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Oil prices, speculation, and fundamentals: Interpreting causal relations among spot and futures prices

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ABSTRACT

A consensus that the world oil market is unified begs the question, where do innovations in oil prices enter the market? Here we investigate where changes in the price of crude oil originate and how they spread by examining causal relationships among prices for crude oils from North America, Europe, Africa, and the Middle East on both spot and futures markets. Results indicate that innovations first appear in spot prices for Dubai–Fateh and spread to other spot and futures prices while other innovations first appear in the far month contract for West Texas Intermediate and spread to other exchanges and contracts. Links between spot and futures markets are relatively weak and this may have allowed the long-run relationship between spot and future prices to change after September 2004. Together, these results suggest that market fundamentals initiated a long-term increase in oil prices that was exacerbated by speculators, who recognized an increase in the probability that oil prices would rise over time.

1. Introduction

A considerable portion of the literature on the price of crude oils focuses on the degree to which they are synchronized. Weiner (1991) analyzes correlations between the prices of crude oils from various parts of the world. Results indicate strong correlations between prices of crude oils that are produced within a region, but correlations weaken when crude oil prices are compared across regions. Based on this result, Weiner (1991) argues that the crude oil market is regionalized.

Conversely, Adelman (1984, 1992) argues that the crude oil market is unified. According to the 'Law of One Price,' arbitrage opportunities realign prices for crude oil if they diverge by amounts greater than differences implied by transportation costs and quality (e.g. sulfur content, API gravity index). Several studies find that prices for crude oils from different parts of the globe cointegrate (Gulen, 1997, 1999; Ewing and Harter, 2000; Bachmeier and Griffin, 2006; Bentzen, 2007). The long-run relationship indicated by cointegration implies that the world oil market is unified. These results seem to have won the day—most analysts agree that the world oil market is unified.

A consensus that the world oil market is unified begs the question, where do innovations in world oil prices enter the market? Price changes can enter the market in two general ways. Changes in prices can appear simultaneously in all markets as new information about the supply/demand balance becomes available. Under these conditions, there would be no causal relationships between prices for different crude oils. Alternatively, changes may first appear in the price of one or more crude oils, and these changes may subsequently spread through the market. In this case, crude oils in which price changes first appear serve as benchmarks towards which the prices of other crude oils equilibrate. From an econometric perspective, the price of these markers would "Granger cause" the price of other crude oils.

The way in which price changes appear and spread through the market lies behind the notion of price discovery, which is the process by which supply, demand, and speculative expectations determine the price for a commodity. This notion is used to investigate the relationship between prices in the spot and futures market, including markets for crude oil, motor gasoline, and home heating oil. Quan (1992) finds that spot prices contain information about futures prices, but futures prices do not contain any information about spot prices. This result is undermined by results that indicate futures prices dominate price discovery relative to spot prices for light sweet crude oils (Schwarz and Szakmary, 1994). Silvapulle and Moosa (1999) find that futures prices lead spot prices, with some evidence for a smaller nonlinear causal relationship from spot prices to futures prices. With regard to geography, Hammoudeh et al. (2004) and Hammoudeh and Li (2004) find that the price for motor gasoline on the New York Mercantile Exchange leads prices in the US Gulf coast, Rotterdam, and Singapore (for Singapore, this causal relationship appears after the 1998 Asian financial crisis).

Building on this literature, price discovery in crude oil markets may generate information about the factors that are responsible for the recent increase in crude oil prices. If price innovations appear first in spot prices, market fundamentals may be an important determinant of

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crude oil prices. Conversely, if price innovations appear first in futures markets, speculation may be an important determinant of prices.

Here we investigate where changes in the price of crude oil originate and how they spread. To do so, we examine the statistical ordering among prices for crude oils from North America, Europe, Africa, and the Middle East on both spot and futures markets. Results indicate that innovations first appear in spot prices for Dubai–Fateh and spread to other spot and futures prices while other innovations first appear in the far month contract for West Texas Intermediate and spread to other exchanges and contracts. Links from prices on futures markets to prices on spot markets are relatively weak and this may have allowed the long run relationship between spot and future prices to change after September 2004. Together, these results suggest that market fundamentals initiated a long-term increase in oil prices that was exacerbated by speculators, who recognized an increase in the probability that oil prices would rise over time.

These results and the methods used to obtain them are described in five sections. Section 2 describes the data and econometric methodology that are used to analyze causal relationships among crude oil prices. These results are described in Section 3. Section 4 maps the spread of price changes and describes what this map implies about the role of market forces, OPEC behavior, and speculation in the recent price increase for crude oil. Section 5 concludes.

