issued (reporting inventory levels for oil, gasoline, and distillate) by the EIA (typically Wednesday), oil, gasoline, and distillate futures prices respond to both the respective unexpected news about changes in inventory for the commodity itself but also to unexpected news about changes in the inventories of the other two commodities. Likewise, the WNGSR (reporting storage levels for natural gas) is typically released by the EIA on Thursdays, and we find that, on Thursdays, oil and distillate futures prices respond inversely to unexpected news about changes in natural gas in storage. Finally, natural gas futures prices respond inversely on Wednesdays to unexpected news about changes in the inventories of oil, gasoline, and distillate.

b. The report finds that the advent of 24-hour electronic trading influenced the reaction of oil, natural gas, gasoline, and distillate futures prices to unexpected information about changes in inventories. Specifically, the response of oil, gasoline, and distillate futures prices became smaller following the advent of electronic trading; interestingly, the opposite is found for natural gas futures prices.

c. Results are presented indicating that the volatility of the futures prices examined around the time of the EIA weekly releases is positively related to the absolute size of the unexpected change in inventories. The response of volatility of gasoline and natural gas prices to the absolute size of the surprise was smaller when the sign of the raw surprise was negative.

d. The response of energy futures prices to unexpected information (measured as the difference between the actual reported value of the variable and a measure of what was expected) is examined for four macroeconomic variables: nonfarm payrolls, retail sales, consumer confidence and a measure of industrial productivity. There is a positive and significant relation between the futures price changes for the commodities we study around the time of day that the data are released and surprises about the variables. However, no relation is found when price changes are measured over the day of the announcement, as well as periods extending out to 20 days after the announcement.

e. Press releases of the Federal Open Market Committee (FOMC) following meetings may reveal changes in monetary policy. The report presents evidence on the relation between changes in the energy futures studied around the time of day the press releases are issued and a market-based measure of surprise changes in the target federal funds rate. The results indicate that in general there is an immediate and inverse response but only for press releases following conference calls of the FOMC. When assessed over the full day on which the announcement is released no statistically significant relation is found.

f. Infusions into and extractions from the Strategic Petroleum Reserve have occurred since its inception, but are not frequent events. Evidence is presented on the futures prices responses of crude oil, gasoline, distillate and natural gas to announcements of planned increases and decreases in crude stored in the SPR. Price changes are measured at the daily frequency. The results indicate that increases in the SPR are associated with positive and statistically significant increases in crude oil prices, and marginally significant increases in gasoline and distillate futures prices, on the day the announcement is released, but have no impact on natural gas futures prices. Conversely, an annonced decrease in the SPR is associated with a decrease in crude oil prices. There is no relation between such announcements and changes in natural gas futures prices.

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## 1. Introduction

This study presents a review of literature focused on the immediate responses of futures prices for oil, gasoline, distillate, and natural gas to the release of unexpected fundamental information and presents and discusses empirical results based upon a sample period that extends extant studies. [1] To the degree that unexpected information causes a shift in market participants' beliefs, and that such futures contracts are viewed as assets, unexpected information may manifest itself in an immediate shift in market prices. We do not explore the long-term consequences of such information. Here we briefly describe the classes of information events that are the focus of this study.

The first class of events we examine includes the impact of unexpected information about changes in the amounts of crude oil, gasoline, distillate, and natural gas in storage in the United States.[2] We explore the response of both price levels and price volatility to news about unexpected changes in inventories. The U.S. Energy Information Administration (EIA) collects and releases information about the amounts of oil, gasoline, distillate, and natural gas in storage in the United States on a weekly basis. Market participants follow these data closely because they provide insight into the current and expected supply and demand for these commodities. Therefore, unexpected

[1] "Beginning with the May 1, 2013 contract, the New York Mercantile Exchange (Nymex) switched its specification for the heating oil futures contract to the ultra-low sulfur diesel specification (ULSD)," (EIA, https://www.eia.gov/todayinenergy/detail.php?id=11211). For convenience we will refer to this product as distillate.

[2] The inventory variables that form the basis for our investigation are the following, as these are the basis for the analyst forecasts reported by Bloomberg: Weekly U.S. Ending Stocks excluding SPR of Crude Oil (Thousand Barrels) [oil], Weekly U.S. Ending Stocks of Total Gasoline (Thousand Barrels) [gasoline], Weekly U.S. Ending Stocks of Distillate Fuel Oil (Thousand Barrels) [distillate], and Weekly Gas in Underground Storage, Total Lower 48 States (Billion Cubic Feet) [natural gas]. Beginning with the May 1, 2013 contract NYMEX transitioned what was previously referred to as the 'Heating Oil' futures contract to ULSD (Ultra Low Sulfur Diesel) a lower sulfur content distillate. For brevity we refer to the inventory involved before and after this shift as 'distillate'. Please refer to: https://www.eia.gov/todayinenergy/detail.php?id=11211.

changes (surprises) will potentially affect both the level and the volatility of futures prices. These information releases occur on a weekly basis.

The second class of events also occur on a regular basis and involve the release of reports pertaining to macroeconomic aggregates. These reports generally are also issued by U.S. government agencies and provide fundamental information about changes in macroeconomic activity. As energy plays an important role in general economic activity, unexpected news about such activity may result in price shifts if the information influences beliefs and expectations. However, as Kilian and Vega (2011) suggest, if prices are largely predetermined, then the impact of such surprises should not be noticeable.

A third class of events, which also occur on a regular basis, are statements released by the U.S. Federal Open Market Committee (FOMC). Press releases issued by the committee potentially reveal information about U.S. monetary policy. As Rosa (2014) and others describe, monetary policy changes may influence energy prices through several possible channels, including exchange rates, inventory carrying costs, supply (drilling and production), demand (through economic growth), and, of recent interest, potentially through a portfolio rebalancing channel if Federal Reserve actions displace private investors in the market, causing them to seek investments in commodities. Unexpected information therefore has the potential to influence energy prices.

The Office of Petroleum Reserves (OPR) of the U.S. Department of Energy (DOE) manages the Strategic Petroleum Reserve (SPR). As indicated by the DOE, “The mission of the OPR is to protect the United States economy from severe petroleum supply interruptions through the acquisition, storage, distribution and management of emergency petroleum stocks and to carry out U.S. obligations under the International Energy Program." The federal government has from time to time announced additions to and withdrawals from the SPR. Unlike changes in inventory held by private parties, these changes are driven by government choice, sometimes in response to a catastrophic event. An important difference between these announcements and those already described is that SPR announcements do not occur on a regular basis. The utility of the SPR and its ability to provide a cushion is a source of debate that recently has received increased attention (Scheitrum et al., 2017; Difiglio, 2014; Patron and Goldwyn, 2013). We do not explore the merits of the SPR program; rather, our focus is on the empirical matter of how market prices are influenced by the decision to change the amount of oil in the reserve.

We begin with a review of previous studies that examine the information events described above and the response of energy futures prices to those events. Next, we present evidence regarding the price responses for the types of events detailed and indicate whether they appear to be transitory or permanent.

Prices play a crucial role in the optimal allocation of resources. The mechanism by which fundamental information is reflected in prices is commonly referred to as the price discovery process (Hasbrouck, 1995). Economic theory argues that futures markets play an important price discovery role and help make markets informationally complete by acting as a conduit for information about underlying fundamental values (Working, 1962; Black, 1976; Grossman, 1977). Speaking of futures markets in general, Black (1976) voiced the opinion, held by many, that among the roles played by futures markets, price discovery—the identification of the information efficient price—may actually be paramount.[3]

The front-month futures contracts for oil, natural gas and refined petroleum products such as gasoline and distillate are among the most liquid of futures contracts traded in the United States.[4] In informationally and operationally efficient liquid securities markets, the arrival of new *unexpected* material information will move the price of the associated security, if that information is related to fundamental valuation (see, among others, Samuelson, 1965; Fama, 1965, 1970; Lo, 2007).

## 2. Evidence Regarding Energy Futures Price Responses to Unexpected Information

### 2.1. Price Response to Unexpected Changes in Inventory

Shifts in expectations about fundamentals related to supply and demand conditions may result in commodity price responses (Kilian and Lee, 2014; Kilian and Murphy, 2014; Gorton et al., 2013; Pirrong, 2012). Inventory at a date *t* equals inventory at *t*-1 plus production less sales of the commodity and any physical loss due to the storage technology. Market participants hold expectations about the change in inventory, so any unexpected change in inventory reveals information about both supply and demand conditions that was not previously available. The EIA releases two reports each week on U.S. inventory conditions for crude oil, gasoline, and distillates (the Weekly Petroleum Status Report highlights, generally released at 10:30 AM ET on Wednesdays) and natural gas (the Weekly Natural Gas Storage Report, generally released at 10:30

[3] In principle, futures and spot prices for commodities conform to a no-arbitrage relation (McDonald, 2013; Ederington et al., 2017). Jarrow and Larsson (2012) have shown that the absence of arbitrage also implies informational market efficiency.

[4] CME Group, http://www.cmegroup.com/education/files/cme-group-leading-products-2017-q1.pdf

AM ET on Thursdays).[5] Studies of the response of energy futures prices to the release of unexpected inventory information have focused on both changes in the level of futures prices and changes in price volatility.

Studies of price response to unexpected changes in inventory typically proceed in the following manner. The first step is to select the energy commodity and the frequency of observation of the futures price series. The majority of recent studies focus on either daily or intraday futures price data. Futures prices are generally used, because spot price data are at best available at the daily frequency and are collected using survey methods, not from an exchange. Futures prices are market-determined and, especially for the front month, the contract is highly liquid. It is common to use the front-month contract prices, although in some cases, longer dated futures are also examined, with the caveat that liquidity falls rapidly as contract maturity lengthens. The data are generally for contracts traded in the United States, typically on NYMEX.

The second step involves computation of surprises in changes in inventories for the energy commodity being examined (crude oil, gasoline, distillate, or natural gas). Because the aim of most studies is to assess how market futures prices change in response to the release of unexpected information a measure of unanticipated information is required. This requires a measure of the expected change. The usual approach is to utilize a consensus survey measure of the expected change in inventory, typically the median forecast from a sample of analyst forecasts, for the commodity being examined. The most common source for the forecast data is Bloomberg, but

[5] A discussion of these reports is deferred until section 3.2.

forecasts obtained from Reuters have also been employed.[6] Unexpected (surprise) information is typically measured following a common approach involving the calculation, $S_{i,t} = \frac{A_{i,t} - E_{i,t}}{\hat{\sigma}_i}$, where $A_{i,t}$ equals the actual value of the measured variable *i* at time *t* and, in this specific case, the change in inventory, $E_{i,t}$ equals the consensus expectation about the change and $\hat{\sigma}_i$ equals the sample standard deviation of the quantity $A_{i,t} - E_{i,t}$.[7] Date *t* represents the calendar day on which information is released (for example, the day the EIA releases the Weekly Petroleum Status Report). The following model is typically estimated as

$$r_{i,t} = \alpha_i + \beta_i S_{i,t} + \varepsilon_{i,t} \tag{1}$$

where $r_{i,t}$ is the log price change for the commodity *i* over a time interval on or around the day *t* on which the information is released and $S_{i,t}$ is the standardized surprise for day *t*, in this case, the standardized unexpected change in inventory for commodity *i*. The time interval over which the log price change is measured could be a day (for example, the close-to-close period) or an intraday interval (for example, the 10:20 AM ET to 10:40 AM ET period) or a multi-day period. The model is cross-sectional; *t* is used here simply to note the date of the information release. The null hypothesis is that the coefficient $\beta_i$ is equal to 0. Studies that examine the impact on price volatility have substituted the absolute value of the log price change for the level change in equation (1) and the absolute value of the standardized surprise for the signed surprise.

[6] For the period February 2003 through the end of 2016, the average number of analysts contributing oil inventory forecasts was 13, while for natural gas the number was 22.

[7] Units of measurement may differ, so to facilitate comparisons, many authors standardize the forecast error by the standard deviation of the error computed across the announcements in the sample (following Balduzzi et al., 2001, and Andersen et al., 2003). The level of inventory has also been used to standardize the forecast error (Halova et al., 2014).

Studies have also been conducted that are based upon time series formulations of log price changes over a calendar sample time period. Models based on daily data as well as intraday data have been examined. The models are often specified as generalized autoregressive conditional heteroscedastic (GARCH) processes. A general representation for the daily model is

$$\begin{aligned} r_t &= \alpha + \beta f\left(S_t\right) + \varepsilon_t \\ \varepsilon_t &= \upsilon_t \sqrt{h_t} \\ h_t &= \gamma_0 + \sum_{q=1}^{Q} \gamma_{1q} \varepsilon_{t-q}^2 + \sum_{s=1}^{S} \gamma_{2s} h_{t-1} \end{aligned} \tag{2}$$

Equation (2) suppresses the *i* subscript for the commodity. The left-hand variable in the mean equation is the daily log price change, and the error is assumed to follow a GARCH process modeled through $h_t$ with $\upsilon \sim N(0,1)$.[8] The equation for returns may also include lags to account for autocorrelation and may include additional explanatory variables.

Recent studies examining the futures price responses of energy commodities to information surprises find an inverse relation between the surprise measure and the change in the log price. The evidence also generally shows that volatility is higher around the time that reports are released. We begin with a discussion of results regarding the effect that crude oil inventory surprises have on energy futures prices.

Chang et al. (2009) study oil inventory surprises and the intraday response of crude oil futures prices. Forecasts are gathered from Bloomberg, and reported inventory is obtained from the EIA's Weekly Petroleum Status Report, which is released (highlights) at 10:30 AM ET, typically on Wednesdays. The period studied extends from June 2003 through March 2005, 96 weeks. The

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[8] Bollerslev (1986, 2009) at http://econ.duke.edu/~boller/Papers/glossary_arch.pdf.

authors compute log price changes in the front-month contract over the period 10:25 AM ET to 10:45 AM ET on the dates the report is released. In contrast to most other studies, the authors measure the forecast error as the forecast of the change in inventory minus the actual change in inventory. The authors estimate equation (1) and find a positive and significant relation. If the surprise had been measured as described above (actual minus expected), the sign of the estimated coefficient would have been negative, as is the case in other studies described below. The authors also show graphically that the cumulative average of the absolute price changes, averaged across all inventory announcements spikes, is flat in the 10 minutes prior to the report release at 10:30 AM ET, spikes at 10:30 AM, and then is relatively flat from that point on. Visual inspection of the graphs suggests that prices on average moved up again at around 11:00 AM ET, but the authors present no formal test of whether the cumulative average return was flat following the announcement. Nonetheless, the result suggests an almost immediate response. The authors estimate several extensions of equation (1) and establish that oil futures prices, in addition to responding significantly to unexpected changes in crude oil inventory, also respond significantly to unexpected changes in gasoline and distillate inventories. The authors also show that the relations strengthen when there is evidence that analyst accuracy is high. In sum, the implied relation between log price changes and unexpected changes in inventory is negative and statistically significant, and the response to the news release is very fast.[9]

Rosa (2013), in a broader study of the impact of macroeconomic news releases on intraday and daily crude oil futures price changes, examines the price responses of crude oil futures prices over the period from 10 minutes prior to the inventory report release through 50 minutes after. The

[9] Here, we are inverting the result reported in the paper because the authors measure unexpected changes as the expected change minus the actual change.

author studies the period January 1999 to June 2011. Surprises are computed as described earlier, and forecasts are from Bloomberg. The author reports that crude oil price responses are negatively and statistically significantly related to unexpected changes in crude oil inventory, gasoline inventory, and distillate inventory, similar to the results reported by Chang et al. (2009).

Elder et al. (2013) study the crude oil futures price response over the 5-minute period immediately following the crude oil inventory announcement. They study front-month prices for the West Texas Intermediate (WTI) crude oil futures contract over the period January 2005 through December 2010. The authors utilize the same standardized surprise measure described earlier $S_{i,t} = \frac{A_{i,t} - E_{i,t}}{\hat{\sigma}_i}$. Bloomberg is the data source. The approach they take in the investigation, however, is different from the approaches followed by Chang et al. (2009) and Rosa (2013). . Elder et al. begin by statistically identifying the time and frequency of jumps in the log price and relate the observed jumps to the timing of the Weekly Petroleum Status Report, among other announcements.[10] The authors find evidence that jumps in WTI futures prices are associated with the release of unexpected inventory news and that an inverse relation exists between the log price change and the unexpected change in inventory. Further, in tests to determine whether prices respond asymmetrically to positive versus negative surprises, the results appear to indicate no asymmetry, but no formal test is presented.

Bjursell et al. (2015) approach the problem in a manner similar to that of Elder et al. (2013), but they include in their study futures prices for crude oil as well as distillate and natural gas, unlike

[10] The statistical methods for jump estimation and testing are those developed by Barndorff-Nielsen and Shepherd (2004b, 2006).

Elder et al. (2013), who focus only on crude oil prices. The authors study the period from January 1, 1990 through December 31, 2007 for crude oil and distillate, and through January 31, 2008 for natural gas, and they work with 5-minute intraday time intervals. Bloomberg is the source for the inventory forecast data. The authors estimate and test for jump components present in each time series using the same methods employed by Elder et al. (2013).[11] The authors find that large jump components in the series are associated with the dates on which the EIA reports are released. They also find that volatility and trading volume tend to be larger on days with jumps occurring at the time of the inventory announcement. They do find that spikes in volatility (measured as the absolute value of the log price change) on days on which a report is released, that are also identified with a jump at 10:30 AM ET, revert quickly to preannouncement levels. In summary, the results presented by Elder et al. (2013) and Bjursell et al. (2015) confirm that intraday jumps in prices are associated generally with the release of inventory reports.

Halova et al. (2014) present evidence that oil, gasoline, distillate, and natural gas futures prices respond inversely to unexpected changes in inventories. The authors study log price changes for the front-month contract during the interval from 5 minutes prior to the report release time through 10 minutes afterwards, over the period July 16, 2003 through June 27, 2012. Unexpected changes in inventories, surprises, are assessed using forecasts obtained from Bloomberg. First, the authors show that the price impacts of positive or negative surprises tend to be immediate do not revert within the 100 minutes following the announcements. The authors point out that the inventory data reported in the Weekly Petroleum Status Report are based upon a survey instrument and are

[11] Refer to fn. 11.

estimates.[12] Halova et al. estimate the model in equation (1) using standard ordinary least squares (OLS) methods, but they also estimate an alternative formulation that imbeds the view that the inventory change observed equals the true inventory change plus a measurement error. This method was first advocated by Rigobon and Sack (2008). Halova et al. find that the intraday futures prices of each commodity—crude oil, gasoline, distillate and natural gas—respond significantly and negatively not only to unexpected changes in its own inventory but also to unexpected changes in the other commodities' inventories. In general, the coefficients estimated by OLS for the relation between price changes and unexpected inventory changes are smaller in absolute value than those estimated by the alternative method. The overall results survive several conditioning tests, but the price responses of crude oil, distillate, and gasoline to unexpected changes in natural gas inventories are weaker during the withdrawal season (November through March) and when there is more dispersion in analysts' forecasts (measured as the standard deviation of analysts' forecasts).