2. Methodology

2.1. Data

To analyze causal relationships between prices for crude oil in various markets, we compile daily price data for crude oils traded in spot and futures markets. We ignore prices for refined petroleum products because previous results indicate that causal relationships run from the price of crude oil to motor gasoline (Kaufmann et al., 2009). The crude oils analyzed include a variety of grades (light versus heavy) from both OPEC and non-OPEC nations. Because we are interested in longer-term price movements, daily observations are averaged to weekly values. Such changes eliminate day-of-the-week effects (Hammoudeh and Li (2004) and effects associated with the time at which geographically disparate markets open and close (Lin and Tamvakis, 2004). Using weekly data instead of daily data reduces the likelihood of finding causal relationship (Schwarz and Szakmary, 1994) therefore, finding causal relationships in weekly observations enhances the reliability our findings. Additionally, there is no evidence that the use of weekly data affects our results—conclusions are relatively unaffected when we repeat the analysis using daily data[1].

The US Energy Information Administration (2008) defines a spot price as the price for a one-time open market transaction for immediate delivery of a specific quantity of product at a specific location where the commodity is purchased “on the spot” at current market rates. To represent prices for crude oil on the spot market, daily observations of spot prices are obtained from Bloomberg L.P. and the Energy Information Administration for five crude oils: West Texas Intermediate (39.6°)(EIA), Brent–Blend (38.3°)(EIA), Maya (22°) (Bloomberg) Bonny Light (37°)(Bloomberg), and Dubai–Fateh (32°) (Bloomberg). Numbers in parentheses are the API gravity index, which is an arbitrary scale that expresses the gravity or density of liquid petroleum products relative to water. Larger numbers indicate lighter grades of crude oil, which have a value of 38° or above. A value of 22° or below indicates a heavy crude while values between 22° and 38° indicate medium grade. Observations start on January 2, 1986 for WTI and Dubai–Fateh, May 20, 1987 for Brent–Blend, August 22, 1988 for Bonny Light, and January 2, 1991 for Maya.

We also compile daily observations for the price of crude oils on futures markets from Bloomberg L.P. The US Energy Information Administration defines a futures contract as a promise to deliver a given quantity of a standardized commodity at a specified place, price, and time in the future. Contracts for crude oil are traded with maturities for each of 18 months in the future, although the number of contracts traded with maturities for ‘far months’ (dates far into the future) are much smaller than traded for near months. These small numbers imply that the market is thin and so prices for far month contracts are less reliable. Under these conditions, we compile data with maturities for 1 month (the near month contract) and 5 months (the far month contract), which is the farthest month contract for which prices are commonly reported.

Relatively few crude oils are traded on futures markets. We compile data for the price of West Texas Intermediate (WTI), which starts on July 1, 1986, Brent Blend, which starts on June 23, 1998, and Dubai–Fateh, which starts in April 3, 2006. No observations are available for contracts for Dubai–Fateh with a five-month maturity. Data are available for other crude oils traded on futures markets, but their sample period is shorter than that for Dubai–Fateh, and so precludes rigorous statistical analysis.

2.2. Statistical methodology

Causal relationships between the price of crude oils are analyzed using two techniques; a two step DOLS error correction model developed by Stock and Watson (1993) and a full information maximum likelihood estimate for a vector error correction model (VECM) developed by Johansen (1988) and Johansen and Juselius (1990). We use both procedures, as opposed to choosing one, because their strengths and weaknesses complement each other. The VECM is used to analyze the relationship among all crude oils simultaneously. But using this procedure to identify individual cointegrating relationships would be very time consuming. Furthermore, the VECM cannot be used to evaluate whether only increases or decreases in price are transmitted from one crude oil to another—an asymmetric causal relationship. Instead, the possibility of an asymmetric relationship between two crude oils is analyzed by modifying the error correction model with a procedure developed by Granger and Lee (1989). This procedure cannot be used to analyze the relationship among the price of three or more crude oils because the DOLS estimator assumes that the right-hand side variables constitute a full rank spectral matrix (Soren Johansen, personal communication). This assumption is not satisfied if the right hand side variables include two or more prices for crude oil because a unified market implies that the prices for crude oil will cointegrate.

To analyze the causal relationship between two crude oils and test whether it is symmetric, we modify the two-step methodology described by Granger and Lee (1989). First, we estimate the long-run relation between the prices for two crude oils. In the second step, the residual from the cointegrating relationship is decomposed and used to estimate the rate of adjustment in unrestricted/restricted error correction models. The restricted model equalizes the rates of adjustment to price increases and price decreases. If this restriction is rejected, the causal relationship is said to be asymmetric.

Long run relationships between the price of two crude oils are given by Eqs. (1) and (2):

$$X_t = \alpha_1 + \beta_1 Y_t + \mu_{1t} \tag{1}$$

[1] Repeating the analysis with daily data generates results that are generally consistent with those reported below. The spot price for Dubai–Fateh and the price of the far month contract for WTI are gateway crudes. Results identify three other gateway crude oils, the near month contracts for WTI and Brent Blend and the far month contract for Brent–Blend. These prices become gateway crudes because the causal relationship from the spot price for Dubai–Fateh to the near month contract for Brent–Blend drops to the 10% level (as opposed to the 5% level indicated by the weekly data). Similarly, the significance of the causal relationship that runs from the far month contract for WTI to the near month contract for WTI drops from the five percent level to the ten percent level. Restrictions on the VECM fail to identify any gateway crude oils.