Bu (2014) examines daily log price changes for the front-month WTI futures contract for the period May 1, 2006 to October 31, 2011. The author estimates the surprise in the change in inventory $S_{i,t}$ using a consensus forecast obtained from Reuters. The author fits a time series GARCH (1,1) model to the data in which the mean equation (log price change) is specified as a function of the surprise, finding a negative and significant relation between price responses and inventory surprises. However, the author finds no evidence that the inventory surprise is statistically significant as an explanatory factor in the variance equation.

[12] The data are assembled using a survey instrument. According to the EIA, "Companies are selected into the EIA weekly sample according to a procedure that assures coverage of 90 percent of each information element" (EIA, 2017). Details about the survey form and which companies must submit are available at https://www.eia.gov/surAvey/form/eia_803/instructions.pdf.

Ye and Karali (2016) examine the reaction of intraday crude oil futures prices to unexpected information about changes in oil inventories for the period August 26, 2012 through December 30, 2013, finding an inverse relation with log price changes and a positive impact on volatility. The authors obtain forecasts of inventory changes from Reuters. They examine both unexpected information revealed by both the EIA reports and reports issued by API (American Petroleum Institute). The authors point out the important distinction that the EIA requires participation (by law), whereas the API is a voluntary survey.[13] The EIA releases the Weekly Petroleum Status Report (highlights) at 10:30 AM ET generally on Wednesdays, and the API releases the Weekly Statistical Bulletin at 4:30 PM ET on Tuesdays. Although the numbers reported by each organization are highly correlated, some differences occur. One question the authors ask in the analysis is whether the EIA report contains more information than the API report. They therefore compute two different surprise variables. The first measures the unexpected change in inventory based on the change reported by the API and the change forecast obtained from Reuters. The second measures the change implied by the EIA's Weekly Petroleum Status Report but uses the change reported by the API as the expectation. The authors estimate a time series model of 5-minute log futures price changes and include both measures of the unexpected change in the model. The model is structured as a GARCH process and controls for potential intraday patterns in volatility. The authors find a negative and statistically significant relation between the 5-minute log futures price change at the time of an announcement and both measures of surprises. However, the authors associate both shocks with the Wednesday log price change between 10:30 and 10:35 AM ET, despite the fact that the API report is released on Tuesdays.

[13] See footnote 13.

Miao et al. (2017) study the daily returns on oil futures as well as options on futures for a menu of futures and options maturities. The authors measure oil inventory surprises in the fashion described earlier (standardized surprises $S_{i,t} = \frac{A_{i,t} - E_{i,t}}{\hat{\sigma}_i}$) where expectations data are from Bloomberg and are median forecasts. The authors find as with the studies mentioned above that prices move down when inventory surprises are positive and move up when inventory surprises are negative on the day the actual inventory data are released. They find no evidence that the response to positive surprises is different in absolute magnitude as compared with the response to negative surprises (no asymmetric effect). Near-the-money option prices are more sensitive to surprises and responses tend to decline as maturity increases. The authors also present evidence suggesting that there is some price movement prior to the information release that is in the direction observed on the day of the release and that there is some persistence in the movement of option prices but not in futures prices following the information release.

Linn and Zhu (2004), Gay et al. (2008), and Chiou-Wei et al. (2013) focus exclusively on the responses of natural gas futures prices to unexpected changes in natural gas in storage. As already described, Halova et al. (2014) also examine natural gas prices as do Bjursell et al. (2015).

Linn and Zhu (2004) identify an increase in the volatility of intraday natural gas futures returns at the time that the Weekly Natural Gas Storage Report is released. The authors study the period January 1, 1999 through October 31, 2002, focusing on 5-minute log futures price changes throughout the day. Two different reports are examined: the weekly report of the American Gas Association, which was published through May 3, 2002, and the EIA's Weekly Natural Gas Storage Report, which commenced May 9, 2002. The authors document significant increases in price change standard deviations at the times when the weekly reports are released, regardless of whether the originator was the AGA or the EIA. The authors also show that, although volatility spikes at the time of the announcement, it returns to a normal level within 30 to 40 minutes.

Gay et al. (2009) study the period April 16, 1997 through August 25, 2005. The authors construct unexpected changes in natural gas inventories using reports issued weekly by the American Gas Association prior to May 9, 2002 and by the EIA thereafter. The authors study the 15-minute intraday log price changes of the nearby natural gas futures contract traded on NYMEX. Forecasts of natural gas inventories are obtained from Bloomberg, but the authors also conduct tests using a variety of statistically based models for forecasting inventory change. The authors find that futures price responses are inversely related to surprises. The authors control for seasonal effects (injection and withdrawal seasons) and continue to find that price responses are inversely related to surprises. With a model using surprises computed from the Bloomberg forecasts, the authors conclude for a model using surprises computed from the Bloomberg forecasts that a positive 1% storage surprise resulted in roughly a 1.3% drop in the natural gas futures price.

Chiou-Wei et al. (2014) focus not on volatility but on the daily price response to unexpected changes in the amount of natural gas in storage. The authors examine both log futures price changes for the front-month contract and spot prices obtained from Platts. Forecasts are obtained from Bloomberg. The authors document an inverse relation between the daily change in natural gas futures prices and the unexpected change in natural gas inventory.  The response is fully impounded into futures prices on the day of the EIA announcement. Interestingly, the spot price reacts on the following day. This occurs because the spot market for gas “nominations" takes place in the morning, so the spot price transactions surveyed by Platts happen largely before the Natural Gas Storage Report is released.[14]

In sum, the evidence indicates that positive surprises about changes in inventories are associated with negative responses by futures prices, and that negative surprises are associated with positive price changes. These results hold across crude oil, gasoline, distillate, and natural gas. Furthermore, the change in the level of prices does not revert but the accompanying increase in volatility dies out relatively quickly.

### 2.2. Price Response to Unexpected Macroeconomic News

As Kilian and Vega (2011) have argued, the question of whether and to what extent macroeconomic news affects energy prices is of economic significance in terms of our understanding of the link between energy prices and real activity and also helps establish how such prices are determined. Studies examining the relation between unexpected macroeconomic news and energy prices have focused on daily as well as intraday price changes, but have also examined multiday time horizons following the information releases.

Kilian and Vega (2011) examine the relation between energy (WTI spot oil and retail gasoline) prices and macroeconomic news using daily spot oil prices for the period 1983-2008 and a wide range of announcements on macroeconomic variables. Their study, like others mentioned below, focuses on what is usually referred to as unexpected information, commonly measured as the

[14] Mu (2007) studies the dynamic behavior of daily natural gas futures prices for the front-month contract and the second nearest maturing contract. He studies the time period January 2, 1997 through December 29, 2000. During this time period, the weekly report on natural gas in storage in the United States was compiled and released by the American Gas Association. The author's primary focus is the impact of weather changes, but he accounts for storage surprises in the time series model he estimates and finds that log price changes are inversely related to storage surprises.

difference between an actual statistic (for example, nonfarm employment) and a consensus forecast. The supermajority of the macroeconomic aggregate measures studied are released on a predictable schedule by departments of the U.S. government. The authors examine announcements of 30 different macroeconomic variables Among the set is the U.S. nonfarm payroll report (Employment Report), which has been shown in the literature focusing of stock and bond price reactions to be a dominant factor; Andersen and Bollerslev (1998) label the Employment Report the "king of kings" of macroeconomic news (pg. 240). Kilian and Vega also study how price changes are related to monetary policy changes; we defer discussion of this until the following section. Unexpected information (surprises) are measured following a common approach in the literature that involves the calculation $S_{k,t} = \frac{A_{k,t} - E_{k,t}}{\hat{\sigma}_k}$, where $A_{k,t}$ equals the actual value of the measured variable *k* at time *t*, $E_{k,t}$ equals the consensus expectation, and $\hat{\sigma}_k$ equals the sample standard deviation of the quantity $A_{k,t} - E_{k,t}$. Kilian and Vega (2011) study announcements for a total of $K$ =30 different economic variables to determine whether the unexpected information revealed in the macroeconomic announcements (measured as $S_{k,t}$) influences changes in daily oil and gasoline log prices. The basic statistical model is essentially the same as equation (1) with the exception that the surprise measure is for an economic magnitude which we index *k* to differentiate it from the inventory change surprise which was indexed *i*. The model is

$$r_{i,t} = \alpha_i + \beta_{i,k} S_{k,t} + \varepsilon_{i,t} \qquad (3)$$

where the dependent variable is the close-to-close log price change from day *t*-1 to *t* for commodity *i* (*t* in this case represents the day of the relevant announcement *k*). The coefficient $\beta_{i,k}$ measures the return response to a one standard deviation news shock. Estimation is therefore cross-sectional. The authors find no evidence that the price of WTI crude oil and the U.S. retail price of gasoline respond significantly to any of the U.S. macroeconomic news announcements they study. Kilian and Vega (2011) also estimate a joint model including all announcements and the period up to 20 days following an announcement, finding that the results do not reject the null hypothesis that there is no relation. The authors conclude that the results support the view that energy prices are predetermined.

Similar results are reported by Roache and Rossi (2010) in a study spanning the period January 2001 to June 2006. The authors focus on daily price changes of futures contracts for a menu of commodities including crude oil, distillate, and natural gas. They measure news surprises as Kilian and Vega (2011) do using $S_{k,t} = \frac{A_{k,t} - E_{k,t}}{\hat{\sigma}_k}$, as described above. The authors' primary model includes all dates in the sample period and includes surprises for each of the $K = 13$ macroeconomic releases examined. The authors include the contemporaneous surprise, as in Kilian and Vega (2011), as well as up to two lags of the surprise and up to two lags of the change in the price. The authors also account for generalized autoregressive conditional heteroscedasticity (Bollerslev, 1986) of the error variance.[15] Specifically, the model in general form is:

$$\begin{aligned} r_t &= \alpha + \sum_{k=1}^{K} \sum_{n=0}^{N} \beta_{k,n} S_{k,t-n} + \sum_{l=1}^{L} \lambda_l \Delta r_{t-l} + \varepsilon_t \\ \varepsilon_t &= \upsilon_t \sqrt{h_t} \\ h_t &= \gamma_0 + \sum_{q=1}^{Q} \gamma_{1q} \varepsilon_{t-q}^2 + \sum_{s=1}^{S} \gamma_{2s} h_{t-1} \end{aligned} \tag{4}$$

It should be noted that this is a time-series model, where $r_t$ is the log price change on any day $t$ and the $i$ subscript for the commodity has been suppressed. There is only weak evidence that

[15] A GARCH(1,1) model. Sadorsky (2006) has found that the GARCH(1,1) model fits oil price data well.

unexpected macroeconomic news affects crude oil, distillate, or natural gas futures prices. However, during one subperiod spanning January 2002 through December 2009, the authors document a positive response of these prices to the surprise in the change in the nonfarm payroll report, although the result is significant at the 5% level only for distillate. The authors explain why they highlight this subperiod: "This period was chosen as its start date corresponds to the beginning of the sustained and broad rise in commodity prices that continued until peaking in July 2008." (p. 381). They find no evidence of asymmetries in response based on the sign of the surprise. Summing up, the authors state: "Our results suggest that commodities have been relatively insensitive to market-wide shocks in the form of macroeconomic news over daily frequencies between 1997 and 2009" (p. 384), which is largely consistent with the results reported by Kilian and Vega (2011).

Chatrath el al. (2012) examine the relation between log futures price changes for WTI oil and surprises measured likewise as $S_{k,t} = \frac{A_{k,t} - E_{k,t}}{\hat{\sigma}_k}$ (see above). The authors examine daily price data for the period January 1990 through December 2009. They also examine intraday price change behavior for the period January 2005 through December 2009. The authors first estimate the same basic statistical model as equation (1) and find no relation between surprises and price changes in their study of daily data, consistent with the results reported by Kilian and Vega (2011). They propose a framework for identifying whether the price response indicates that these commodities constitute an asset that is priced by supply and demand for stocks, in contrast to being priced based upon the flow of supply and demand for the commodity as a good. They estimate a model that accounts for a potential asymmetry of response by dividing surprises into two groups by their sign (positive or negative) and conditioning on the convenience yield prevailing at the time of the announcement. The extended model is

$$r_t = \alpha + \sum_{k=1}^{3} \beta_k^- d_{t-1}^y S_{k,t}^- + \sum_{k=1}^{3} \beta_k^+ d_{t-1}^y S_{k,t}^+ + \varepsilon_t \quad (5)$$

where the superscript '–' indicates that the surprise was negative and '+' that the surprise was positive and the return is the log futures price change for crude oil. The authors estimate the convenience yield on day *t* using the nearby contract price, the spot price, and the one-month LIBOR rate.[16] The $d_t^y$ are dummy variables obtained by dividing the sample into three equal parts (terciles) based on the estimated convenience yields.[17] The results provide little evidence of a relation between surprises and price changes. The authors conclude: "On a broader front, we are unable to reject the null that crude prices are determined by flow demand and flow supply."

Chatrath el al. (2012) investigate whether log price changes in short windows around the announcement time are related to surprises. They find that surprise changes in nonfarm payrolls, retail sales, and a measure of consumer confidence are positively and significantly related to 5-minute, 10-minute and 30-minute returns, unlike the returns based upon daily data, for which no relation is found. Nevertheless, the authors conclude that, overall, the results are more consistent with the view that oil is a flow-driven commodity.

Elder et al. (2013) study a set of macroeconomic news announcements similar to those studied by Kilian and Vega (2011) and Chatrath el al. (2012), but they focus on the 5-minute period immediately following the announcement. They study front-month prices for the WTI crude oil futures contract over the time period January 2005 through December 2010. The authors utilize

[16] The daily spot price data are obtained from the EIA website.

[17] It is unclear whether the terciles are based on the estimated daily convenience yields for every day during the sample period. The authors also estimate an alternative model in which the dummy variables are based on a standardized measure of inventory stocks.

the same standardized surprise measure described above, $S_{k,t} = \frac{A_{k,t} - E_{k,t}}{\hat{\sigma}_k}$. The approach they take in the investigation, however, is different from that of the studies mentioned above. The authors begin by statistically identifying when jumps in the log price series occur and determining their frequency; they then relate the jumps observed in the data to the timing of the macroeconomic reports and the size of the unexpected change. The authors find evidence that jumps in WTI futures prices are associated with the release of unexpected macroeconomic news in the 5-minute period following the news release. In particular, they find that more than 70% of the jumps in oil prices during the 5-minute interval ending at 8:35 AM ET are preceded by a relatively small number of economic news releases. The nonfarm employment report is found to be an important factor, similar to the results reported by Chatrath el al. (2012).

As part of a larger study on the relation between crude oil futures price changes and unexpected changes in monetary policy, Rosa (2013) examines intraday returns spanning the period from 10 minutes before an announcement through 50 minutes following. Part of the study reports results associated with the estimation of equation (1), where surprises are measured as described above. The period studied spans January 1999 to June 2011. Rosa finds evidence of a statistically significant (at the 5% level) relation between intraday price changes and surprises associated with industrial production and nonfarm payrolls (employment), and a weak relation with a measure of consumer confidence. However, for models based upon daily data, the author finds no statistically significant relations. The results are consistent with those of Kilian and Vega (2011) and Chatrath el al. (2012).

Chan and Gray (2017) extend the framework of investigation by estimating models based on daily log price changes for WTI crude oil, Brent crude oil, distillate, New York Harbor unleaded gasoline, gasoil, and natural gas. The period studied is from January 2, 1992 through June 30, 2014. The authors relate the price change data to four macroeconomic aggregates. In contrast to prior studies, the authors define relevant surprises as those that exceed a given threshold, arguing that only "large" surprises are relevant. They estimate time series models that incorporate both conditional autoregressive heteroscedasticity (specifically the GARCH model developed by Bollerslev, 1986) and jumps that may reflect either symmetric or asymmetric responses to positive and negative surprises. The model specifies the mean jump size as a function of a dummy variable that takes the value 1 on announcement days and 0 otherwise. The results provide little support for the existence of a link between jump size in these markets and the announcements studied. The authors conclude that, "Taken together, there is little evidence of a statistically significant change in the probability of observing a jump on scheduled announcement days" (Chan and Gray, 2017, p. 84.). The results, which are based upon daily price change data, are consistent with the results based upon daily data reported by Kilian and Vega (2011) and Chatrath et al. (2012).

Overall, the evidence generally shows no relation between the surprises emphasized in the studies described in this section and changes in daily log prices, but some evidence indicates very short term (intraday) price reaction. This suggests that whatever reaction is observed may at best be transitory.

Kurov and Stan (2016) examine the intraday response of crude oil futures prices to unexpected macroeconomic news accounting for monetary policy uncertainty.[18] The authors measure the response of crude oil futures prices over a 10-minute period from 5 minutes before to 5 minutes

[18] The authors also examine the futures prices for the E-mini S&P 500, 10-year Treasury note, and the U.S. Dollar Index. The working paper can be accessed at https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2776357.

after each macroeconomic news release examined. The period studied begins January 26, 2012, when the FOMC began reporting members' individual assessments, and ends April, 30, 2014. The authors argue that uncertainty decreased after January 26, 2012, but increased following testimony by Federal Reserve Chairman Ben Bernanke on May 22, 2013 before the Joint Economic Committee of the U.S. Congress, when he indicated that the Federal Reserve might begin to taper down the size of the bond buying program that was under way. The authors compute surprises following the convention already discussed, $S_{k,t} = \frac{A_{k,t} - E_{k,t}}{\hat{\sigma}_k}$.[19] During the period prior to May 22, 2013, the authors find that the 10-minute response of crude oil futures prices was statistically significantly related at the 1% significance level to a number of macroeconomic news items for a model including all announcements examined. Those found to be significantly related to the change in the crude oil futures price include initial unemployment claims, nonfarm employment, the unemployment rate, personal income, consumer credit, new home sales, durable goods orders, the Institute for Supply Management (ISM) manufacturing index, consumer confidence, pending home sales, and the Chicago Purchasing Managers' Index. Two of these (nonfarm employment and consumer confidence) correspond to the results reported by Chatrath el al. (2012). The authors estimate a subsequent model that includes a dummy variable for the period after May 22, 2013 along with an interaction variable equal to the dummy times the surprises. They find that the response of crude oil futures prices to macroeconomic news during the period of higher monetary policy uncertainty is smaller (closer to zero) across the macroeconomic releases. These results provide evidence that conditioning the market price reaction to macroeconomic news on the

[19] It appears that the authors obtained the macroeconomic announcements and forecasts from Haver Analytics data archives.

monetary policy regime is important for the time period studied. It remains to be tested whether the results dissipate at the daily return measurement interval.