$$Y_t = \alpha_2 + \beta_2 X_t + \mu_{2t} \tag{2}$$

in which X and Y are the price for the two crude oils being analyzed, α's and β's are regression coefficients and the μ's are regression errors. Eq. (1) is specified on the assumption that the price of crude oil Y "Granger causes" the price of crude oil X while Eq. (2) is specified on the assumption that the price of crude oil X "Granger causes" the price of crude oil Y. Nominal prices are used because indices for price levels are not available at daily or weekly frequencies nor will analyzing nominal data affect the results. Dividing the nominal price of crude oil X and Y on both sides of Eq. (1) or (2) by the same deflator will not affect conclusions about cointegration or causal order.

Eqs. (1) and (2) are estimated using dynamic ordinary least squares, DOLS (Stock and Watson, 1993), because the variables in Eqs. (1) and (2) contain a stochastic trend and as described in the introduction, they cointegrate. For variables that cointegrate, DOLS generates asymptotically efficient estimates of the regression coefficients. As such, the use of DOLS improves previous analyses, which estimate cointegrating relationships using ordinary least squares (OLS) on either levels of first differences (Quan, 1992; Schwarz and Szakmary, 1994; Silvapulle and Moose, 1999). The number of lags and leads specified by the DOLS estimator is chosen using the Bayesian information criterion (Schwarz, 1978). Values for α and β estimated by DOLS represent the long-run cointegrating relationship between nominal prices. DOLS does not estimate the short-run dynamics because this is not necessary for asymptotically efficient estimation of the cointegrating relationship (Stock and Watson, 1993).

Causal relationships between the price of crude oils X and Y are determined in a second step by estimating error correction models. First, we decompose the residual (ε_t) from the cointegrating relationship (e.g. $\varepsilon_{1t} = X_t - (\hat{\alpha}_1 - \hat{\beta}_1 Y_t)$) that is estimated from Eqs. (1) and (2) based on positive or negative changes in the potentially causal price variable. For example, the residual from the cointegrating relationship that is estimated using Eq. (1) is decomposed based on the price change for crude oil Y using Eqs. (3) and (4):

$$^{+}\varepsilon_{1t} = (\Delta Y_t > 0)^{*}\varepsilon_{1t} \tag{3}$$

$$^{-}\varepsilon_{1t} = (\Delta Y_t \leq 0)^{*}\varepsilon_{1t} \tag{4}$$

in which Δ is the first difference operator (e.g. $\Delta Y_t = Y_t - Y_{t-1}$). Conversely, the residual from the cointegrating relationship estimated from Eq. (2) would be decomposed based on the price change for crude oil X.

To test whether the price of crude oil price Y "Granger causes" the price of crude oil X, the residuals are included in unrestricted and restricted error correction models that are given by Eqs. (5) and (6) respectively:

$$\Delta X_t = \phi + {}^{+}\gamma^{+}\varepsilon_{1t-1} + {}^{-}\gamma^{-}\varepsilon_{1t-1} + \sum_{i=1}^{s}\delta_i \Delta X_{t-i} + \sum_{i=1}^{s}\theta_i \Delta Y_{t-i} + \tau_t \tag{5}$$

$$\Delta X_t = \phi + \gamma\varepsilon_{1t-1} + \sum_{i=1}^{s}\delta_i \Delta Y_{t-i} + \sum_{i=1}^{s}\theta_i \Delta X_{t-i} + \tau_t \tag{6}$$

in which τ is a normally distributed random regression error and the number of lags (s) is chosen using the Akaike Information criterion (Akaike, 1973). Eqs. (5) and (6) are estimated using OLS (all variables are $I(0)$) and the standard errors are calculated using the procedure developed by Newey and West (1987). To test whether crude oil X "Granger causes" crude oil Y, modified versions of Eqs. (5) and (6) specify ΔY as the dependent variable and ε_2 is used in place of ε_1.

A causal relationship is indicated by negative values for γ, $^{-}\gamma$, or $^{+}\gamma$. If the price of crude oil X is below the long-run equilibrium implied by the price of crude oil Y, the residual from the cointegrating relationship (ε) is negative. Under these conditions, a negative value for γ, $^{-}\gamma$, or $^{+}\gamma$ will move the price of crude oil X towards the equilibrium value implied by the price of crude oil Y. Similarly, a negative value for γ, $^{-}\gamma$, or $^{+}\gamma$ will move the price for crude oil X towards the long-run equilibrium value implied by the price of crude oil Y if the current price of X is above the equilibrium value.

The symmetry of a causal relationship between the price of crude oils X and Y is tested by imposing a restriction that equalizes the two rates of adjustment, $^{+}\gamma$ and $^{-}\gamma$. The restricted model (Eq. (6)) specifies a causal relationship that is symmetric and is given by γ. Eqs. (5) and (6) are used to test the null hypothesis $^{+}\gamma = {}^{-}\gamma$ using the F-form of the Wald test, which can be evaluated against a χ^2 distribution with 1 degree of freedom.

The Wald test, along with t-tests on γ, $^{+}\gamma$, and $^{-}\gamma$, are used to determine the nature of the causal relationship between the prices of crude oils. A value of the Wald test on Eq. (5) that fails to reject the null hypothesis and a value of γ in Eq. (6) that is not statistically different from zero indicates that there is no causal relationship between the prices of crude oils. That is, they move together (for all of the crude oil prices analyzed here, Eqs. (1) and (2) cointegrate) but are driven by the price of some other crude oil or respond simultaneously to new information about the determinants of oil prices. If the Wald test fails to reject the null hypothesis and the value of γ is negative and is statistically different from zero, these results indicate that there is a symmetric causal relationship from the price of crude oil Y to the price of crude oil X. That is, both increases and decreases in the price of crude oil Y "Granger cause" changes in the price of crude oil X.

If the Wald test rejects the null hypothesis, and the value of $^{+}\gamma$ and/or $^{-}\gamma$ is negative and statistically different from zero, the causal relationship between the crude oils is asymmetric. Asymmetry can be both bi-direction or unidirectional. Bi-directional asymmetry (both $^{+}\gamma$ and $^{-}\gamma$ are statistically significant) indicates that crude oil X responds to both increases and decreases in the price of Y, but the rates of adjustment differ. A unidirectional ($^{+}\gamma$ or $^{-}\gamma$ is statistically significant) indicates that an increase or decrease in the price of crude oil Y "Granger causes" the price of crude oil X. The direction of the causality is indicated by the coefficient that is statistically different from zero. For example, if only $^{+}\gamma$ is negative, this result indicates that only increases in the price of crude oil Y "Granger cause" changes in the price of crude oil X. Allowing for an asymmetric causal relationship also goes beyond previous methodologies (Quan, 1992; Schwarz and Szakmary, 1994; Silvapulle and Moose, 1999; Hammoudeh and Li, 2004), but builds on work by Hammoudeh et al. (2008).

To evaluate the degree to which conclusions about the causal relationship between the prices of two crude oils are robust, we test whether the values of γ, $^{+}\gamma$ and/or $^{-}\gamma$ are stable over the sample period. Unlike Hammoudeh and Li (2004), who use the Asian Financial crisis as a breakpoint *a priori*, we use an iterative version of the Quandt Likelihood Ratio statistic (Quandt, 1960). This procedure defines a dummy (D_t) variable that has a value of zero before a possible break point and one thereafter. This dummy variable is included in the unrestricted or restricted version of Eqs. (5) and (6) as follows:

$$\Delta X_t = \alpha + {}^{+}\gamma^{+}\varepsilon_{1t-1} + {}^{+}\gamma^{*+}D_t\varepsilon_{1t-1} + {}^{-}\gamma^{-}\varepsilon_{t-1} + {}^{-}\gamma^{*+}D_t\varepsilon_{t-1} + \sum_{i=1}^{s}\delta_i \Delta X_{t-i} + \sum_{i=1}^{s}\theta_i \Delta Y_{t-i} + \tau_t \tag{7}$$

$$\Delta X_{t-1} = \alpha + \gamma\varepsilon_{t-1} + \gamma^{*}D\varepsilon_{1t-1} + \sum_{i=1}^{s}\delta_i \Delta Y_{t-i} + \sum_{i=1}^{s}\theta_i \Delta X_{t-i} + \tau_t \tag{8}$$

Eq. (8) is used if the Wald F-test indicates the causal relationship is symmetric—if the causal relationship is asymmetric, Eq. (7) is estimated. For Eq. (7), the dummy variable is applied to only the term that is statistically different from zero.

Eqs. (7) and (8) are estimated iteratively, once for each possible change date for a subsample that is defined by 5% trimming relative

Table 1
Regression results for error correction models which indicate a causal relationship.