### 2.3. Price Response to Surprise Changes in Monetary Targets: The federal funds rate

Rosa (2014), Anzuini et al. (2013), Barsky and Kilian (2004), and others have argued that monetary policy changes can influence energy prices through several potential channels. These include exchange rates through the influence of changes in interest rates, inventory carrying costs through the cost of borrowing, supply (drilling and production) through the cost of capital in general, demand through economic growth, and, of recent interest, potentially through a portfolio rebalancing channel. The latter arises if the Federal Reserve displaces private investors in some segments of the capital market, causing those investors to seek alternative investments, which could include commodities. News revealing surprises in changes in monetary policy thus could influence energy prices, and if oil prices are affected, the prices of petroleum-based products such as gasoline and distillate will be affected as well.

Since May 1999, the FOMC has issued a press release following each of its meetings that contains an assessment of the macroeconomic environment and any policy changes.[20] These press releases therefore potentially alter the information set available to participants in commodity futures markets. Rather than employ survey forecasts, the standard method in the literature has been to utilize capital market data to infer unexpected changes in the target federal funds rate at the time of the press release. Kuttner (2001) has shown that one can infer surprises in changes in the target Federal funds rate by using changes in the implied Federal funds rate inferred from Federal Funds

[20] "Starting with the May 1999 meeting, the FOMC announced that it had made no change in policy and initiated the practice of releasing a statement after every meeting regardless of whether the stance of policy had changed" (Wynne, 2013), Federal Reserve Bank of Dallas, https://www.dallasfed.org/research/eclett/2013/el1308.cfm.

Futures prices, scaled by a factor related to the days in the month.[21] Two primary models have been examined in the literature:

$$r_{i,t} = \alpha_i + \beta_i TS_t + \varepsilon_{i,t} \tag{6}$$

and

$$r_{i,t} = \alpha_i + \beta_{i1} TS_t + \beta_{i2} PS_t + \varepsilon_{i,t} \tag{7}$$

where $TS_t$ equals the target rate change surprise on date *t*, the date of the FOMC press release, $PS_t$ is a measure of the path of monetary policy, and $r_{i,t}$ is the log futures price change for commodity *i* over a time interval on or around day *t* (which again could be an intraday interval, a single day or multiple days) Some papers focus on equation (6), whereas others estimate both (6) and (7).

In addition to their analysis of the relation between unexpected macroeconomic announcements and daily log price changes, Kilian and Vega (2011) also investigate the impact of FOMC's post-meeting announcements using a model akin to equation (6). They find no effect of such announcement surprises on daily oil or gasoline prices based upon regressions of log price changes on surprises.[22]

In their broader study of macroeconomic announcements, described earlier, Roache and Rossi (2010) also examine the relation between Federal funds rate surprise changes and changes in daily crude oil, distillate, and natural gas prices. They document no relation overall; in a set of results

[21] Piazzesi and Swanson (2008) find that the one-day change in the Federal Funds Futures rate as a measure of the surprise change in policy is not influenced by the presence of a risk premium; they conclude that this is because the risk premium moves slowly and a one-day differencing essentially differences it out. We return to the specifics of the calculation in section 6.

[22] In a study focused on measuring the impact of target rate change surprises on stock prices, Rosa (2011) concludes that, although the approach of regressing price changes on target surprises may have shortcomings, "on the whole the event study method should be preferred" to the instrumental variables method suggested by Rigobon and Sack (2004).

focused on the period 2002-2009, they find a significant and negative relation between the change in the crude oil price and the target rate surprise, but they find no relation for distillate or natural gas. The result also depends upon controlling for lagged values of changes in a U.S. dollar index. Studying the time period January 1999 to June 2011, Rosa (2014) focuses on the time interval from 10 minutes prior to the FOMC press release through 50 minutes after, in contrast to daily intervals in his examination of the responses of WTI futures prices for the front-month contract to conventional and unconventional monetary policy. He documents a sharp inverse response to monetary policy surprises in intraday prices of WTI crude oil futures and examines the price reactions to 1) the surprise change to the current federal funds target rate, 2) the surprise component to the future path of policy, and 3) the unanticipated announcement of future large-scale asset purchases. Rosa computes target surprises following Kuttner (2001), as described earlier, and computes the surprise component to the future path of policy following methods outlined in Gurkaynak et al. (2005), estimating a model like (7). The author finds that changes in the WTI futures price are significantly negatively related to target surprises and that price volatility also is related to target surprises. He concludes: “I find that, on average, a hypothetical unanticipated 100-basis-point hike in the federal funds target rate is associated with roughly a 3% decrease in WTI crude oil prices” (p. 295). His results also show a negative and significant reaction in futures prices to the announcement of two large asset purchase programs announced by the Federal Reserve in March 2009 and November 2010. He finds no evidence that a “path of policy” factor affects prices. The author specifies that the responses of distillate futures prices and natural gas futures prices are similar to those found for oil: the target surprise is negatively related to prices, but the path variable is never significant. Finally, he extends the analysis to daily data and, like Kilian and Vega (2011), finds that the point estimate in a regression of price changes on the target surprise is negative, but he cannot conclude that it is significantly different from zero.

Basistha and Kurov (2015) also examine the effect of monetary policy surprises on oil, gasoline, and distillate futures prices at intraday, daily, and monthly horizons. The authors measure monetary policy changes using the target surprise measure proposed by Kuttner (2001) and the path surprise variable of Hausman and Wongswan (2011).[23] For press releases during the period January 1994 through December 2008, the authors examine the change in price over the period from 10 minutes before to the press release through 3 hours afterward. Using intraday energy futures data, the authors find a negative response of oil, gasoline and distillate prices to unexpected changes in the federal funds target rate, and, like Rosa (2014), they find no relation with a "path of policy" variable. One interesting result reported by the authors, however, is that the relation between price changes and the target surprise is largely driven by the subset of meetings that were unscheduled. In further analyses, they find that the accumulated responses after several days are statistically insignificant, which is largely consistent with the results reported by Kilian and Vega (2011) and Rosa (2014). Finally, the authors formulate and estimate a structural vector autoregression model using monthly data, finding no statistically significant relation.

Overall, the evidence generally shows an intraday reaction of energy futures prices to target rate surprises, but no relation at the daily or longer frequencies. Similar to the results regarding macroeconomic announcement surprises, this suggests that the responses may be transitory.

[23] The path variable that the authors compute is the change in the one-year ahead Eurodollar futures rate.

### 2.4. Price Response to Announced Changes in the Strategic Petroleum Reserve

The U.S. Strategic Petroleum Reserve (SPR) was established in 1977 to act as a backstop against major petroleum supply interruptions. According to DOE statistics, the SPR's capacity is 727 million barrels, and the current fill level is 689 million barrels, providing roughly 94 days of import protection.[24] The Energy Policy Act of 2005 authorized an increase to 1 billion barrels, but decisions about expansion sites have not been concluded. Presidents are authorized both to release oil from the SPR and to increase the amount of oil held in the SPR. Several authors have suggested that the SPR is simply too small to be an effective tool for moderating price behavior (Taylor and Van Doren, 2005; Considine, 2006), but others disagree (Medlock and Jaffe, 2009). The debate over the SPR's utility recently has received increased attention (Scheitrum et al., 2017; Difiglio, 2014; Patron and Goldwyn, 2013). We do not explore the merits of the SPR program; our focus is only on the market price consequences of decisions to add or release oil to or from it.

As noted by Scheitrum et al. (2017, p. 485), the Energy Policy and Conservation act states that a severe energy supply interruption shall be deemed to exist if the President determines that

A. an emergency situation exists and there is a significant reduction in supply which is of significant scope and duration;
B. a severe increase in the price of petroleum products has resulted from such an emergency situation; and
C. such increase is likely to cause a major adverse impact on the national economy."

(p. 485, citing the U.S. Energy Policy and Conservation Act, Public Law 94.163, as amended through Public Law 113.67 (2013))

[24] https://www.eia.gov/dnav/pet/pet_stoc_typ_d_nus_SAS_mbbl_m.htm.

Little attention has been given to the impact of news regarding changes in the amount of oil held in the SPR on oil and petroleum product prices. Using an event study structure, Demirer and Kutan (2010) find no statistically significant reactions in their examination of how daily spot oil and crude oil futures prices behave following announcements about additions to and releases from the SPR.[25] The typical approach in these types of studies is to assess how prices changed at the time of a news release relative to a benchmark. Such exercises proceed by first identifying the dates of the relevant events (news announcements). This is followed by postulating a "normal" or benchmark model for the price changes being analyzed and estimating the parameters of the model for a period prior to the event (so as to avoid using data that might be influenced by the events being studied). The conditional predictions of price changes from the model are then subtracted from the actual price changes to obtain "abnormal" changes. For events (of like nature) that occur on multiple dates, the abnormal returns are then averaged and potentially cumulated over a specified time period following the event. In other words, the results are centered on the event dates. Statistical tests of the null hypothesis that the average abnormal return (averaged across the N event dates) is equal to 0 can then be conducted, as can tests of the cumulative effects. A dummy variable formulation can also be constructed with suitable alignment of the data.[26]

Demirer and Kutan's (2010) results are potentially consistent with recent evidence presented by Scheitrum et al. (2017). Scheitrum et al. study the link between stocks of oil held privately in the United States and government actions taken to change the amount of oil held in the SPR. Some of the results indicate a substitution effect from SPR changes to private inventory changes. However,

[25] The news releases are dated, but records of the time of day of the releases are not available.
[26] See Thompson (1995) and MacKinlay (1997).

the results vary depending on which president was in office at the time of the SPR action, which suggests that decisions regarding the SPR may sometimes have either no price impact or an impact opposite to what was intended. For example, actions taken by President G. W. Bush to fill the SPR had a significant and negative impact on private stocks.

## 3. Empirical Analysis of Energy Futures Price Responses to Unexpected Information

### 3.1. Futures Prices

We study front month futures contracts trade prices[27] for the NYMEX Crude Oil, Henry Hub Natural Gas, RBOB Gasoline Physical, and NY Harbor ULSD contracts, which for brevity's sake we refer to respectively as oil, natural gas, gasoline, and distillate.[28] We examine price behavior around the release times of information regarding inventories (including information regarding the SPR), macroeconomic variables, and monetary policy. Both intraday and daily log price changes are studied. All log price changes are multiplied by 100. We sometimes refer to the change in the natural log price as a return. The earliest start date for the intraday analysis is May 18, 1999, and the latest date is June 30, 2017. Depending upon the announcements studied, the starting date is sometimes after the 1999 date. The time period covered by the daily data is May 1999 through June 2017. The futures contracts we examine began trading effectively on a 24-hour trading schedule on June 6, 2006. Closing was set at 5:15 PM ET and opening at 6:00 PM ET by the CME at the time. Beginning on September 21, 2015, the closing time was reset to 5:00 PM ET.[29] The

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[27] The method for rolling from a maturing contract to the next maturing contract uses daily tick volume for the current and next back-month contracts and rolls to the next contract when the daily tick volume of the back-month contract exceeds the daily tick volume of the current month contract.

[28] For contract details, see the website of either the CME Group, http://www.cmegroup.com/trading/energy/crude-oil/light-sweet-crude.html, or the EIA, https://www.eia.gov/dnav/pet/pet_pri_fut_s1_d.htm. As mentioned earlier, "Beginning with the May 1, 2013 contract, the New York Mercantile Exchange (NYMEX) switched its specification for the heating oil futures contract to the ultra-low sulfur diesel specification (ULSD)" (EIA, https://www.eia.gov/todayinenergy/detail.php?id=11211). For the sake of convenience, we refer to this product as distillate.

[29] See http://www.cmegroup.com/market-regulation/files/15-384.pdf.

price data are sourced from the commercial provider Tick Data, which obtains the data through direct feeds.[30]

## 3.2. Price Response to Unexpected Changes in Inventory

### 3.2.1. Introduction

Crude oil is the "main ingredient" of refined petroleum products. Elsewhere, Ederington et al. (2016) find that oil prices are the primary driver of product prices. However, individual markets for petroleum products exist, and shifts in supply and demand conditions lead to changes in inventories of these goods, as is also the case for natural gas.

This section assesses the response of the futures prices of oil, gasoline, distillate and natural gas to unexpected information about the quantities of these products in storage. Information on quantities in storage for any given week is reported by the U.S. Energy Information Administration in the Weekly Petroleum Status Report and the Weekly Natural Gas Storage Report. These data allow us to calculate the actual change in inventory between reporting dates. Expectations about the change in storage are gathered from Bloomberg, which assembles forecasts from industry experts. These two measures allow us to compute unexpected changes in inventories. The EIA reports are released during the trading day. We examine the relation between futures price changes and unexpected changes in inventory. Our study covers the time period July 16, 2003 to June 30, 2017. We examine the relation between futures price changes of oil, gasoline, distillate and natural gas and unexpected changes in inventories of those commodities stored in the United States. A key set of ingredients potentially affecting the futures prices of energy commodities are changes in supply

[30] https://www.tickdata.com/. Alex Kurov kindly shared with us the oil price data he and his coauthors studied in Halova et al. (2014), and we find almost exact correspondence between our data and theirs, which was sourced from a competing provider.

and demand conditions and the balancing complement, changes in inventory (changes in the amount of the commodity in storage). Shifts in expectations about fundamentals related to supply and demand conditions may result in price responses (Kilian and Lee, 2014; Kilian and Murphy, 2014; Gorton et al., 2013; Pirrong, 2012). Inventory at a date *t* equals inventory at *t*-1 plus production less sales of the product and any physical loss due to the storage technology. Hence, the change in inventory impounds information about both supply and demand conditions. Unexpected changes in inventories (surprises) are the differences between the actual inventory changes implied by the weekly EIA reports and a measure of market expectations about changes in the amount stored. The reports issued by the EIA occur regularly each week at a preset time of day.

We show that the price response to positive and negative surprises occurs within 5-6 minutes of the report release and does not reverse within the following three hours. In addition, intraday changes in the level of futures prices during a 15-minute window around the time that the EIA reports are released are shown to be inversely related to the sign of the surprise. Volatility spikes at the time of an announcement but then dies out. Intraday shifts in volatility are shown to be positively related to the absolute value of the surprise. We also present evidence that the Chicago Mercantile Association's shift to effectively 24-hour electronic trading in June 2006 had a significant impact on the level of reactions to the surprises we study, resulting in less pronounced response coefficients for the period following the shift to electronic trading. However, no such result is found for the response of volatility. Finally, we find no evidence that the volatility response to the absolute value of the surprise is influenced by whether the raw surprise was positive or negative.

### 3.2.2. Inventory Reports

The EIA compiles and reports weekly estimates of the amount of oil, gasoline, distillate, and natural gas in storage in the United States. Key highlights on oil, gasoline, and distillate inventory estimates are released each Wednesday at 10:30 AM (Eastern Time) in the Weekly Petroleum Status Report Highlights (WPSR) for the measurement period ending the prior Friday.[31] The data are assembled using a survey instrument. According to the EIA, "Companies are selected into the EIA weekly sample according to a procedure that assures coverage of 90 percent of each information element" (EIA, 2017).[32] Reporting data for the WPSR is mandatory, and the EIA currently (2017) indicates that 75 respondents are involved. Similarly, inventory estimates for natural gas are reported in the Weekly Natural Gas Storage Report (WNGSR) released by the EIA each Thursday at 10:30 AM (Eastern Time). The report provides estimates of natural gas in underground storage for the lower 48 United States. Respondents are a sample of U.S. natural gas storage operators. Reporting is mandatory, and the EIA currently (2017) indicates that 85 respondents are involved.[33] The report is released on alternate days when a holiday falls on a Thursday. Deferred releases generally occur the following day of the week.

We obtain all report release dates for both the WPSR and the WNGSR from Bloomberg and compare that record to data available from the EIA website. We focus on surprise changes in inventory, thus comparing actual reported data to consensus forecasts. We obtain consensus forecasts from Bloomberg, discussed in more detail in the following section. The inventory

[31] For an example of the report, please see https://www.eia.gov/petroleum/supply/weekly/.
[32] Details about the survey form and which companies must submit are available at https://www.eia.gov/surAvey/form/eia_803/instructions.pdf.
[33] For an example of the Weekly Natural Gas Storage Report, please see http://ir.eia.gov/ngs/ngs.html. Details about the survey form and which companies must submit are available at https://www.eia.gov/survey/form/eia_912/instructions.pdf.

variables that form the basis for our investigation are the following, as these are the basis for the analyst forecasts reported by Bloomberg:

- Weekly U.S. Ending Stocks excluding SPR of Crude Oil (Thousand Barrels) [oil]
- Weekly U.S. Ending Stocks of Total Gasoline (Thousand Barrels) [gasoline]
- Weekly U.S. Ending Stocks of Distillate Fuel Oil(Thousand Barrels) [distillate]
- Weekly Gas in Underground Storage, Total Lower 48 States (Billion Cubic Feet) [natural gas]

Henceforth when referring to these inventories, we will generally use the shorthand terms "oil," "gasoline," "distillate," and "natural gas." Weekly changes in inventory are computed from the inventory levels reported by the EIA, and robustness tests are conducted using the levels reported by Bloomberg.[34] Visual inspection of the levels and changes confirms that inventory changes exhibit variability.

#### 3.2.3. Analyst Forecasts of Changes in Inventory

Bloomberg compiles analyst estimates of inventory changes on a weekly basis. The change is measured relative to the prior week's actual level. The EIA reports are released each Wednesday for crude oil and refined products and each Thursday for natural gas, reporting inventory levels as of the prior Friday. The Wednesday report also contains information on gasoline and distillate inventories. The analyst forecasts of inventory change compiled by Bloomberg measure predicted changes as of the same Friday as the data reported by the EIA. We obtain the analyst forecast data from the archives of Bloomberg and utilize the median forecasted change in inventory as a benchmark for the expected change.[35] The oil inventory forecast data and the forecast data for

[34] Refer to https://www.eia.gov/dnav/pet/pet_stoc_wstk_dcu_nus_w.htm for oil, gasoline, and distillate inventory data and to https://www.eia.gov/dnav/ng/ng_stor_wkly_s1_w.htm for natural gas inventory data.
[35] Gay et al. (2009) and Halova et al. (2014) are among the studies that also employ the median forecast.

gasoline and distillate begin with the release on July 16, 2003, and extend to the release for the week ending June 30, 2017. For the sake of comparison, we use the same sample period for the natural gas inventory forecasts.

Table 1 presents statistics on the actual weekly changes in inventory reported by the EIA, the raw surprises equal to the actual change minus the median forecasted changes compiled and reported by Bloomberg. The table also reports the cross-sectional standard deviations of the raw surprises. Tests of the null hypothesis, that the mean raw surprise is equal to 0, never reject the null for each of the commodities. Likewise, tests that the median raw surprise is equal to 0 never reject the null as well. The average absolute value of the raw surprises as well as the standard deviation of the surprises tends to be larger for oil than for gasoline and distillate.

#### 3.2.4. Unexpected Changes in Inventory and Price Changes

A deduction that follows from the efficient market hypothesis is that prices of assets traded in an efficient market will respond to the arrival of unexpected fundamental information about the determinants of asset value, such as supply and demand conditions. This hypothesis has its genesis in the rational expectations hypothesis.[36] Shifts in expectations about supply and demand conditions will result in changes in inventory (Kilian and Lee, 2014; Kilian and Murphy, 2014; Gorton et al., 2013; Pirrong, 2012). A resource balance condition describes inventory changes: ending inventory equals beginning inventory plus production minus sales of the product less any incidental losses or product consumed by the storage process.[37] Unexpected changes in the

[36] The roots of the hypothesis can be traced back to Samuelson (1965) and Fama (1963; 1970). Recent work extending these thoughts has been proposed by Lo (2007) in a framework he refers to as the Adaptive Market Hypothesis.
[37] An inference about price elasticities is one important insight that potentially could be gleaned from the reaction to an unexpected change in inventory. However, because changes in inventory potentially reflect shifts in both supply and demand, it is not possible to separate out each effect without more specific information.

inventories of oil, natural gas, or refined petroleum products therefore potentially reveal unexpected information about shifts in supply and demand conditions.

Market participants form an expectation about the change in the level of inventory in storage for each of the commodities we study. We designate the expectation as $E\left[\Delta I_t\right]$, which equals the expected change between date *t*-1 and date *t*. These expectations are then confirmed or refuted when the actual change, $\Delta I_t$, is revealed by data reported by the EIA.[38] The difference is what we will refer to as a raw surprise,

$$\Delta I_t - E\left[\Delta I_t\right]. \tag{8}$$

As mentioned earlier, the information revealed each week in the EIA reports for oil and natural gas are based upon estimates from a sample of storage facility operators. The values reported are thus sample statistics. Despite this, it is nevertheless possible to show that unexpected news about the change in inventory will also give rise to price adjustments in the direction predicted by the sign of the surprise, even when the news contains some noise.[39] The environment we analyze involves a *public* release of information (about inventory) that is based upon estimates of the inventory level and thus reflects noise. Kim and Verrecchia (1991) present a theoretical model of price changes for a risky asset when the new public information released contains noise. When traders act rationally, given that they are receiving signals that contain noise, Kim and Verrecchia show that a price change in response to unexpected information can be characterized by the following relation:

[38] We are being a bit causal here in referring to the "actual" change; as mentioned earlier, the levels reported by the EIA are based upon a survey instrument and a sample that encompasses 90% coverage.
[39] The result takes advantage of the assumption that the news released is public and that market participants employ Bayesian updating when revising beliefs about the value of the underlying asset. An example model is available from the authors upon request.

$$P_t - P_{t-1} = \theta\left(Surprise + Noise\right) \quad (9)$$

where the parameter $\theta$ depends upon the precision of the new information and *Surprise*, paraphrasing their words, is the difference between the announced new information and an average of traders' expectations about the information at the time of the announcement. This theoretical setting is akin to the environment we analyze. The data released by the EIA each week are estimates; nevertheless, operators designated by the EIA are required to submit reports, and coverage is 90%.[40] Therefore, if the information released is truly a surprise, we expect $\theta$ to be statistically significant. We concede, however, that the response to surprises about the change in inventory will nonetheless be influenced by the precision of the underlying information. This raises the question of whether to assume that market participants can tease out the actual change in inventory from the announcement of the statistical estimate. We choose the conservative assumption that noise is present and that market participants treat the statistical estimate as the best available data when assessing any surprises.[41]

#### 3.2.5. Intraday Price Response

Figures 1 through 4 present graphs showing the cumulative average log price changes of crude oil, natural gas, gasoline, and distillate for a span of time surrounding the release of the report containing inventory data for each respective commodity. Each figure also includes a graph of the average absolute log price changes.

The first graph in each set presents the cumulative log price change from 30 minutes prior to the information release through 180 minutes following for positive inventory change surprises and

[40] Details on the survey form and which companies must submit it are available at https://www.eia.gov/surAvey/form/eia_803/instructions.pdf

[41] Halova et al. (2014) alternatively assume in their model specification that market participants are able to separate out any noise, but this, of course, requires a structural assumption regarding the true inventory surprise and the noise.

separately for negative inventory surprises. The underlying data are 1-minute log price changes, so the means are practically 0. As each of the figures illustrates, the average price adjustment is immediate and in the direction expected. An unexpected positive change in inventory results in a decrease in prices, while an unexpected negative change results in an increase in prices. Using the plateau reached after 100 minutes, we observe that the response is generally complete for each commodity within 5 to 7 minutes following the announcement. Further, in the case of the inventory announcements studied here, the adjustments are not reversed within the 180 minutes following the information release. Finally, there is no evidence that the futures prices begin moving appreciably prior to the information releases.

Absolute returns have been used as a proxy for volatility within several contexts and can be justified theoretically (Barndorff-Nielsen and Shephard, 2003; Barndorff-Nielsen et al., 2004a). Absolute returns also have been shown to be strong predictors of volatility (Forsberg and Ghysels, 2007; Zheng et al., 2014). The second graph in each set presents the average absolute return for each minute surrounding the release of the WPSR and the WNGSR. The bars displayed in the figures are separated into those associated with positive inventory surprises and those associated with negative inventory surprises. First, there is a noticeable spike around the time that information is released, and this occurs for each of the commodities. Second, volatility dies out following the release of the report but does not return to its preannouncement level until roughly the 100 minute mark.

Summing up, the energy futures prices studied here adjust rapidly, within minutes, to unexpected positive and negative inventory change surprises. Moreover, although volatility increases at the time of an announcement, it returns to its preannouncement level after roughly 100 minutes.

### 3.2.6. Further Evidence on Price Responses to Unexpected Changes in Inventory

We estimate the general relation between futures returns and unexpected changes in inventory. The basic model is described by the following:

$$r_{i,t} = \alpha_i + \beta_i S_{i,t} + \varepsilon_{i,t} \tag{10}$$

The subscript *i* is an index for the commodity (oil, natural gas, gasoline, or distillate), and *t* denotes the date on which information on the actual change in inventory is released. The surprise is measured as described earlier as $S_{i,t} = \frac{A_{i,t} - E_{i,t}}{\hat{\sigma}_i}$. Finally, $r_{i,\tau}$ is the 15-minute return (log price change x 100) from 10:25 AM through 10:40 AM for commodity *i* and date *t*. The graphs displayed in Figures 1 through 4 suggest that our choice is conservative, as the adjustments tend to be completed within 10 minutes on average. The coefficients of the model are estimated via a cross-sectional regression. We compute standard errors following Huber (1967) and White (1980, 1982) for tests of the null hypotheses that the estimated coefficients are equal to zero.

### 3.2.7. Basic Model Results

Table 2 presents the results of estimating equation (10) for each of the commodities. Columns 1, 3, and 5 show the relation between the price responses and the own inventory change surprises. The results show that there is a negative and statistically significant relation between the price responses and the unexpected change in inventory. The estimated coefficient on the surprise $\hat{\beta}_i$ can be interpreted as the response $r_{i,t}$ for a one-standard-deviation shock (increase or decrease in the raw surprise). For example, Table 1 shows that the standard deviation of the crude oil inventory raw surprise is equal to 3326 (1000 barrels). The estimated coefficient for the standardized crude oil inventory surprise from column 1 of Table 2 equals -0.292, indicating that an unexpected increase in crude oil inventory by one standard deviation would translate into a decrease in the oil futures price of approximately -0.30% over the 15-minute interval studied. One interpretation is that when the actual change in inventory exceeds what was expected, the information conveyed is that inventory grew abnormally, suggesting oversupply in the market and resulting in a price decrease.

Columns 2, 4, and 6 of the table account for the possibility that there is independent information contained in inventory changes for each of the commodities. Chang et al. (2009) argue that aggregate market effects may have an impact on the price response. We approach this question by estimating models in which we include the inventory change surprises associated with each of the oil-related commodities (oil, gasoline, and distillate). The results indicate that each disclosure reveals unexpected news and that, once again, an inverse relation exists. This suggests that shifts in supply and demand conditions across all three markets—oil, gasoline, and distillate—affect the prices in each market.[42] This is perhaps not a surprise. Consider, for example, how changes in refined product inventories could potentially influence crude oil prices. Specifically, if gasoline and distillate inventories drop more than expected (i.e., in our parlance, the surprises are negative), this would be consistent with a net increased demand and a positive impact on gasoline and distillate prices. Consequently, an increase in gasoline prices could increase demand for oil and place upward pressure on oil prices. The results are consistent with this interpretation.

[42] For a comprehensive study of the production and transportation infrastructure and supply and demand for transportation fuels, see https://www.eia.gov/analysis/transportationfuels/padd1n3/pdf/transportation_fuels_padd1n3.pdf .

Columns 7 and 8 examine the question of whether natural gas prices respond to the oil, gasoline, and distillate surprises on the day the latter are released. The results show that there is a statistically significant inverse relation between natural gas futures returns and the inventory change surprises of oil, gasoline, and distillate, at the time those data are released by the EIA (on Wednesdays). The results indicate that supply and demand conditions in the oil and oil-related markets, as reflected by unexpected changes in inventories of those commodities, also affect natural gas prices at the time they are announced, and that natural gas prices respond to that information. This result means that it is rational for market participants to make inferences about general supply and demand conditions for energy products from the oil market complex. Likewise, as Villar and Joutz (2006) have observed, "Economic theory suggests that natural gas and crude oil prices should be related because natural gas and crude oil are substitutes in consumption and also complements, as well as rivals, in production" (p. 1). Some have argued that a long-run stable relation exists between oil prices and natural gas prices (Villar and Joutz, 2006; Hartley et al., 2008; Brigida, 2014).

Finally, column 9 of Table 2 displays the estimated relation between natural gas futures returns and the unexpected change in natural gas in inventory, where the return is for the 15-minute period surrounding the WNGSR's release. Consistent with the own inventory effects found for oil, gasoline, and distillate, there is a negative and statistically significant relation between natural gas returns and the natural gas inventory surprise.

The results presented in columns 7 and 8 of Table 2 indicate that natural gas prices respond to news about changes in inventories for oil, gasoline, and distillate. Table 3 reports results showing how oil, gasoline, and distillate futures returns respond, on the day the WNGSR is released (typically Thursdays), to news about unexpected changes in natural gas in inventory. The results indicate that oil and distillate futures returns exhibit a negative and statistically significant response to unexpected changes in natural gas inventory at the time the WNGSR is released.

In summary, we find a statistically significant inverse relation between the futures returns for oil, gasoline, distillate, and natural gas and the surprises regarding the change in own inventory for each. Likewise, the results presented in Tables 2 and 3 indicate that the market gleans relevant information about each asset from the announcements pertaining to the three other markets.

#### 3.2.8. The Shift to Electronic Trading

In 2006, the energy futures contracts we study began trading effectively on a 24-hour schedule.[43] Following this shift, pit trading volume declined and, by 2017, ended completely. This change has led to a tremendous increase in the volume of trading, especially by institutions, as shown in a recent study by Raman et al. (2017). One result documented in Raman et al. (2017) is that electronic trading in oil futures has, based upon several measures, improved market quality and pricing efficiency of oil futures contract prices, and similar results would arguably be true of other commodity futures contracts as well.

We examine the impact of the shift in trading venue by constructing a dummy variable, $E_t$, which takes the value 1 for dates on or after June 6, 2006, and 0 otherwise.[44] The base models discussed earlier are extended to the following structure, which includes an interaction variable to assess the impact on the response coefficient.

[43] Trading that traditionally had been conducted by an open outcry system (pit trading) was replaced by electronic trading, essentially effective with the advent of 24-hour electronic trading on June 6, 2006, by the NYMEX.

[44] Closing was set at 5:15 PM ET and opening at 6:00 PM ET. Beginning with September 21, 2015, the closing time was reset to 5:00 PM ET (see http://www.cmegroup.com/market-regulation/files/15-384.pdf).

$$r_{i,t} = \alpha_i + \beta_{i,E} E_t + \beta_{i,S} S_{i,t} + \beta_{i,SE} \left( S_{i,t} \bullet E_t \right) + \varepsilon_{i,t} . \tag{11}$$

The model is estimated for each of the commodities we study, and the results are presented in Table 4.

The estimated coefficients of the interaction variable for the oil, gasoline, and distillate futures price response models are always positive. The estimated coefficients of the interaction variables for the gasoline and distillate futures price change models are significantly different from zero, but the estimated coefficient for the oil price model is not. These results indicate that, except for oil, the commodities' price responses became more muted during the period in which trading occurred largely on a 24-hour schedule. In contrast, the estimated coefficient of the interaction variable in the natural gas futures price model is negative and significant.

Separately, we also estimate the impact of the natural gas storage surprise on the oil, gasoline, and distillate futures returns at the time the WNGSR is issued (typically on Thursdays). The results are documented in Table 5. The estimated coefficient of the interaction variable is not significantly different from 0 for the oil, gasoline, or distillate models, although the signs of the estimated coefficients are always positive.

In summary, the advent of electronic trading has generally muted the response of oil, gasoline, and distillate returns to their respective surprises, but has exacerbated the response of natural gas to its own surprise.

### 3.2.9. The Relation Between Volatility and Unexpected Inventory Changes

Volatility of futures prices is a cornerstone of derivative valuation and risk management. In this section, we examine the relation between volatility and inventory change surprises following a framework similar to that used earlier.

Absolute returns have been used as a proxy for volatility in several contexts and can be justified theoretically (Barndorff-Nielsen and Shephard, 2003; Barndorff-Nielsen et al., 2004a). Absolute returns also have been shown to be strong predictors of volatility (Forsberg and Ghysels, 2007; Zheng et al., 2014). The volatility measure we employ is the absolute value of the 15-minute return around the time of the weekly release.

In contrast to our earlier analysis of return responses, we convert the surprises to absolute values because volatility cannot be negative. Further, it is possible that volatility may respond asymmetrically to positive versus negative surprises. We therefore construct a dummy variable that takes the value 1 if the surprise is negative and 0 otherwise. We then interact this dummy variable with the absolute values of the surprises. We begin, however, by estimating models of the following form, which do not account for potential asymmetric responses.

$$\left|r_{i,t}\right| = \beta_0 + \beta_i \left|S_{i,t}\right| + \omega_{i,t} \tag{12}$$

Results are presented in Tables 6 and 7. Table 6 documents that volatility is positively related to the absolute value of the own surprise for each of the commodities. Interestingly, as shown in Table 7, volatility for each commodity is related to the absolute surprise for natural gas on the day the WNGSR is released, whereas, as shown in Table 6, volatility of each is related only to the own surprise on the day the WPSR is released.

Table 8 explores the impact of the shift to electronic trading on the volatility response. The estimated model has the following form:

$$\left|r_{i,t}\right| = \beta_{i,0} + \beta_{i,E} E_t + \beta_i \left|S_{i,t}\right| + \beta_{i,SE}\left(\left|S_{i,t}\right| \bullet E_t\right) + \omega_{i,t} \tag{13}$$

The results reported in Table 8 document that the response of volatility to own surprises was unaffected by the shift to electronic trading, and the coefficients of the interaction variables are never statistically significantly different from zero.

Much has been written about the potential for asymmetric volatility responses to good and bad news in the markets for financial securities and in energy futures markets (see, for example, Lee and Zyren, 2007; Efimova and Serletis, 2014). We next examine the impact on volatility of negative versus positive inventory surprises.

We define the dummy variable $D_{S<0}$ = 1 if $S_{i,t} < 0$, and 0 otherwise. Constructing an interaction term, the dummy variable model to be estimated has the following form:

$$\left|r_{i,t}\right| = \beta_{i,0} + \beta_{i,D}\left(D_{S<0}\right) + \beta_{i,S}\left|S_{i,t}\right| + \beta_{i,SD}\left\{\left|S_{i,t}\right| \bullet D_{S<0}\right\} + \omega_{k,t} \tag{14}$$

Table 9 presents the estimation results for equation (14). The results show that the estimated coefficient of the dummy variable indicating a negative surprise is not significantly different from zero in the oil and distillate models, but is positive and significant at the 1% level in the gasoline model and is positive and significant at the 10% level in the natural gas model. Likewise, the estimated coefficients of the interaction variable are not significant in the oil and distillate models but are negative and significant in the gasoline and natural gas models. The response of volatility to the own surprises themselves continue to be positive and statistically significant, as in the results presented earlier.

In summary, we conclude that volatility is positively related the absolute size of unexpected changes in inventory for each of the energy commodities we study, but that there are asymmetric response effects influencing gasoline futures price changes and natural gas futures price changes.

### 3.2.10. Daily Price Effects

We also investigate the relation between inventory change surprises and daily log price changes. We present results for regressions of daily price changes on the day the inventory reports are released on the standardized inventory change surprise variable. Results are presented for several daily periods: The day of the information release identified as (0,0), the day following (1,1), the two day period following the release (1,2) and the second day following the release (2,2). In addition results are presented for the oil, gasoline and distillate models for days (1,1), (1,2) and (2,2) which include both the individual surprise for each commodity as well as the surprise for natural gas which is generally in the WNGSR the day following the release of the WPSR. Panel A of Table 10 reports the results for the regressions which include only the own surprises for the commodities while Panel B presents the results which also include the natural gas inventory surprises.

The results presented in Panel A of Table 10 indicate that there is a negative and statistically significant price response to the own inventory surprise for each commodity on the day the inventory report is released for each commodity. There are not statistically significant relations between the surprises and the price changes of oil, gasoline or distillate over the two days following the report release. In contrast, we find that natural gas futures prices experience a negative and statistically significant decrease not only on the day the information is released by also the day after, although the magnitude of the response the day after is only about 1/5 as large as the response on the announcement day. The results for oil are consistent with those found by Miao et al. (2017).

The day following the release of the petroleum report is the day the natural gas storage report is released. Panel B of Table 10 presents results for the days following the petroleum report release for oil, gasoline and distillate price changes but includes both the own inventory surprises as well as the natural gas inventory surprise. The results presented in Panel A for the days following the petroleum report release are not influenced by the inclusion of the natural gas inventory change surprise.

### 3.3. Price Response to Unexpected Macroeconomic News

Kilian and Vega (2011) have argued that establishing the relation between energy prices and real macro activity is crucial to our understanding of how such prices are both linked to real activity and are determined.[45] In this section, we turn our attention to how prices respond to a set of macroeconomic news releases. We restrict our attention to the following releases: the U.S. Employees on Nonfarm Payrolls Month-to-Month Change (U.S. Bureau of Labor Statistics, release time 8:30 AM ET, monthly); the U.S. Retail Sales Month-to-Month % Change (U.S. Bureau of the Census, release time 8:30 AM ET, monthly); the U.S. Consumer Confidence Index (Conference Board, release time 10:00 AM ET, monthly); and the U.S. ISM Manufacturing Composite Index (National Association of Purchasing Managers, release time 10:00 AM ET, monthly). The intraday analysis spans the period July 16, 2003, to July 17, 2017, while the analysis of daily price responses spans February 1993 through May 2017.