Causal variable	Bonny light	Brent spot	WTI spot	Maya spot	WTI near month	Brent near month	Brent far month	Dubai near month
Dubai–Fateh spot	$\mathrm{ADF}=-6.83^{*}$ $\chi^2(1)=0.10$ $\rho=-0.07^{*}$ $\mathrm{Sup}\ F=4.43$	$\mathrm{ADF}=4.95^{*}$ $\chi^2(1)=0.3$ $\gamma=-0.71^{+}$ $\mathrm{Sup}\ F=31.1^{**}$ 2007:07:26 $\gamma=-0.93^{**}$		$\mathrm{ADF}=5.58^{*}$ $\chi^2(1)=1.91$ $\rho=-0.07^{*}$ $\mathrm{Sup}\ F=3.95$		$\mathrm{ADF}=-4.72^{*}$ $\chi^2(1)=0.01$ $\gamma=-0.04$ $\mathrm{Sup}\ F=15.19^{**}$ 2007:01:11 $\gamma=-0.75^{**}$	$\mathrm{ADF}=-3.89^{*}$ $\chi^2(1)=0.34$ $\gamma=-0.09$ $\mathrm{Sup}\ F=10.82^{*}$ 2006:08:03 $\gamma=-0.15^{*}$	
Bonny light spot		$\mathrm{ADF}=-5.04^{*}$ $\chi^2(1)=2.3$ $\gamma=-0.28^{**}$ $\mathrm{Sup}\ F=23.2^{**}$ 2007:01:11 $\gamma=-0.63^{**}$	$\mathrm{ADF}=-4.76^{*}$ $\chi^2(1)=23.9^{**}$ ${}^{-}\gamma=-0.17^{**}$ $\mathrm{Sup}\ F=6.59$	$\mathrm{ADF}=-3.78^{*}$ $\chi^2(1)=0.66$ $\gamma=-0.04^{*}$ $\mathrm{Sup}\ F=4.64$	$\mathrm{ADF}=-4.60^{*}$ $\chi^2(1)=0.01$ $\gamma=-0.04$ $\mathrm{Sup}\ F=15.19^{**}$ 2007:01:11 $\gamma=-0.75^{**}$			
Brent spot			$\mathrm{ADF}=-6.40^{*}$ $\chi^2(1)=4.46^{*}$ ${}^{-}\gamma=-0.162^{*}$ $\mathrm{Sup}\ F=6.64$		$\mathrm{ADF}=-6.20^{**}$ $\chi^2(1)=6.8^{**}$ ${}^{-}\gamma=-0.16^{*}$ $\mathrm{Sup}\ F=7.12$			
WTI near month								$\mathrm{ADF}=-3.89^{*}$ $\chi^2(1)=6.73^{**}$ ${}^{+}\gamma=-0.26^{**}$ $\mathrm{Sup}\ F=5.94$
WTI far month				$\mathrm{ADF}=-3.76^{*}$ $\chi^2(1)=0.04$ $\gamma=-0.03^{*}$ $\mathrm{Sup}\ F=7.63$	$\mathrm{ADF}=-4.42^{*}$ $\chi^2(1)=4.95^{*}$ ${}^{-}\gamma=-0.13^{*}$ $\mathrm{Sup}\ F=7.25$		$\mathrm{ADF}=-3.96^{*}$ $\chi^2(1)=4.08^{*}$ ${}^{+}\gamma=-0.15^{*}$ $\mathrm{Sup}\ F=14.4^{*}$ 2007:01:11 ${}^{-}\gamma=-0.23^{*}$	
Brent near month		$\mathrm{ADF}=-5.54^{*}$ $\chi^2(1)=0.82^{*}$ $\gamma=-0.29^{*}$ $\mathrm{Sup}\ F=12.21^{*}$ 1990:09:20 $\gamma=-0.31^{**}$		$\mathrm{ADF}=-3.91^{*}$ $\chi^2(1)=0.13$ $\gamma=-0.04^{*}$ $\mathrm{Sup}\ F=5.13$	$\mathrm{ADF}=-5.56^{*}$ $\chi^2(1)=13.9^{**}$ ${}^{-}\gamma=-0.21^{**}$ $\mathrm{Sup}\ F=10.96^{+}$		$\mathrm{ADF}=-3.74^{*}$ $\chi^2(1)=4.12^{*}$ ${}^{+}\gamma=-0.08^{+}$ $\mathrm{Sup}\ F=13.08^{*}$ 2007:03:01 ${}^{+}\gamma=-0.18^{**}$	$\mathrm{ADF}=-4.93^{*}$ $\chi^2(1)=6.17^{**}$ ${}^{+}\gamma=-0.56^{**}$ $\mathrm{Sup}\ F=8.81$
Brent far month				$\mathrm{ADF}=-3.94^{*}$ $\chi^2(1)=0.18$ $\gamma=-0.04^{*}$ $\mathrm{Sup}\ F=6.55$				

Prices in column 1 is the crude oil from which the causal relationship originates.
Prices in the first row is the crude oil to which the causal relationship runs.
ADF refers to the *a* test of the OLS residual from Eq. (3).
$\chi 2(1)$ is a test of symmetry in the error correction model.
Sup *F* is the maximum value for the Quandt Likelihood ratio statistic.
Date refers to the week (year:month:day) for the highest value for the Quandt Likelihood ratio statistic.
Second value of γ refers to the value in the period that starts with the date given on the previous line.

to the full sample period. For each possible date of change, the coefficient(*s*) associated with the dummy variable *D* is restricted to zero and this restriction is evaluated with an *F*-test. The largest value of the *F* statistic calculated from all possible dates of change is termed the Sup *F* test and is evaluated against a non-standard distribution (Hansen, 1997). Values that exceed the critical value ($p<.05$) indicate that the causal relationship between the prices of the two crude oils changes in a statistically measurable manner during the sample period.

For cases in which a change is detected, we evaluate the causal relationship between the price of crude oils by re-estimating Eqs. (1)–(6) with a sub-sample that starts with the date associated with the largest value of the *F* test. We recognize that the date of this maximum value does not define precisely the change in the relationship, but it is a reasonable approximation to test whether the causal relationship between the two crude oils is present during the most recent period. Furthermore, we recognize that the procedure described above tests for only a single break, and that the causal relationship may change several times during the sample period.

The DOLS/ECM procedure examines the causal relationship between the prices of two crude oils. It is well understood that conclusions about causal order can be influenced by the variables included in the statistical model. To determine the effect of omitted variable bias on results generated by the bi-variate approach given by Eqs. (1)–(8), we estimate a vector error correction model (VECM):

$$\Delta y_t = \Gamma_1 \Delta y_{t-1} + \ldots + \Gamma_{k-1} \Delta y_{t-k+1} + \Pi y_{t-1} + \varepsilon_t \tag{9}$$

in which *y* is a vector that includes the ten prices analyzed above.

Causal relationships are derived from the error correction mechanism (ECM), which is given by the term Πy_{t-1}. If there are one or more cointegrating relationships, the ECM can be reformulated as follows:

$$\Pi y_{t-1} = \alpha \beta' [1, y_{t-1}']' \tag{10}$$

The one in the term $[1, y_{t-1}']'$ indicates that a constant may be included in the cointegrating relationship. β' is the matrix of coefficients (the cointegrating vector) that creates a stationary combination of nonstationary variables, i.e. the cointegration relationship, and α is a vector of variables that represent the rate at which the price of a particular crude oil adjusts to disequilibrium in the cointegrating relationships.

The value(s) of α are analogous to the γ in Eq. (6) and are used to evaluate causal relationships among the prices in the *y* vector. To test whether price changes originate in a particular crude oil, we test restrictions that make all elements of α associated with the price for an individual crude oil equal to zero, which is a test of weak