[45] Oil and natural gas continue to be important contributors to the overall energy mix (50+%)[EIA: https://www.eia.gov/todayinenergy/detail.php?id=31892, IEA: https://www.iea.org/publications/freepublications/publication/KeyWorld2016.pdf ]

Following Kilian and Vega (2011) and others (see section 2.2), we obtain from Haver Analytics at-the-time forecasts and as-first-released data for each of the aforementioned announcements. From these data, we construct the standardized surprise variable described earlier, $S_{k,t} = \frac{A_{k,t} - E_{k,t}}{\hat{\sigma}_k}$, where $A_{k,t}$ is the actual value of the indicator $k$ reported on date $t$, $E_{k,t}$ is the consensus forecast, and $\hat{\sigma}_k$ is the sample standard deviation of the difference $A_{k,t} - E_{k,t}$. Standard deviations of the raw surprises computed over the 1993-2017 period are as follows: change in nonfarm payrolls (month-to-month), 92.5 (000); retail sales (month-to-month % change), 56.1%; Consumer Confidence Index, 5.12; ISM Manufacturing Composite Index, 1.95.

Summarizing the results, we find evidence of an immediate, intraday response of energy futures prices to the information surprises studied, similar to results presented by Chatrath el al. (2012). However, we also find that the information surprises bear no relation to price responses measured over the day of the announcement, or periods extended out to 20 days after the announcement. These latter results are consistent with results reported by Kilian and Vega (2011), Chatrath el al. (2012), and Rosa (2013).

#### 3.3.1. Intraday Price Response

Among macroeconomic variables reported, the unexpected change in U.S. Employees on Nonfarm Payrolls Month-to-Month Change (U.S. Bureau of Labor Statistics, release time 8:30 AM ET, reported monthly) has been found to have a significant relation to a variety of financial assets. In this section, we focus on oil futures prices. Figure 5 presents the cumulative average log price changes for oil futures prices from 20 minutes prior to the release of the nonfarm payroll report through 180 minutes following. Curves are displayed separately for announcements of positive surprises and announcements of negative surprises. The underlying data are 1-minute log price changes, so the mean price changes are near 0. As the figure illustrates, there is a sharp and immediate response at the time the report is released, and oil prices respond in the same direction as the sign of the surprise. However, for positive surprises, prices revert to slightly less than the preannouncement level within 30 minutes, whereas for negative surprises, prices drift downward but plateau after roughly 75 minutes. There is no evidence that prices drift up or down prior to the release of the report.[46]

The second graph displays the behavior of average absolute returns, a proxy for volatility, by minute relative to the time of the announcement. Volatility spikes at the time of the announcement but then reverts, settling at a somewhat higher level relative to the preannouncement level.

#### 3.3.2. Further Evidence on the Intraday Price Response

We estimate the following model, in the spirit of the literature described in section 2.2.

$$r_{i,t} = \alpha_{i,k} + \beta_{i,k} S_{k,t} + \varepsilon_{i,t} \qquad (15)$$

The first set of results are based upon the price response within a 15-minute interval that begins 5 minutes prior to the information release and ends 10 minutes following. The estimated coefficient $\hat{\beta}_i$ measures the response of the log price change (return) to a one-standard-deviation shock (raw surprise).

Table 11 presents the results from estimation of equation (15) for each of the energy commodities and each of the macroeconomic surprises: Panel A, nonfarm payroll; Panel B, retail sales; Panel

[46] Kurov et al. (2017) study the intraday responses of stock and bond futures prices to macroeconomic news surprises and find evidence of pre-announcement price drift for select number of announcements.

C, ISM manufacturing composite index; Panel D consumer confidence index. The log price change is measured from 5 minutes prior to the announcement through 10 minutes after. Similar to Chatrath el al. (2012), we find that the response coefficients of oil, gasoline, distillate, and natural gas are always positive and statistically significant for the nonfarm payroll surprises, consistent with the curves displayed in Figure 5. Similar results are found for the remaining announcements in the case of oil, gasoline, and distillate. We conclude that the energy futures prices studied here do in fact respond significantly within a short window surrounding the announcements. However, as we discuss in the next section, the results differ when price changes are measured over the full day of the announcement.

#### 3.3.3. Price Responses to Macroeconomic News Surprises, Daily Frequency

As shown in Figure 12, we also examine the relation between log price changes measured over several daily time intervals: a) the day of the announcement (denoted by column heading (0,0)); b) the day of the announcement plus the following day (denoted (0,1)); and c) the day of the announcement through 20 days following the announcement (denoted (0,20)). Results from estimating equation (15) are presented in Table 12 for each of the energy commodities and for each of the four macroeconomic news releases. The table is divided into four panels, each associated with a different macroeconomic announcement. The results show uniformly that the relation between log price changes for the intervals examined and the standardized surprises are not statistically different from zero at conventional levels. These results are consistent with those reported by Kilian and Vega (2011) as well as Chatrath el al. (2012) and Rosa (2013). The results also are supported by the data displayed in Figure 5, which shows that short run changes are quickly erased for positive surprises.

### 3.4. Price Response to Surprise Changes in Monetary Targets: The Federal Funds Rate

### 3.4.1. Introductory Remarks and Target Surprises

We follow the existing literature (described in section 2.3) by first identifying the dates and times when the FOMC issued press releases following its meetings. This information is obtained from the website of the Federal Reserve.[47] We focus on the time period February 3, 1999, through December 16, 2008, because the federal funds rate target range changed little following that date.[48] The usual time of the press release following a meeting of the FOMC occurred at 2:15 PM ET on either a Tuesday or a Wednesday.[49] There were, however, instances during the sample period when a press release was issued at a time other than those mentioned. These occurred generally in conjunction with a conference call meeting.

If a press release reveals information regarding monetary policy, the information should be reflected in key variables targeted by monetary policy. One variable that has become the standard for assessing such surprises is a measure of the surprise change in the federal funds target rate as assessed by the capital market. The advantage of this number is that it reflects market beliefs at the time of the press release and after. The target rate surprise, generally termed the target surprise, can be constructed using the method described in Kuttner (2010). This measure has been widely adopted in the literature.[50] Kuttner (2010) shows that the surprise, or unanticipated change in the target federal funds rate, can be computed from federal funds futures prices. The calculation is

[47] For press releases issued after 2011, see https://www.federalreserve.gov/newsevents/pressreleases.htm. For press releases issued in 2011 or earlier, see https://www.federalreserve.gov/monetarypolicy/fomc_historical_year.htm.

[48] This occurred only three times: on December 16, 2015 (change from 0-0.25 to 0.25-0.50; effective Fed Funds rate change from 0.15 to 0.37); December 15, 2016 (change from 0.25-0.50 to 0.50-0.75; effective Fed Funds rate change from 0.41 to 0.66); and March 16, 2017 (change from 0.50-0.75 to 0.75-1.00; effective Fed Funds rate change from 0.66 to 0.91). The quantitative easing program QE1 began in November 2008.

[49] Confirmation that the release time changed on 3/20/2013 to 2:00 PM is available at https://www.federalreserve.gov/monetarypolicy/fomcpresconf20130320.htm.

[50] This includes Piazzesi and Swanson (2008) as well as the research reviewed in section 2.3.

$$TS_t = \Delta f_t \frac{D}{D-d} \tag{16}$$

where $\Delta f_t$ equals the change in the current month federal funds rate implied by the front month futures prices, $D$ equals the number of days in the month, and $d$ is the day of the month on which the press release is issued (on which the meeting is held). The intuition is that, based upon the information revealed in the press release, market participants revise their beliefs about the expected target rate and impound those beliefs in the federal funds futures price. The intraday analysis utilizes a target surprise measured over an intraday interval surrounding the press release, based on intraday observations of the federal funds futures price. The analysis of daily log price changes utilizes a target surprise measured using observations of the federal funds futures price on the day before the press release and the close for the day of the press release. We examine the responses of energy futures prices for crude oil, gasoline, distillate, and natural gas futures prices in the period surrounding the dates and times on which the FOMC press releases were issued, and we investigate how those price changes are related to the target surprises.[51]

### 3.4.2. Intraday Price Response

We have emphasized earlier the potential channels that might connect changes in monetary policy and oil prices. In this section, we focus on the behavior of crude oil futures prices surrounding press release issuances following FOMC meetings. Figure 6 presents the cumulative average log price change from 30 minutes prior to the time of the press release through 150 minutes following, with positive and negative target surprises shown separately. The underlying data are 1-minute log price changes, so the mean price changes are near 0. In the case of negative surprises, prices drop

[51] Daily federal funds futures prices are obtained from DataStream. We are grateful to Alex Kurov for supplying the measures of intraday surprises studied in Basistha and Kurov (2015). Those authors compute intraday surprises using federal funds futures prices observed 10 minutes before the press release and 20 minutes after.

over the 30 minutes following the release but then trend upward for the next 40 minutes, plateauing roughly thereafter. There is no apparent movement prior to the press release. In contrast, prices rise prior to press releases associated with positive surprises and fall at the announcement, thereafter roughly plateauing.

The second graph shown in Figure 6 presents average abnormal oil returns on a minute-by-minute basis from 10 minutes prior to the time of the press release through 150 minutes after. The graph shows that volatility spikes at the time of the press release and gradually dies out over the next 150 minutes.

#### 3.4.3. Intraday Relation Between Log Price Changes and Target Surprises

Following Rosa (2014), we compute log price changes for the period from 10 minutes prior to the issuance of the press release through 50 minutes following. We note however, that the behavior shown in Figure 6 over the 60 minute period does not give a clear indication of the relation between the target surprise and the intraday log price change. As we noted earlier, Roas (2014) documents a negative relation. Basisthan and Kurov (2015) examine the change in price over the period from 10 minutes before the press release through 3 hours afterward and also find a negative relation, Basistha and Kurov (2015) however present evidence that the relation between target surprises and oil futures returns around the time of FOMC press releases is driven by information released following special meetings. These special meetings involve conference calls. We therefore present results for two separate models. The first model treats the target surprise as the sole explanatory variable:

$$r_{i,t} = \alpha_i + \beta_i TS_t + \varepsilon_{i,t} \tag{17}$$

where $r_{i,t}$ is the log price change of commodity *i* for the intraday interval measured on the date of the press release, *t*, and $TS_t$ is the target rate surprise for the time interval. The second model controls for conference call meetings. We test the null hypothesis that the type of meeting does not influence the price response using the following specification:

$$r_{i,t} = \alpha_i + \beta_{i,C} D_{C,t} + \beta_{i,TS} TS_t + \beta_{i,DTS} \left( D_{C,t} \bullet TS_t \right) + \varepsilon_{i,t} \tag{18}$$

where $D_{C,t}$ takes the value 1 if the meeting involved a conference call, and 0 otherwise. If there is no difference in response to the target surprise between regular and special meetings, we would expect $\beta_{i,DTS}$ not to be significantly different from 0. We study the period February 3, 1999, through December 16, 2008. Following the end of 2008, target rates were set and held at very low levels, essentially eliminating target rate changes as a policy tool. We therefore restrict our attention here to the period prior to the end of 2008.

Table 13 reports the results. The results shown in columns 1 through 4 indicate a negative response of oil price changes and natural gas price changes to the target surprise measure; however, neither is significantly different from zero. The results reported in columns 5 through 8 show that the price responses to target surprises are uniformly negative, but only the result for natural gas is significantly different from zero at conventional levels.. It should be noted, however, that the coefficients of both the dummy variables for conference calls and the coefficients of the interaction variables are negative and significantly different from zero. These results suggest that information revealed following the conference calls during the sample period had a differential and negative effect, but that otherwise there was no statistically significant relation between responses and target surprises consistent with the results reported by Basistha and Kurov (2015).[52]

#### 3.4.4. Response at the Daily Frequency

Rosa (2014) and Basistha and Kurov (2015) find no statistically significant relation when price changes are measured over days in the immediate vicinity of the press release date. We examine the relation between log price changes measured over the day of the announcement, focusing on crude oil, gasoline, and distillate prices. Table 14 reports the results of estimating equation (17). The results indicate a negative response coefficient for oil futures prices and gasoline futures prices, but neither is significantly different from zero at the 5% level. Furthermore, the response coefficient for the distillate model is also not significantly different from zero. The results indicate no statistically significant relation between target surprises and log price changes for any of the commodities for the day of the press release. The results are similar to those reported by Kilian and Vega (2011), Rosa (2014), and Basistha and Kurov (2015). These results are consistent with the patterns in the behavior of prices shown in Figure 6.[53]

### 3.5. Price Response to Announced Changes in the Strategic Petroleum Reserve

From time to time, the President has made decisions to inject or withdraw crude oil from the SPR, which are then implemented by the Department of Energy. The Energy Policy and Conversation act states that a "severe energy supply interruption shall be deemed to exist if the President determines that

A. an emergency situation exists and there is a significant reduction in supply which is of significant scope and duration;

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[52] Separate results incorporating a measure of the path of monetary policy do not change the conclusions.

[53] In unreported results, we also estimate equation (7) $r_{i,t} = \alpha_i + \beta_{i1} TS_t + \beta_{i2} PS_t + \varepsilon_{i,t}$ including the variable *PS*, which is an indicator of the path of monetary policy. The estimated coefficients for neither *TS* nor *PS* are ever significantly different from zero.

B. a severe increase in the price of petroleum products has resulted from such an emergency situation; and

C. such increase is likely to cause a major adverse impact on the national economy" (p. 485, as cited in the U.S. Congress, Energy Policy and Conservation Act, Public Law 94.163, as amended through Public Law 113.67 (2013)).

Adjustments of the amount held in the SPR either take supply off the market or add supply to the market thereby potentially influencing prices. We investigate the impact of such additions and withdrawals that have occurred since the SPR was created. The frequency of such actions is not large. We identify 26 dates between February 11, 1999, and February 21, 2017, inclusive, on which news was released. In 16 cases, the announcement indicated an increase in the SPR; in 10 cases, a decrease was announced. The sources of the announcement data are the records and website of the U.S. Department of Energy. The time of day of each announcement is not available, so for this analysis, we are restricted to examining daily price changes.

### 3.5.1. Price Response at the Daily Frequency

We compute daily log futures price changes for crude oil, natural gas, gasoline, and distillate and estimate models that account for whether the news release indicated a planned increase or decrease in crude held in the SPR. The model estimated has the following form:

$$r_{i,t} = \alpha_i + \beta_{i,C} D_{C,t} + \varepsilon_{i,t} \tag{19}$$

where the dummy variable $D_{C,t}$ takes the value 1 if the announcement indicated an increase in the crude held in the SPR, and 0 otherwise. Table 15 reports the estimation for several daily time intervals: a) the day of the announcement (denoted by column heading (0,0)); and, b) the day of the announcement plus the following day (denoted (0,1)). As the amounts involved are not always clear, we restrict the analysis to the dichotomous model displayed as equation (19).

We find that crude oil, gasoline, and distillate prices respond positively to announcements of planned increases in storage in the SPR. These responses are significantly different from zero at the 5% level for crude oil, and at the 10% level for distillate and gasoline. There is no statistically significant response in natural gas prices. Conversely, the response to announcements of decreases in the SPR storage is negative and significant at the 5% level for crude oil on the day of the announcement. Although the point estimates of gasoline's and distillate's responses to announcements of decreases are also negative, those response coefficients are not significantly different from zero at conventional levels. The results suggest that planned increases in the SPR have a positive impact on futures prices of oil and petroleum products. However, an important caveat is in order. The small sample size available to us makes it difficult to generalize, so the results should be interpreted with that in mind.

## 4. Summary

This study reviews the existing literature that has focused on the intraday and daily changes in the futures prices of crude oil, gasoline, distillate, and natural gas in response to information releases about a) inventories stored in the United States, b) macroeconomic indicator variables, c) monetary policy through unexpected target rate changes, and d) increases and decreases in the amount of crude oil stored in the SPR. The emphasis in the literature is on the response to unexpected information. After reviewing the extant literature we present empirical results which confirm but also extend our understanding of how energy futures prices respond to unexpected information for the four categories of events. We explore the speed at which prices respond to the unexpected information revealed in the announcements listed above and provide evidence generally confirming results documented in the literature but provide additional insights into the responses on an intraday level in contrast to a daily level. We study only the prices of energy futures contracts traded in the United States and only the front month contract prices for oil, gasoline, distillate and natural gas.

We present evidence that oil, natural gas, gasoline, and distillate futures prices respond inversely not only to information about unexpected changes in the product's own inventory, but that there are cross-product effects as well. Specifically, on the day the WPSR is issued (reporting inventory levels for oil, gasoline, and distillate) by the EIA (typically Wednesday), oil, gasoline, and distillate futures prices respond to both the respective unexpected news about changes in inventory for the commodity itself but also to unexpected news about changes in the inventories of the other two commodities. Likewise, the WNGSR (reporting storage levels for natural gas) is typically released by the EIA on Thursdays, and we find that, on Thursdays, oil and distillate futures prices respond inversely to unexpected news about changes in natural gas in storage. Finally, natural gas futures prices respond inversely on Wednesdays to unexpected news about changes in the inventories of oil, gasoline, and distillate.

The study finds that the advent of 24-hour electronic trading influenced the reaction of oil, natural gas, gasoline, and distillate futures prices to unexpected information about changes in inventories. Specifically, the response of oil, gasoline, and distillate futures prices became smaller following the advent of electronic trading; interestingly, the opposite is found for natural gas futures prices. Results are presented indicating that the volatility of the futures prices examined around the time of the EIA weekly releases is positively related to the absolute size of the unexpected change in inventories. The response of volatility of gasoline and natural gas prices to the absolute size of the surprise was smaller when the sign of the raw surprise was negative.

Prices respond positively at the time of the information release to unexpected news about the macroeconomic aggregates we study but in the case of oil futures prices tend to revert when the surprise is positive. There is no relation between such surprises and daily measures of price changes. The immediate reaction of prices to unexpected changes in the target federal funds rate (as inferred from federal funds futures prices) after FOMC press releases following meetings is negative for press releases that follow conference call meetings, but is otherwise insignificant.

Finally, on the day of the information release, energy futures prices react at the daily frequency to announcements of increases in the amount of oil to be stored in the SPR and react negatively to announcements of decreases. These results are found for oil, gasoline and distillate futures prices but not for natural gas futures prices. These results, however, should be viewed with caution due to the small sample size.