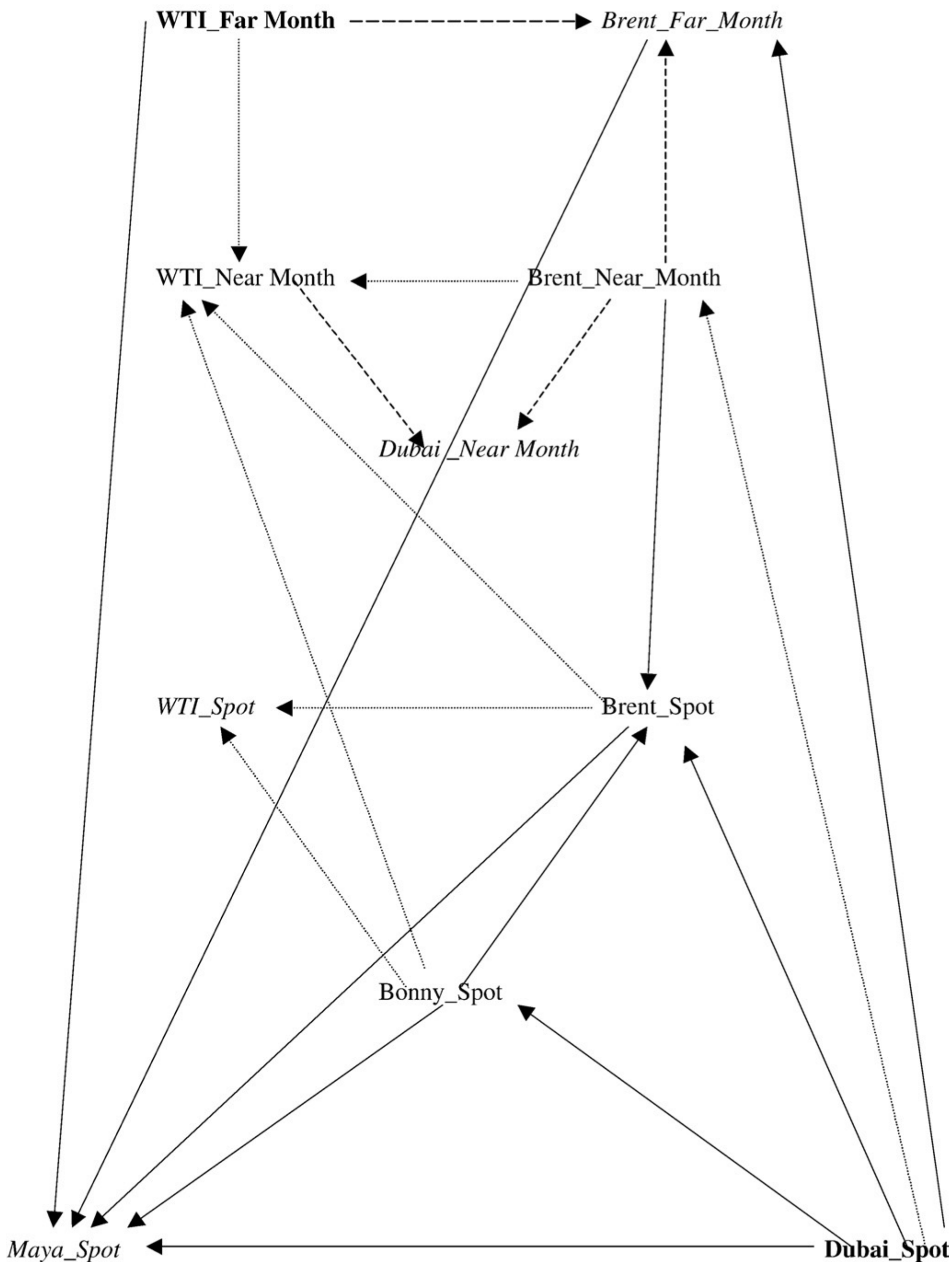

Fig. 1. Causal relationships identified by the error correction models that run from the price of the crude oil at the arrow's start to the price of the crude oil at the arrow's point. Solid lines represent symmetric relationships (both price increases and price decreases affect the price of the crude oil at the arrow's point). Dotted lines represent asymmetric relationships in which only price reductions in the crude at the arrow's start are transmitted to the price at the arrow's point while dashed lines represent asymmetric relationships in which only price increases are transmitted. Crude oil prices in bold are gateways through which innovations enter the market while prices in italics are 'dead-ends' prices that have no causal effect on the price for the other crude oils in this figure.

exogeneity (Juselius, 2006). This restriction is evaluated with a test statistic that is distributed as a χ^2 with degrees of freedom equal to the number of cointegrating relationship in the VECM. The number of cointegrating relationships is determined using the λ_{trace} statistic and visual examination of all cointegrating relationships (Juselius, 2006).

Failure to reject the null hypothesis would indicate that all of the alpha's associated with the price equation for a particular crude are not statistically different from zero. Such a result would indicate that the price for a crude oil does not respond to disequilibrium in any of the cointegrating relationships. We interpret this result to indicate that changes in the price of that crude oil do not originate in the price for any of the other crude oils in the y vector. Instead, price innovations appear first in that crude oil and spread to the prices of other crude oils in the y vector. Conversely, rejecting restrictions that make all elements of α for the price equation of an individual crude oil equal to zero would indicate that the price of that crude oil responds to changes in the price of crude oils in one or more of the cointegrating relationships. Econometrically, this indicates that the price of this crude oil is "Granger caused" by the price of other crude oils. As such, price innovations do not enter the market via this crude oil, rather they appear in this crude oil via adjustments to the price other crude oils in the cointegrating relationships.

3. Results

Analyzing prices for ten crude oils implies a maximum of ninety [10 choose 2) $\times$ 2] bi-variate relationships. All parings cointegrate, as indicated by augmented Dickey Fuller statistics estimated from the OLS regression errors of Eqs. (1) and (2). The finding of cointegration implies that diagnostic statistics for the results of all parings can be interpreted reliably. Furthermore, cointegration between the near and 5 month contracts extends results found by Silvapulle and Moosa (1999), who find that prices for the near month and 3 month contracts for WTI cointegrate, but prices for the near month and 6 month contracts do not cointegrate. Our result would seem to diminish the maturity effect with regard to market efficiency for crude oil prices.

Of the ninety error correction models estimated, statistically significant ($p<.05$) values for γ, $^{+}\gamma$, *or* $^{-}\gamma$ identify twenty-one causal relationships (Table 1). These twenty-one relationships are greater than the five (.05 * 90) relationships that are expected due to repeated testing at the 5% significance level. Furthermore, there is no case in which the value of γ, $^{+}\gamma$, *or* $^{-}\gamma$ is statistically significant and positive, which would imply an unstable equilibrium between prices. Together, these results suggest that the error correction models identify causal relationships between the prices of two crude oils. Of the twenty-one causal relationships, eleven originate in the spot market, six originate in near month contracts traded on futures markets, and four originate in far month contracts (Fig. 1).

These twenty-one linkages create three categories of crude oils; (1) crude oils whose price “Granger cause” the price of other crude oils but are not “Granger caused” by the price of other crude oils analyzed here, (2) crude oils whose price both “Granger cause” and are “Granger caused” by prices for other crude oils analyzed here, and (3) crude oils whose price are only “Granger caused” by the price of other crude oils—they do not “Granger cause” the price of any of the crude oils analyzed here.

The first category, crude oils which “Granger cause” the price of other crude oils but are not “Granger caused” by the price of other crude oils, can be considered ‘gateways’ through which price innovations enter the market and spread to other crude oils. As such, these crude oils dominate the process of price discovery. ‘Gateway’ crude oils include the far month contract for WTI and the spot price for Dubai–Fateh. The five causal relationships that originate from the spot price for Dubai–Fateh is the greatest of the crude oils analyzed.

Both the spot price for Bonny Light and the near month contract for Brent Blend “Granger cause” the price for four other crude oils, but these prices also are “Granger caused” by the spot price for Dubai–Fateh. As such, the spot price for Bonny Light and the near month contract for Brent Blend, along with the near month contract for WTI and the far month contract for Brent Blend, are members of a second category of crude oils, those that both “Granger cause” and are “Granger caused” by prices for other crude oils. As such, the prices for crude oils in this category both receive and transmit innovations in oil prices.