## 5. Figures

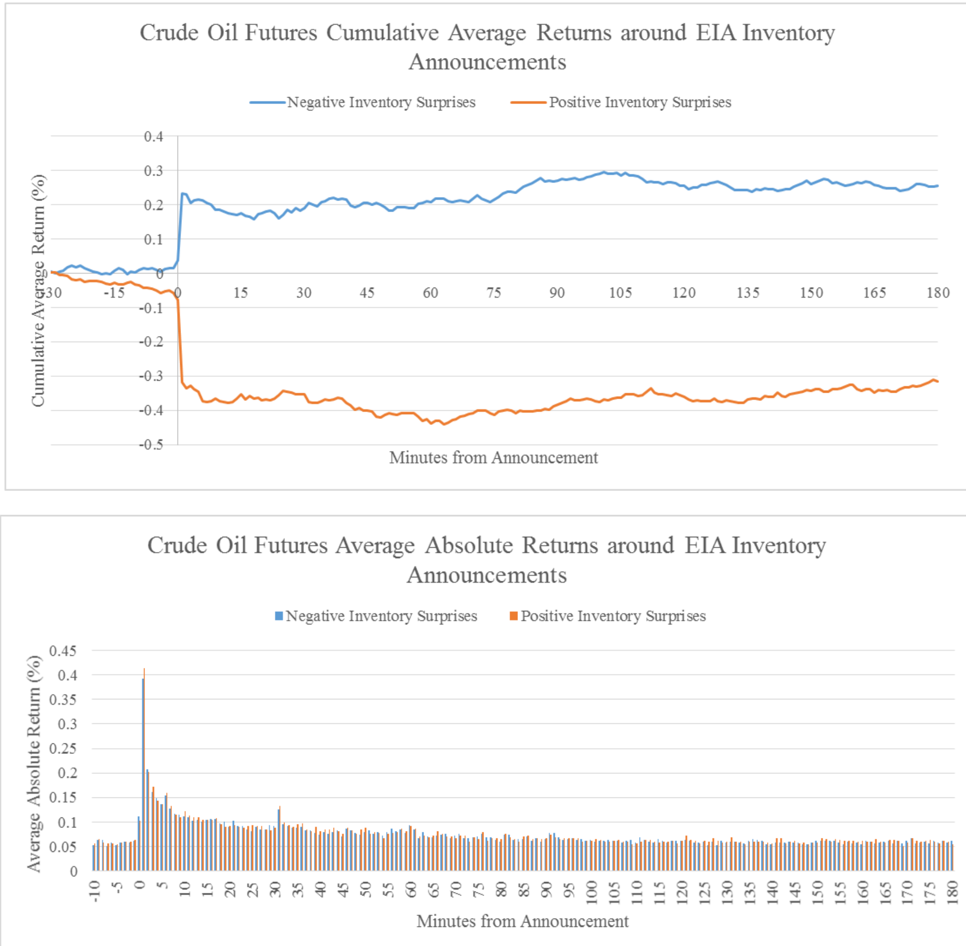



Figure 1

Intraday oil futures price response to positive and negative unexpected changes in oil inventory based upon 1-minute log price changes for the front month contract. Top graph: Cumulative average log price changes are displayed beginning 30 minutes prior to the release of the Weekly Petroleum Status Report by the United State Energy Information Administration. Bottom graph: Average absolute returns by minute for positive and negative surprises (-10 through +180 minutes). Sample period 7/16/2003 – 6/30/2017.

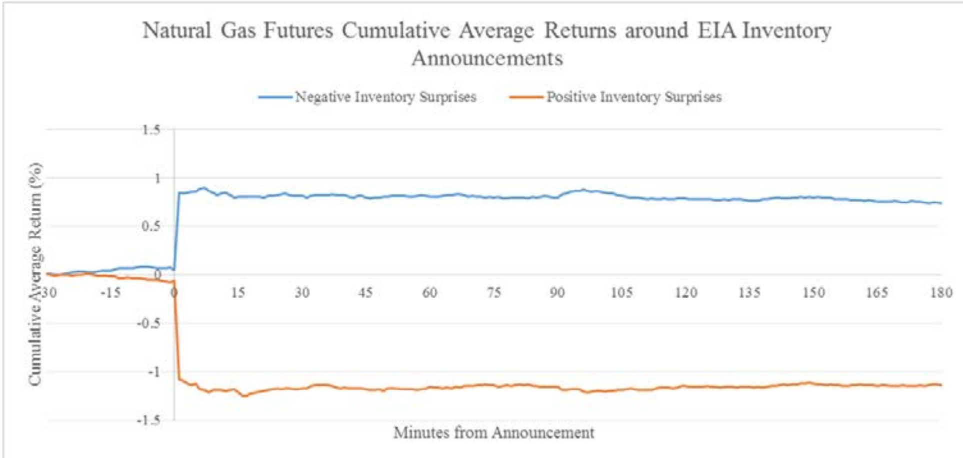
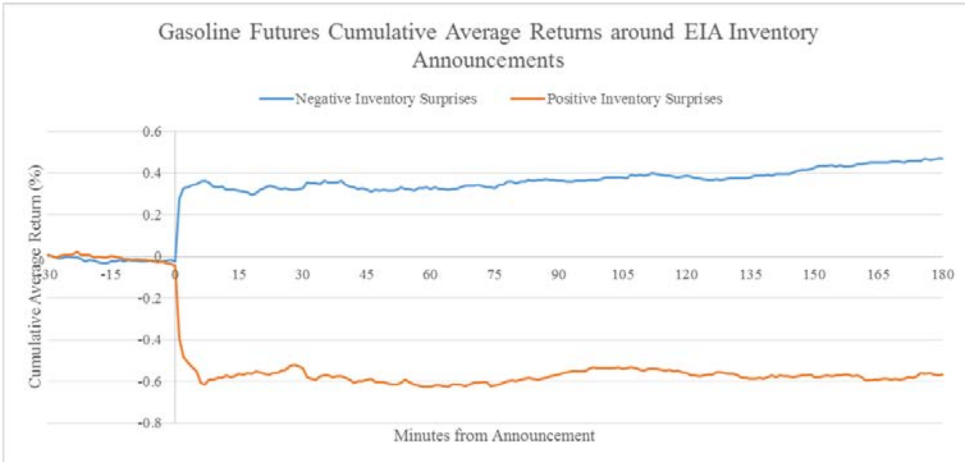




Figure 2

Intraday natural gas futures price response to positive and negative unexpected changes in natural gas inventory based upon 1-minute log price changes for the front month contract. Top graph: Cumulative average log price changes are displayed beginning 30 minutes prior to the release of the Weekly Natural Gas Storage Report by the United State Energy Information Administration through 180 minutes following. Bottom graph: Average absolute returns by minute for positive and negative surprises (-10 through +180 minutes). Sample period 7/16/2003 – 6/30/2017.



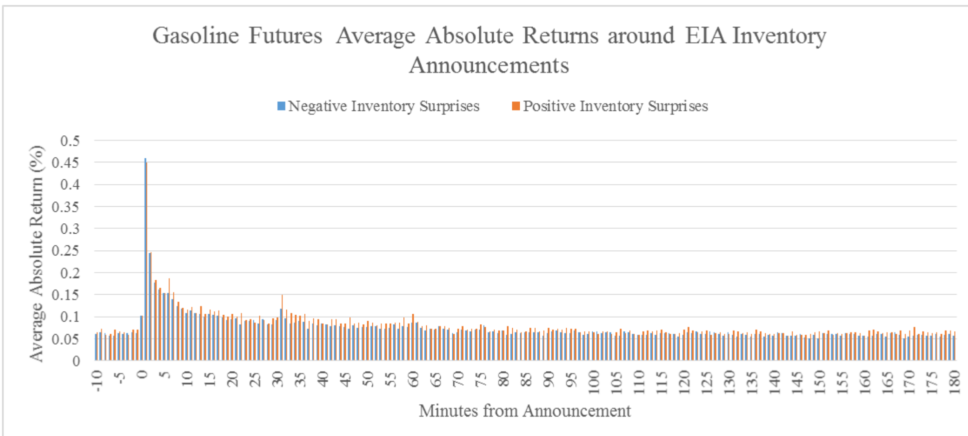
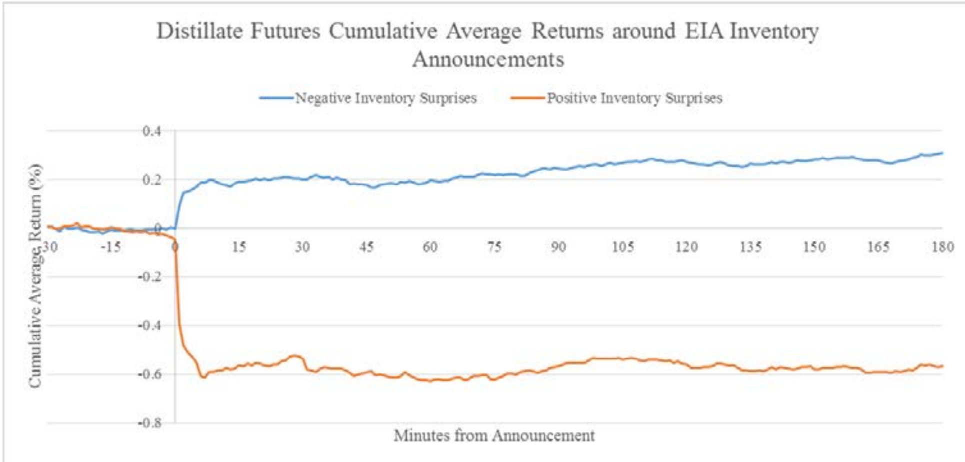




Figure 3

Intraday gasoline futures price response to positive and negative unexpected changes in gasoline inventory based upon 1-minute log price changes for the front month contract. Top graph: Cumulative average log price changes are displayed beginning 30 minutes prior to the release of the Weekly Petroleum Status Report by the United State Energy Information Administration through 180 minutes following. Bottom graph: Average absolute returns by minute for positive and negative surprises (-10 through +180 minutes). Sample period 7/16/2003 – 6/30/2017.



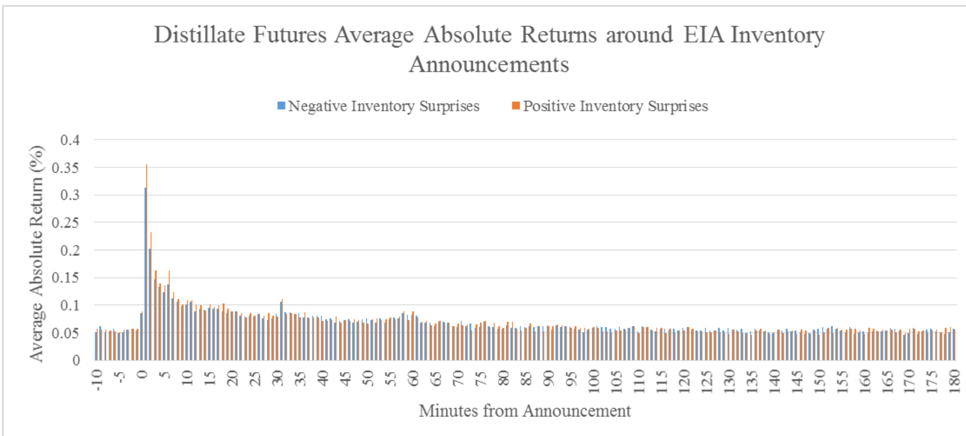
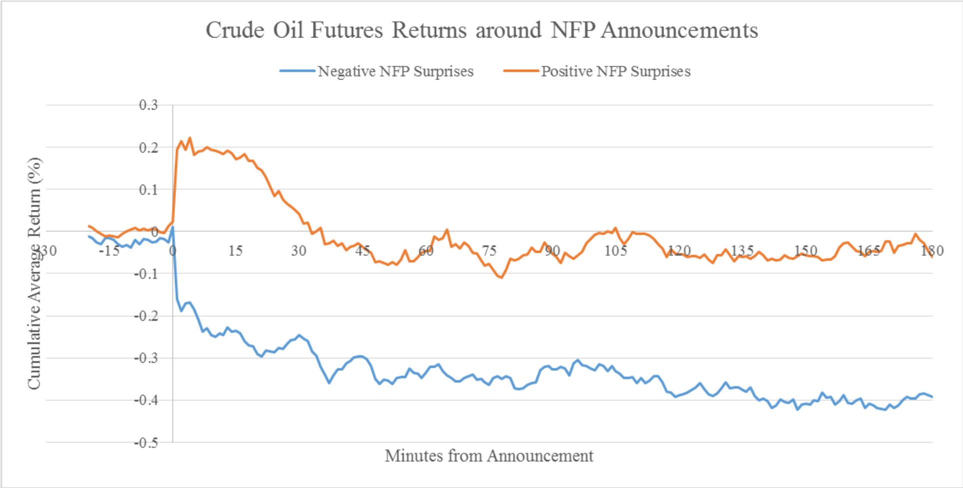




Figure 4

Intraday distillate futures price response to positive and negative unexpected changes in gasoline inventory based upon 1-minute log price changes for the front month contract. Top graph: Cumulative average log price changes are displayed beginning 30 minutes prior to the release of the Weekly Petroleum Status Report by the United State Energy Information Administration through 180 minutes following. Bottom graph: Average absolute returns by minute for positive and negative surprises (-10 through +180 minutes). Sample period 7/16/2003 – 6/30/2017.



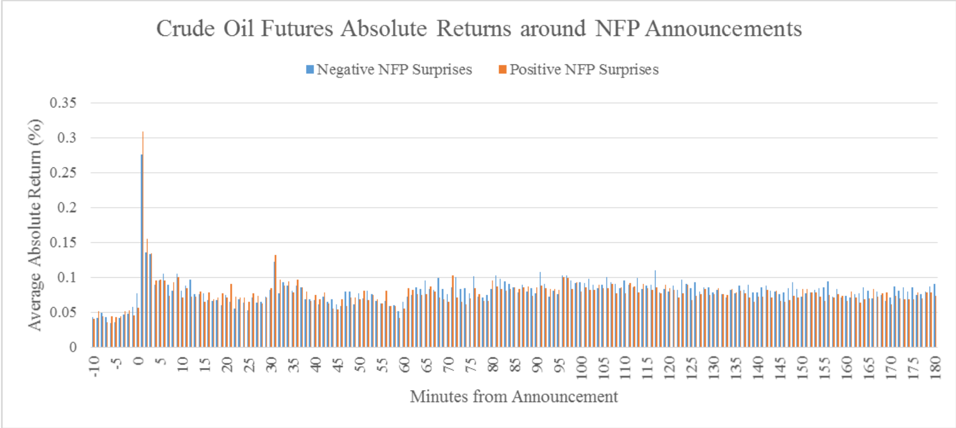
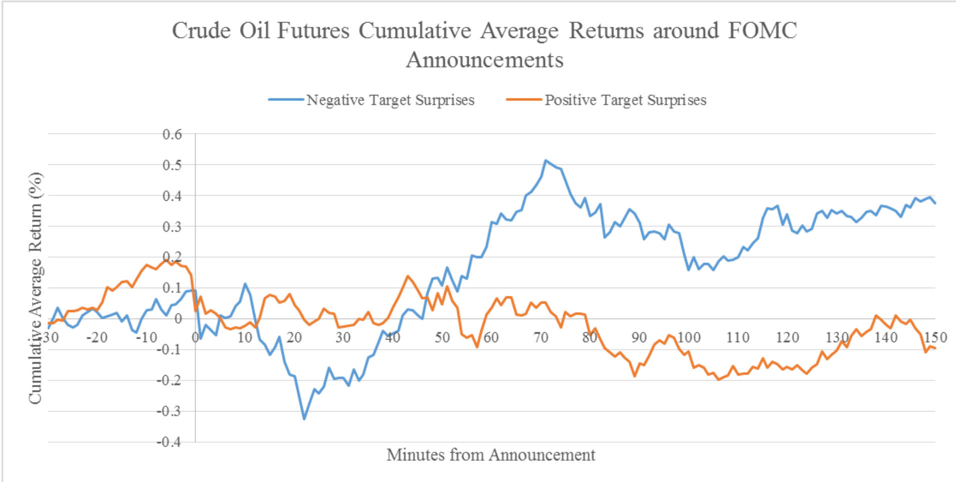




Figure 5

Intraday oil futures price response to positive and negative surprises in the changes in the U.S. Employees on Nonfarm Payrolls Month-to-Month Change (U.S. Bureau of Labor Statistics) based upon 1-minute log price changes for the front month contract. Top graph: Cumulative log price changes are displayed beginning 20 minutes prior to the release of the report through 180 minutes following. Bottom graph: Average absolute returns by minute for positive and negative surprises (-10 through +180 minutes). Sample period 7/16/2003 – 6/30/2017.



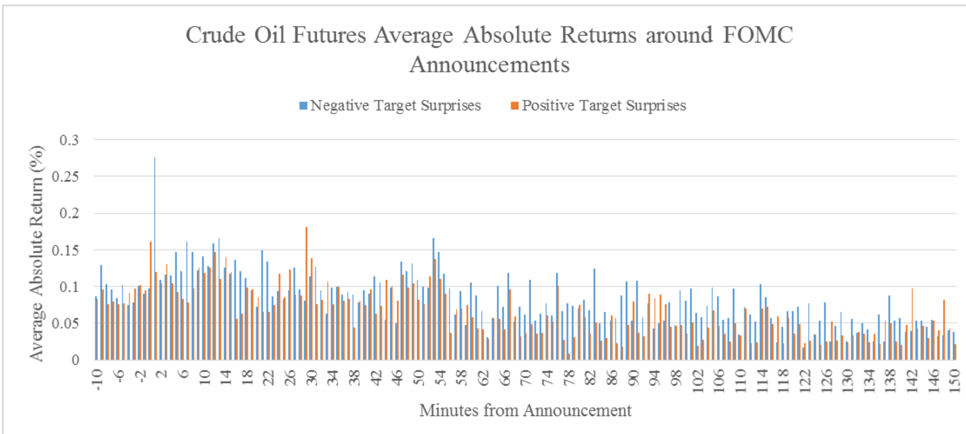




Figure 6

Intraday oil futures price response to positive and negative target federal funds surprises following Federal Reserve Open Market Committee meetings based upon 1-minute log price changes for the front month contract. Top graph: Cumulative log price changes are displayed beginning 30 minutes prior to the release of the report through 150 minutes following. Bottom graph: Average absolute returns by minute for positive and negative surprises (-10 through +150 minutes). Period sampled is 5/18/1999 – 12/16/2008.

## 6. Tables

**Table 1**

**Actual and Forecasted Inventory Changes**

**Weekly changes in inventory.** Raw surprises equal actual change in inventory minus median of analysts' forecasted changes. Actual changes in weekly reported inventory are from the archives of the U.S. Energy Information Administration. Refer to https://www.eia.gov/dnav/pet/pet_stoc_wstk_dcu_nus_w.htm for oil, gasoline, and distillate inventory data and to https://www.eia.gov/dnav/ng/ng_stor_wkly_s1_w.htm for natural gas inventory data. Forecasts of weekly changes are from Bloomberg and the analyst forecast summary reports posted on Bloomberg. The sample period is 7/16/2003 – 6/30/2017. Oil, gasoline, and distillate are stated in thousands of barrels. Natural gas is stated in billion cubic feet (BCF). Tests of the null hypothesis that the raw surprise is equal to 0 are never rejected.

| | Oil | Gasoline | Distillate | Natural Gas |
|---|---|---|---|---|
| Average Actual Change | 319.60 | 38.72 | 55.07 | 1.47 |
| Average Raw Surprise (Average Actual Change - Median Forecasted Change) | -19.07 | 73.84 | 56.02 | 0.36 |
| Average of Absolute Value of Raw Surprises | 2568.39 | 1715.81 | 1407.18 | 6.35 |
| Standard Deviation of Raw Surprise | 3326.59 | 2163.65 | 1827.45 | 8.39 |
| Number of Analysts Contributing Forecasts | 12.62 | 12.81 | 12.82 | 22.30 |

**Table 2**

**Basic Model Estimation Results**

Results presented in this table are for estimation of the model $r_{i,t} = \alpha_i + \beta_i S_{i,t} + \varepsilon_{i,t}$, where $r_{i,t}$ is the 15-minute return from 10:25 AM ET to 10:40 AM ET on the date *t* the WPSR or the WNGSR is issued by the EIA for commodity *i*. The explanatory variable is the standardized unexpected change in inventory for commodity *i* computed as the difference between the actual change from the prior week as implied by the EIA report and the Bloomberg analyst median forecast of the change, standardized by the standard deviation of the raw deviations.

The t-statistics are based on White's heteroscedasticity-adjusted standard errors and are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively. The sample period is 7/16/2003 – 6/30/2017.

| | Oil | | Gasoline | | Distillate | | Natural Gas | | |
|---|---|---|---|---|---|---|---|---|---|
| Variables | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| Oil Surprise | -0.292*** | -0.329*** | | -0.191*** | | -0.226*** | -0.094*** | -0.112*** | |
| | (-8.99) | (-10.84) | | (-5.82) | | (-8.44) | (-3.22) | (-4.04) | |
| Gasoline Surprise | | -0.234*** | -0.516*** | -0.484*** | | -0.169*** | | -0.105*** | |
| | | (-8.14) | (-13.67) | (-13.27) | | (-6.58) | | (-3.12) | |
| Distillate Surprise | | -0.208*** | | -0.134*** | -0.355*** | -0.333*** | | -0.107*** | |
| | | (-6.65) | | (-3.34) | (-10.02) | (-9.71) | | (-2.58) | |
| Natural Gas Surprise | | | | | | | | | -1.005*** |
| | | | | | | | | | (-15.51) |
| Intercept | -0.088*** | -0.073*** | -0.090*** | -0.085*** | -0.088*** | -0.082*** | -0.090*** | -0.083*** | -0.187*** |
| | (-3.00) | (-2.79) | (-2.81) | (-2.76) | (-3.23) | (-3.26) | (-2.76) | (-2.58) | (-3.35) |
| Observations | 729 | 729 | 727 | 727 | 729 | 729 | 729 | 729 | 725 |
| Adjusted $R^2$ | 0.117 | 0.290 | 0.262 | 0.306 | 0.187 | 0.299 | 0.010 | 0.044 | 0.310 |

**Table 3**

**Basic Model – Natural Gas Surprise**

Results presented in this table are for estimation of the model $r_{i,t} = \alpha_i + \beta_i S_{i,t} + \varepsilon_{i,t}$, where $r_{i,t}$ is the 15-minute return from 10:25 AM ET to 10:40 AM ET on the date *t* the WPSR or the WNGSR is issued by the EIA for commodity *i*. The explanatory variable is the standardized unexpected change in natural gas inventory computed as the difference between the actual change from the prior week as implied by the EIA report and the Bloomberg analyst median forecast of the change, standardized by the standard deviation of the raw deviations. The sample period is 7/16/2003 – 6/30/2017.

The t-statistics are based on White's heteroscedasticity-adjusted standard errors and are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively. The sample period is 7/16/2003 – 6/30/2017.

| | Oil | Gasoline | Distillate | Natural Gas |
|---|---|---|---|---|
| Variables | (1) | (2) | (3) | (4) |
| Natural Gas Surprise | -0.066*** | -0.037 | -0.066*** | -1.005*** |
| | (-2.93) | (-1.36) | (-3.09) | (-15.51) |
| Intercept | -0.032* | -0.028 | -0.021 | -0.187*** |
| | (-1.82) | (-1.40) | (-1.21) | (-3.35) |
| Observations | 725 | 722 | 725 | 725 |
| Adjusted $R^2$ | 0.018 | 0.003 | 0.019 | 0.310 |

**Table 4**

**The Impact of Electronic Trading**

Results presented in this table are for estimation of the model

$r_{i,t} = \beta_{i,0} + \beta_{i,E} E_t + \beta_{i,S} S_{i,t} + \beta_{i,SE} \left( S_{i,t} \bullet E_t \right) + \varepsilon_{i,t}$, where $r_{i,t}$ is the 15-minute return from 10:25 AM ET to 10:40 AM ET on the date *t* the WPSR or the WNGSR is issued by the EIA for commodity *i*. The explanatory variable is the standardized unexpected change in inventory for commodity *i* computed as the difference between the actual change from the prior week as implied by the EIA report and the Bloomberg analyst median forecast of the change, standardized by the standard deviation of the raw deviations. The variable labeled $E_t$ in the model takes the value 1 for all reports issued or or after June 6, 2006, and 0 otherwise. For expository purposes, we refer to *E* in the table using the notation *Electronic*.

The t-statistics are based on White's heteroscedasticity-adjusted standard errors and are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively. The sample period is 7/16/2003 – 6/30/2017.

| | Oil | Gasoline | Distillate | Natural Gas |
|---|---|---|---|---|
| Variables | (1) | (2) | (3) | (4) |
| Oil Surprise | -0.429*** | | | |
| | (-4.48) | | | |
| Gasoline Surprise | | -0.746*** | | |
| | | (-6.47) | | |
| Distillate Surprise | | | -0.664*** | |
| | | | (-6.34) | |
| Natural Gas Surprise | | | | -0.708*** |
| | | | | (-6.53) |
| Electronic | 0.024 | 0.071 | 0.044 | 0.221 |
| | (0.30) | (0.79) | (0.53) | (1.57) |
| Electronic× Oil Surprise | 0.158 | | | |
| | (1.56) | | | |
| Electronic× Gas Surprise | | 0.276** | | |
| | | (2.27) | | |
| Electronic× Distillate Surprise | | | 0.363*** | |
| | | | (3.28) | |
| Electronic× Natural Gas Surprise | | | | -0.455*** |
| | | | | (-3.44) |
| Intercept | -0.106 | -0.147* | -0.122 | -0.366*** |
| | (-1.45) | (-1.76) | (-1.54) | (-2.89) |
| Observations | 729 | 727 | 729 | 725 |
| Adjusted $R^2$ | 0.118 | 0.272 | 0.211 | 0.325 |

**Table 5**

**Electronic Trading Model – Natural Gas Surprise**

Results presented in this table are for estimation of the model

$r_{i,t} = \beta_{i,0} + \beta_{i,E} E_t + \beta_{i,S} S_{i,t} + \beta_{i,SE} \left( S_{i,t} \bullet E_t \right) + \varepsilon_{i,t}$, where $r_{i,t}$ is the 15-minute return from 10:25 AM ET to 10:40 AM ET on the date *t* the WPSR or the WNGSR is issued by the EIA for commodity *i*. The explanatory variable is the standardized unexpected change in natural gas inventory computed as the difference between the actual change from the prior week as implied by the EIA report and the Bloomberg analyst median forecast of the change, standardized by the standard deviation of the raw deviations. The variable labeled *E* in the model takes the value 1 for all reports issued on or after June 6, 2006, and 0 otherwise. For expository purposes, we refer to *E* in the table using the notation *Electronic*.

The t-statistics are based on White's heteroscedasticity-adjusted standard errors and are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively. The sample period is 7/16/2003 – 6/30/2017.

| | Oil | Gasoline | Distillate | Natural Gas |
|---|---|---|---|---|
| Variables | (1) | (2) | (3) | (4) |
| Natural Gas Surprise | -0.085** | -0.087** | -0.116*** | -0.708*** |
| | (-2.21) | (-2.09) | (-2.62) | (-6.53) |
| Electronic | 0.024 | 0.042 | 0.031 | 0.221 |
| | (0.47) | (0.65) | (0.51) | (1.57) |
| Electronic× Natural Gas Surprise | 0.030 | 0.078 | 0.078 | -0.455*** |
| | (0.63) | (1.43) | (1.59) | (-3.44) |
| Intercept | -0.051 | -0.060 | -0.045 | -0.366 |
| | (-1.04) | (-0.99) | (-0.76) | (-2.89) |
| | | | | |
| Observations | 725 | 722 | 725 | 725 |
| Adjusted $R^2$ | 0.016 | 0.007 | 0.024 | 0.325 |

**Table 6**

**The Response of Volatility to Inventory Surprises**

Results presented in this table are for estimation of the model $|r_{i,t}| = \beta_0 + \beta_i |S_{i,t}| + \omega_{i,t}$, where $|r_{i,t}|$ is the absolute value of the 15-minute return from 10:25 AM ET to 10:40 AM ET on the date *t* the WPSR or the WNGSR is issued by the EIA for commodity *i*. The explanatory variable is the absolute value of the standardized unexpected change in inventory computed as the difference between the actual change from the prior week as implied by the EIA report and the Bloomberg analyst median forecast of the change, standardized by the standard deviation of the raw deviations.

The t-statistics are based on White's heteroscedasticity-adjusted standard errors and are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively. The sample period is 7/16/2003 – 6/30/2017.

| | Oil | | Gasoline | | Distillate | | Natural Gas | | |
|---|---|---|---|---|---|---|---|---|---|
| Variables | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| Oil Surprise | 0.123*** | 0.117*** | | 0.022 | | 0.020 | -0.032 | -0.036 | |
| | (3.26) | (3.03) | | (0.50) | | (0.61) | (-0.90) | (-1.02) | |
| Gasoline Surprise | | 0.068* | 0.233*** | 0.227*** | | 0.031 | | 0.024 | |
| | | (1.69) | (4.17) | (4.29) | | (0.81) | | (0.50) | |
| Heating oil Surprise | | 0.052 | | 0.036 | 0.149*** | 0.143*** | | 0.032 | |
| | | (1.09) | | (0.55) | (2.85) | (2.76) | | (0.65) | |
| Natural Gas Surprise | | | | | | | | | 0.582*** |
| | | | | | | | | | (7.94) |
| Intercept | 0.516*** | 0.427*** | 0.531*** | 0.492*** | 0.467*** | 0.431*** | 0.577*** | 0.536*** | 0.910*** |
| | (16.46) | (7.95) | (12.68) | (7.21) | (12.01) | (7.92) | (14.64) | (7.72) | (15.72) |
| Observations | 729 | 729 | 727 | 727 | 729 | 729 | 729 | 729 | 725 |
| Adjusted $R^2$ | 0.016 | 0.022 | 0.038 | 0.037 | 0.025 | 0.024 | -0.001 | -0.002 | 0.098 |

**Table** 7

**Volatility Model – Natural Gas Surprise**

Results presented in this table are for estimation of the model $|r_{i,t}| = \beta_0 + \beta_i |S_{i,t}| + \omega_{i,t}$, where $|r_{i,t}|$ is the absolute value of the 15-minute return from 10:25 AM ET to 10:40 AM ET on the date *t* the WPSR or the WNGSR is issued by the EIA for commodity *i*. The explanatory variable is the absolute value of the standardized unexpected change in inventory computed as the difference between the actual change from the prior week as implied by the EIA report and the Bloomberg analyst median forecast of the change, standardized by the standard deviation of the raw deviations.

The t-statistics are based on White's heteroscedasticity-adjusted standard errors and are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively. The sample period is 7/16/2003 – 6/30/2017.

| | Oil | Gasoline | Distillate | Natural Gas |
|---|---|---|---|---|
| Variables | (1) | (2) | (3) | (4) |
| Natural Gas Surprise | 0.084*** | 0.105*** | 0.096*** | 0.582*** |
| | (3.14) | (3.27) | (4.22) | (7.94) |
| Intercept | 0.269*** | 0.271*** | 0.237*** | 0.910*** |
| | (13.45) | (12.07) | (12.72) | (15.72) |
| Observations | 725 | 722 | 725 | 725 |
| Adjusted $R^2$ | 0.024 | 0.027 | 0.033 | 0.098 |

**Table 8**

**Volatility Model – Electronic Trading Regime**

Results presented in this table are for estimation of the model

$\left|r_{i,t}\right| = \beta_{i,0} + \beta_{i,E} E_t + \beta_i \left|S_{i,t}\right| + \beta_{i,SE}\left(\left|S_{i,t}\right| \bullet E_t\right) + \omega_{i,t}$ where $\left|r_{i,t}\right|$ is the absolute value of the 15-minute return from 10:25 AM ET to 10:40 AM ET on the date *t* the WPSR or the WNGSR is issued by the EIA for commodity *i*. The explanatory variable is the absolute value of the standardized unexpected change in inventory for commodity *i* computed as the difference between the actual change from the prior week as implied by the EIA report and the Bloomberg analyst median forecast of the change, standardized by the standard deviation of the raw deviations. The variable labeled *E* in the model takes the value 1 for all reports issued on or after June 6, 2006, and 0 otherwise. For expository purposes, we refer to *E* in the table using the notation *Electronic*. The sample period is 7/16/2003 – 6/30/2017.

The t-statistics are based on White's heteroscedasticity-adjusted standard errors and are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively. The sample period is 7/16/2003 – 6/30/2017.

| | Oil | Gasoline | Distillate | Natural Gas |
|---|---|---|---|---|
| Variables | (1) | (2) | (3) | (4) |
| Oil Surprise | 0.239** | | | |
| | (2.36) | | | |
| Gasoline Surprise | | 0.348** | | |
| | | (2.23) | | |
| Distillate Surprise | | | 0.335*** | |
| | | | (2.68) | |
| Natural Gas Surprise | | | | 0.559*** |
| | | | | (4.74) |
| Electronic | -0.111 | -0.241** | -0.249*** | 0.108 |
| | (-1.38) | (-2.18) | (-2.60) | (0.84) |
| Electronic× Oil Surprise | -0.117 | | | |
| | (-1.08) | | | |
| Electronic× Gas Surprise | | -0.119 | | |
| | | (-0.71) | | |
| Electronic× Distillate Surprise | | | -0.192 | |
| | | | (-1.41) | |
| Electronic× Natural Gas Surprise | | | | 0.066 |
| | | | | (0.44) |
| Intercept | 0.589*** | 0.709*** | 0.643*** | 0.805*** |
| | (8.12) | (7.03) | (7.41) | (7.39) |
| Observations | 729 | 727 | 729 | 725 |
| Adjusted $R^2$ | 0.031 | 0.072 | 0.098 | 0.098 |

**Table 9**

**Volatility Model – Asymmetric Response Test**

Results presented in this table are for estimation of the model

$|r_{i,t}| = \beta_{i,0} + \beta_{i,D}\,(D_{S<0}) + \beta_{i,S}\,|S_{i,t}| + \beta_{i,SD}\,\{|S_{i,t}| \bullet D_{S<0}\} + \omega_{k,t}$, where $|r_{i,t}|$ is the absolute value of the 15-minute return from 10:25 AM ET to 10:40 AM ET on the date *t* the WPSR or the WNGSR is issued by the EIA for commodity *i*. The explanatory variable is the absolute value of the standardized unexpected change in inventory computed as the difference between the actual change from the prior week as implied by the EIA report and the Bloomberg analyst median forecast of the change, standardized by the standard deviation of the raw deviations. The dummy variable $D_{S<0} = 1$ if $S_{i,t} < 0$, and 0 otherwise. For expository purposes, the table refers to the dummy variable as the "Negative Surprise Dummy." The t-statistics are based on White's heteroscedasticity-adjusted standard errors and are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively. The sample period is 7/16/2003 – 6/30/2017.

| | 7/16/2003 – 6/28/2017 | | | |
|---|---|---|---|---|
| | Oil | Gasoline | Distillate | Natural Gas |
| Variables | (1) | (2) | (3) | (4) |
| Negative Oil Surprise Dummy | -0.014 | | | |
| | (-0.22) | | | |
| Oil Surprise | 0.173*** | | | |
| | (3.02) | | | |
| Negative Gasoline Surprise Dummy | | 0.161** | | |
| | | (2.05) | | |
| Gasoline Surprise | | 0.355*** | | |
| | | (4.10) | | |
| Negative Distillate Surprise Dummy | | | 0.058 | |
| | | | (0.78) | |
| Distillate Surprise | | | 0.194*** | |
| | | | (2.68) | |
| Negative Natural Gas Surprise Dummy | | | | 0.217* |
| | | | | (1.76) |
| Natural Gas Surprise | | | | 0.713*** |
| | | | | (6.86) |
| Negative Oil Surprise Dummy × Oil Surprise | -0.092<br>(-1.22) | | | |
| Negative Gasoline Surprise × Gas Surprise | | -0.288***<br>(-2.88) | | |
| Negative Distillate Surprise × Distillate Surprise | | | -0.136<br>(-1.40) | |
| Negative Natural Gas Surprise × Natural Gas Surprise | | | | -0.339**<br>(-2.30) |
| Intercept | 0.520*** | 0.464*** | 0.453*** | 0.831*** |
| | (12.02) | (7.57) | (8.33) | (12.07) |
| Observations | 729 | 727 | 729 | 725 |
| Adjusted $R^2$ | 0.021 | 0.053 | 0.029 | 0.103 |

**Table 10**

**Daily Log Price Changes and Surprises**

Results presented in this table are for estimation of the model $r_{i,t} = \alpha_i + \beta_i S_{i,t} + \varepsilon_{i,t}$, where $r_{i,t}$ is a single day or multi-day return relative to the date *t* the WPSR or the WNGSR is issued by the EIA for commodity *i*. The explanatory variable is the standardized unexpected change in inventory for commodity *i* computed as the difference between the actual change from the prior week as implied by the EIA report and the Bloomberg analyst median forecast of the change, standardized by the standard deviation of the raw deviations. Panel A displays results for oil, gasoline, distillate and natural gas futures returns regressed on own inventory surprises. Panel B presents results for oil, gasoline and distillate returns regressed on oil inventory change surprises as well as the natural gas inventory change surprise. The following notation defines the interval over which the log price change is computed: (0,0), day of the report release; (1,1), the day following the release; (1,2), the day following the release through the second day following; (2,2) the second day following the release.

The t-statistics are based on White's heteroscedasticity-adjusted standard errors and are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively. The sample period is 7/16/2003 – 6/30/2017.

**Panel A: Response of Commodity Log Price Changes to Own Inventory Change Surprises**

| | Crude Oil | | | | Gasoline | | | | Distillate | | | | Natural Gas | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) |
| Interval | (0,0) | (1,1) | (1,2) | (2,2) | (0,0) | (1,1) | (1,2) | (2,2) | (0,0) | (1,1) | (1,2) | (2,2) | (0,0) | (1,1) | (1,2) | (2,2) |
| Inventory Surprise | -0.374*** | -0.051 | -0.111 | -0.061 | -0.479*** | -0.096 | -0.209* | -0.114 | -0.390*** | 0.026 | -0.017 | -0.042 | -1.142*** | 0.223** | 0.130 | -0.093 |
| | (-4.13) | (-0.61) | (-0.95) | (-0.74) | (-4.27) | (-1.16) | (-1.80) | (-1.41) | (-5.14) | (-0.35) | (-0.16) | (-0.57) | (-8.25) | -2.19 | -0.74 | (-0.63) |
| Intercept | 0.076 | 0.131 | 0.218** | 0.087 | 0.123 | 0.193** | 0.310*** | 0.117 | 0.225*** | 0.140* | 0.083 | -0.058 | -0.141 | 0.024 | -0.079 | -0.103 |
| | (0.86) | (1.53) | (2.00) | (1.13) | (1.26) | (2.26) | (2.75) | (1.49) | (2.90) | (1.86) | (0.82) | (-0.83) | (-1.04) | (0.23) | (-0.48) | (-0.78) |
| Observations | 729 | 729 | 729 | 729 | 729 | 729 | 729 | 729 | 729 | 729 | 729 | 729 | 729 | 729 | 729 | 729 |
| Adjusted R-squared | 0.022 | -0.001 | 0.000 | -0.001 | 0.031 | 0.000 | 0.003 | 0.001 | 0.032 | -0.001 | -0.001 | -0.001 | 0.090 | 0.005 | -0.001 | -0.001 |

**Table 10 (continued)**

**Panel B: Response of Commodity Log Price Changes to Own Inventory Change Surprises and Natural Gas Surprises**

| | Crude Oil | | Gasoline | | Distillate | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Interval | (1,1) | (1,2) | (1,1) | (1,2) | (1,1) | (1,2) |
| Oil Surprise | -0.051 | -0.112 | | | | |
| t-statistic | (-0.61) | (-0.94) | | | | |
| Gas Surprise | | | -0.095 | -0.214* | | |
| t-statistic | | | (-1.15) | (-1.85) | | |
| Distillate Surprise | | | | | 0.027 | -0.020 |
| t-statistic | | | | | (0.37) | (-0.198) |
| Natural Gas Surprise | 0.006 | 0.088 | -0.018 | 0.064 | -0.018 | 0.050 |
| t-statistic | (0.06) | (0.75) | (-0.21) | (0.51) | (-0.24) | (0.42) |
| Intercept | 0.131 | 0.214** | 0.194** | 0.308*** | 0.141* | 0.080 |
| t-statistic | (1.54) | (1.97) | (2.28) | (2.74) | (1.87) | (0.80) |
| Observations | 729 | 729 | 729 | 729 | 729 | 729 |
| Adjusted R-squared | -0.002 | 0.000 | -0.001 | 0.002 | -0.003 | -0.002 |

**Table 11**

**Intraday Responses to Macroeconomic Surprises**

Columns 1 through 4 display estimation results for the following model:

$$r_{i,t} = \alpha_{i,k} + \beta_{i,k} S_{k,t} + \upsilon_{i,t}$$

where $r_{i,t}$ is the log futures price change for the interval from 5 minutes before the announcement through 10 minutes after for commodity *i* on the date *t* the information is released for the macro measure *k*. *S* denotes the surprise measure, and the subscript *k* identifies the macroeconomic variable. The explanatory variable is the standardized surprise measured as the actual as-reported value minus the median forecast standardized by the standard deviation of the raw deviations. Results are presented as follows: Panel A, response to U.S. nonfarm payrolls report; Panel B, response to U.S. retails sales announcement; Panel C, response to ISM Manufacturing Composite Index release; Panel D, response to U.S. consumer confidence index release. The t-statistics are based on White's heteroscedasticity-adjusted standard errors and are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively.

**Panel A: Response to nonfarm payroll report**

| | (1)<br>Crude Oil | (2)<br>Natural Gas | (3)<br>Gasoline | (4)<br>Distillate |
|---|---|---|---|---|
| $S_{NFP}$ | 0.307*** | 0.124* | 0.288*** | 0.239*** |
| t-statistic | (4.57) | (1.73) | (4.14) | (4.05) |
| Intercept | -0.00227 | -0.0134 | -0.0392 | -0.0429 |
| t-statistic | (-0.057) | (-0.341) | (-1.025) | (-1.364) |
| Observations | 164 | 164 | 151 | 157 |
| Adjusted R-squared | 0.167 | 0.033 | 0.159 | 0.169 |

**Table 11 (continued)**
**Panel B: Response to U.S. retail sales announcement**

| | (1) Crude Oil | (2) Natural Gas | (3) Gasoline | (4) Distillate |
|---|---|---|---|---|
| $S_{RS}$ | 0.111*** | 0.098*** | 0.074* | 0.057* |
| t-statistic | (2.86) | (2.74) | (1.75) | (1.67) |
| Intercept | 0.03 | (0.03) | 0.047** | 0.043** |
| t-statistic | (1.47) | (0.97) | (2.15) | (2.34) |
| Observations | 166 | 166 | 146 | 155 |
| Adjusted R-squared | 0.09 | 0.04 | 0.04 | 0.03 |

**Panel C: Response to ISM Manufacturing Composite Index release**

| | (1) Crude Oil | (2) Natural Gas | (3) Gasoline | (4) Distillate |
|---|---|---|---|---|
| $S_{ISM}$ | 0.0884*** | 0.0383 | 0.0536** | 0.0590** |
| t-statistic | (3.75) | (0.88) | (2.02) | (2.39) |
| Intercept | 0.033 | 0.056 | 0.002 | 0.000 |
| t-statistic | (1.22) | (1.55) | (0.06) | (0.01) |
| Observations | 288 | 281 | 285 | 286 |
| Adjusted R-squared | 0.033 | 0.000 | 0.009 | 0.014 |

**Table 11 (continued)**
**Panel D: Response to consumer confidence index release**

| | (1) Crude Oil | (2) Natural Gas | (3) Gasoline | (4) Distillate |
|---|---|---|---|---|
| $S_{CC}$ | 0.044** | 0.014 | 0.026 | 0.033* |
| t-statistic | (2.16) | (0.44) | (0.99) | (1.85) |
| Intercept | 0.013 | -0.057 | 0.038* | 0.013 |
| t-statistic | (0.72) | (-1.653) | (1.73) | (0.77) |
| Observations | 168 | 166 | 158 | 158 |
| Adjusted R-squared | 0.029 | -0.005 | 0.002 | 0.018 |

**Table 12**

**Daily Responses to Macroeconomic Surprises**

Results presented are from estimation of the model:

$$r_{i,t} = \alpha_{i,k} + \beta_{i,k} S_{k,t} + \upsilon_{i,t}$$

where $r_{i,t}$ is the daily log futures price change for commodity *i* on the date *t* the information is released for the macro measure *k*. *S* denotes the surprise measure, and the subscript *k* identifies the macroeconomic variable. Results are presented as follows: Panel A, response to U.S. nonfarm payrolls report; Panel B, response to U.S. retails sales announcement; Panel C, response to ISM Manufacturing Composite Index release; Panel D, response to U.S. consumer confidence index release. The explanatory variable is the standardized surprise measured as the actual as-reported value minus the median forecast standardized by the standard deviation of the raw deviations. *S* denotes the surprise measure, and the subscript identifies the macroeconomic variable. The interval (0,0) denotes the close-to-close log price change for the day of the announcement, (0,1) is the close-to-close change for the day of the announcement and the following day, and (0,20) is the close-to-close log price change for the day of the announcement through 20 trading days following. The t-statistics are based on White's heteroscedasticity-adjusted standard errors and are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively.

**Panel A: Response to nonfarm payroll report**

| | Crude Oil | | | Gasoline | | | Distillate | | | Natural Gas | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) |
| Interval | (0,0) | (0,1) | (0,20) | (0,0) | (0,1) | (0,20) | (0,0) | (0,1) | (0,20) | (0,0) | (0,1) | (0,20) |
| $S_{NFP}$ | 0.134 | 0.177 | 0.386 | 0.026 | 0.127 | 0.673 | 0.088 | 0.21 | 0.54 | 0.121 | 0.070 | 0.7 |
| t-statistic | (0.98) | (1.14) | (0.64) | (0.20) | (0.83) | (1.05) | (0.67) | (1.45) | (0.82) | (0.91) | (0.25) | (0.85) |
| Intercept | 0.029 | -0.273 | 0.688 | 0.052 | -0.342** | 0.624 | -0.010 | -0.301** | 0.596 | -0.038 | -0.227 | 0.538 |
| t-statistic | (0.25) | (-1.59) | (1.30) | (0.45) | (-2.09) | (1.04) | (-0.09) | (-1.97) | (1.17) | (-0.27) | (-0.94) | (0.62) |
| Observations | 293 | 293 | 293 | 293 | 293 | 293 | 293 | 293 | 293 | 293 | 293 | 293 |

**Table 12 (continued)**
**Panel B: Response to U.S. retail sales announcement**

| | Crude Oil | | | Gasoline | | | Distillate | | | Natural Gas | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) |
| Interval | (0,0) | (0,1) | (0,20) | (0,0) | (0,1) | (0,20) | (0,0) | (0,1) | (0,20) | (0,0) | (0,1) | (0,20) |
| $S_{RS}$ | -0.102 | -0.299 | 0.67 | -0.162 | -0.302 | 0.353 | -0.075 | -0.16 | 0.842 | -0.156 | -0.394 | 0.521 |
| t-statistic | (-0.35) | (-0.52) | (0.72) | (-0.61) | (-0.57) | (0.49) | (-0.28) | (-0.30) | (0.93) | (-0.86) | (-1.29) | (0.80) |
| Intercept | -0.032 | 0.194 | 0.428 | 0.019 | 0.078 | 0.551 | -0.002 | 0.082 | 0.526 | 0.106 | 0.413 | 0.218 |
| t-statistic | (-0.25) | (0.98) | (0.72) | (0.16) | (0.40) | (0.87) | (-0.02) | (0.42) | (0.95) | (0.60) | (1.53) | (0.27) |
| Observations | 292 | 292 | 292 | 292 | 292 | 292 | 292 | 292 | 292 | 292 | 292 | 292 |

**Panel C: Response to ISM Manufacturing Composite Index release**

| | Crude Oil | | | Gasoline | | | Distillate | | | Natural Gas | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) |
| Interval | (0,0) | (0,1) | (0,20) | (0,0) | (0,1) | (0,20) | (0,0) | (0,1) | (0,20) | (0,0) | (0,1) | (0,20) |
| $S_{ISM}$ | 0.177 | 0.137 | 0.623 | 0.178 | 0.187 | 0.551 | 0.198 | 0.187 | 0.604 | 0.154 | 0.529 | 1.564* |
| t-stat | (1.21) | (0.64) | (0.93) | (1.07) | (0.80) | (0.64) | (1.35) | (0.90) | (0.93) | (0.60) | (1.54) | (1.73) |
| Intercept | 0.073 | 0.063 | 0.363 | 0.093 | 0.075 | 0.305 | -0.056 | -0.0451 | 0.296 | -0.126 | -0.171 | 0.124 |
| t-stat | (0.49) | (0.32) | (0.67) | (0.60) | (0.36) | (0.51) | (-0.37) | (-0.23) | (0.56) | (-0.60) | (-0.59) | (0.14) |
| Observations | 292 | 292 | 292 | 292 | 292 | 292 | 292 | 292 | 292 | 292 | 292 | 292 |

**Table 12 (continued)**
**Panel D: Response to consumer confidence index release**

| | Crude Oil | | | Gasoline | | | Distillate | | | Natural Gas | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) |
| Interval | (0,0) | (0,1) | (0,20) | (0,0) | (0,1) | (0,20) | (0,0) | (0,1) | (0,20) | (0,0) | (0,1) | (0,20) |
| $S_{CC}$ | 0.007 | -0.151 | 1.232* | 0.152 | 0.066 | 1.285* | 0.048 | -0.091 | 1.232* | 0.223 | 0.166 | 0.623 |
| t-stat | (0.06) | (-0.76) | (1.86) | (1.13) | (0.30) | (1.78) | (0.43) | (-0.46) | (1.82) | (0.99) | (0.50) | (0.64) |
| Intercept | -0.071 | 0.261 | 0.482 | -0.145 | 0.142 | 0.501 | 0.021 | 0.376** | 0.6 | 0.550** | 0.735** | 0.664 |
| t-stat | (-0.62) | (1.54) | (0.86) | (-1.02) | (0.64) | (0.76) | (0.18) | (2.10) | (1.11) | (2.19) | (2.08) | (0.70) |
| Observations | 292 | 292 | 292 | 292 | 292 | 292 | 292 | 292 | 292 | 292 | 292 | 292 |

**Table 13**

**Intraday Response to FOMC Press Releases**

Results presented in this table are for estimation of the models

$r_{i\tau,t} = \alpha_i + \beta_i TS_t + \varepsilon_{i\tau,t}$ and $r_{i\tau,t} = \alpha_{i0} + \beta_{i1} D_i + \beta_{i2} TS_t + \beta_{i3}\left(D_{it} \bullet TS_t\right) + \varepsilon_{i\tau,t}$, where $r_{i\tau,t}$ is the log price change from 10 minutes prior to the FOMC press release through 50 minutes following, which could have included a conference call, of commodity *i* for the intraday interval measured on the date of the press release, *t*. The explanatory variable is the target rate surprise *TS* computed following Kuttner (2010) as described in Section 6.2. A dummy variable *D* takes the value 1 when the meeting was a conference call and 0 otherwise.

The t-statistics are based on White's heteroscedasticity-adjusted standard errors and are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively.

| | (1) Crude Oil | (2) Natural Gas | (3) Gasoline | (4) Distillate | (5) Crude Oil | (6) Natural Gas | (7) Gasoline | (8) Distillate |
|---|---|---|---|---|---|---|---|---|
| Conf. Call | | | | | -7.001*** | -11.24*** | -49.31*** | -14.35*** |
| t-statistic | | | | | (-9.788) | (-19.67) | (-16.02) | (-14.66) |
| p-value | | | | | (0.00) | (0.00) | (0.00) | (0.00) |
| *TS* | -1.205 | -0.852 | 4.47 | 1.123 | -1.214 | -6.127** | -1.963 | -0.878 |
| t-statistic | (-1.097) | (-0.534) | -0.75 | -0.62 | (-0.775) | (-2.329) | (-1.356) | (-0.681) |
| p-value | (0.28) | (0.59) | (0.46) | (0.54) | (0.44) | (0.02) | (0.18) | (0.50) |
| *TS* x Conf. Call | | | | | -16.89*** | -19.86*** | -110.2*** | -31.89*** |
| t-statistic | | | | | (-6.087) | (-5.992) | (-10.65) | (-9.418) |
| p-value | | | | | (0.00) | (0.00) | (0.00) | (0.00) |
| Constant | -0.080 | -0.180 | -0.152 | -0.039 | -0.040 | -0.104 | 0.148* | 0.048 |
| t-statistic | (-0.887) | (-1.18) | (-0.493) | (-0.34) | (-0.487) | (-0.788) | -1.82 | -0.63 |
| p-value | (0.38) | (0.24) | (0.62) | (0.74) | (0.63) | (0.43) | (0.07) | (0.53) |
| Observations | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 |
| Adjusted R-squared | 0.00563 | -0.00893 | 0.000535 | -0.00508 | 0.337 | 0.402 | 0.918 | 0.697 |

**Table 14**

**Daily Response to FOMC Press Releases**

Results presented in this table are for estimation of the model $r_{i,t} = \alpha_i + \beta_i TS_t + \varepsilon_{i,t}$, where $r_{i\tau,t}$ is the daily log price change for days, *t*, on which the FOMC issued a press release following a meeting, which could have included a conference call meeting, for commodity *i*. The explanatory variable is the target rate surprise *TS* computed following Kuttner (2010) as described in Section 3.4.

The t-statistics are based on White's heteroscedasticity-adjusted standard errors and are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively.

| | Oil | Gasoline | Distillate |
|---|---|---|---|
| Variables | (1) | (2) | (3) |
| Target Rate Surprise | -4.232* | -2.065 | 1.075 |
| | (-1.74) | (-0.89) | (0.52) |
| Intercept | -0.296 | -0.077 | -0.004 |
| | (-0.92) | (-0.25) | (-.02) |
| Observations | 88 | 88 | 88 |
| Adjusted $R^2$ | 0.010 | -0.005 | -0.009 |

**Table 15**

**Daily Responses to Announcements of Changes to the Strategic Petroleum Reserve**

Results presented are from estimation of the model:

$$r_{i,t} = \alpha_i + \beta_{i,C}\left(D_{C,t}\right) + \varepsilon_{i,t}$$

where $r_{i\tau,t}$ is the daily log price change for commodity *i* on the day an announcement about a planned changed in the quantity of oil held in the U.S. Strategic Petroleum Reserve was announced. The dummy variable $D_{C,t}$ takes the value 1 if the announcement indicated an increase in the amount of crude stored in the SPR, and 0 otherwise. The interval (0,0) denotes the close-to-close log price change for the day of the announcement, (0,1) is the close-to-close change for the day of the announcement and the following day. The t-statistics are based on White's heteroscedasticity-adjusted standard errors. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively.

| | Crude Oil | | Gasoline | | Distillate | | Natural Gas | |
|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (4) | (5) | (7) | (8) | (10) | (11) |
| Interval | (0,0) | (0,1) | (0,0) | (0,1) | (0,0) | (0,1) | (0,0) | (0,1) |
| $D_{C,t}$ (Increase in SPR) | 2.486** | 2.596 | 2.828* | 2.870 | 2.291* | 1.760 | 1.178 | 1.607 |
| t-statistic | (2.61) | (1.68) | (1.85) | (1.02) | (2.06) | (0.97) | (0.58) | (0.62) |
| Intercept | -1.474** | -1.933 | -1.438 | -1.642 | -1.294 | -1.276 | -0.0602 | -0.638 |
| t-statistic | (-2.05) | (-1.51) | (-1.07) | (-0.61) | (-1.47) | (-0.79) | (-0.03) | (-0.26) |
| Observations | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 |
| R-squared | 0.214 | 0.112 | 0.146 | 0.056 | 0.152 | 0.045 | 0.02 | 0.023 |
| Adjusted $R^2$ | 0.181 | 0.075 | 0.111 | 0.016 | 0.117 | 0.004 | -0.021 | -0.018 |

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