Finally, spot prices for WTI and Maya are members of a third category, crude oils whose price is only “Granger caused” by the price of other crude oils. As such, these two crude oils can be viewed as ‘dead-ends’—they receive innovations from other crude oils but do not affect the price for any of the other crude oils that are analyzed here. Although their classification as dead-ends probably is not expected *a priori*, their classification may be explained *post hoc*. Maya spot is illiquid (it is not traded on any futures market (Hammoudeh et al., 2008) and this would tend to weaken its ability to influence the price of other crude oils. WTI is considered a ‘broken’ benchmark by many (Davis, 2007; Fattouh, 2007), in part because of declining output and bottlenecks in transportation networks that reduce arbitrage opportunities relative to other crude oils. For example, the pipeline that transports WTI can only move the crude north towards Cushing, OK—WTI cannot be moved south towards the Gulf of Mexico; therefore it cannot be exported outside the US.

Consistent with prevalence of asymmetry described by Hammoudeh et al. (2008), the twenty-one causal relationships show varying degrees of asymmetry. Only ten of the relationships are symmetric—both positive and negative changes in prices are transmitted to prices of the other crude oils. Eleven of the relationships are asymmetric. This large fraction is greater than expected from the repeated testing of the null hypothesis $^{+}\gamma=^{-}\gamma$ and the relatively low power of the F form of the Wald test to reject this null hypothesis (Cook et al., 1999). For seven of the asymmetric linkages, only negative price changes are transmitted from one crude oil to another. For the other four linkages, only positive price changes are transmitted.

Table 2
Exclusion tests on an unrestricted VECM (Eq. (9)–(10)).

Price	$\Pi=8$	$\Pi=7$
WTI spot	$\chi2(8)=41.58^{**}$	$\chi2(7)=41.58^{**}$
Brent–Blend spot	$\chi2(8)=27.64^{**}$	$\chi2(7)=27.29^{**}$
Dubai–Fateh spot	$\chi2(8)=14.97^{+}$	$\chi2(7)=11.74$
Maya_spot	$\chi2(8)=36.90^{+}$	$\chi2(7)=35.43^{**}$
Bonny_light	$\chi2(8)=23.52^{**}$	$\chi2(7)=22.80^{**}$
Brent–Blend_near month	$\chi2(8)=27.07^{**}$	$\chi2(7)=23.66^{**}$
Brent–Blend_far month	$\chi2(8)=20.47^{**}$	$\chi2(7)=20.09^{**}$
WTI_near month	$\chi2(8)=18.12^{*}$	$\chi2(7)=18.02^{*}$
WTI_far month	$\chi2(8)=11.87$	$\chi2(7)=11.81$

**Value exceeds $p<.01$, *$p<.05$, and $+p<.10$.

For thirteen of the twenty-one causal relationships, the Sup F statistic fails to reject the null hypothesis. This suggests that these thirteen causal relationships are stable over the sample period. The causal relationship is not stable in the eight error correction models for which the Sup F test rejects the null hypothesis. Three of these causal relationships are significant ($p<.05$) during both the entire sample period and the period that starts with the largest value for the Quandt Likelihood statistic. Conversely, three of the causal relationships are statistically detectable after the break only—there is no causal relationship over the entire sample period. For the causal relationship that runs from the spot price for Dubai–Fateh to the spot price for Brent–Blend and the causal relationship that runs from the near month contract for Brent–Blend to the far month contract for Brent–Blend, the relationship is significant at the 10% level for the entire sample period and is significant at the 5% level after the break.

The crude oils that the bi-variate analyses of casual order identify as ‘gateways’ are confirmed by exclusion tests on the VECM. Restrictions that make all elements of α equal to zero for the price of an individual crude oil generally are rejected strongly (Table 2). Exceptions include the spot price of Dubai–Fateh and the far month price for WTI. These results are not sensitive to the rank of Π. Although the λ_{trace} statistic clearly indicates that Π has a rank of eight, visual examination of the unrestricted cointegrating relationships suggests that the 8th cointegrating relationship is not stationary (Juselius, 2006), and so we repeat the exclusion tests in which Π is given a rank of seven.

4. Discussion

The results described above can be used to explore competing explanations for the rise in oil prices towards the end of the sample period. These explanations feature two mechanisms. One explanation posits that the rise is driven by changes in market fundamentals that affect the supply/demand balance for crude oil. An alternative explanation posits that the price rise is driven by speculation.

The ‘map’ of causal relationships among crude oil prices given by Fig. 1 can be used to evaluate hypotheses about the role of speculation and market fundamentals. If hypotheses about the importance of speculation are correct, we would expect to see price innovations enter the oil market via near and/or far month contracts that are traded on future markets. Contracts sold on futures markets generally do not require the purchaser to take delivery of the oil, and can be implemented immediately with little up-front cash (Silvapulle and Moosa, 1999). As such, these contracts are specifically designed to be

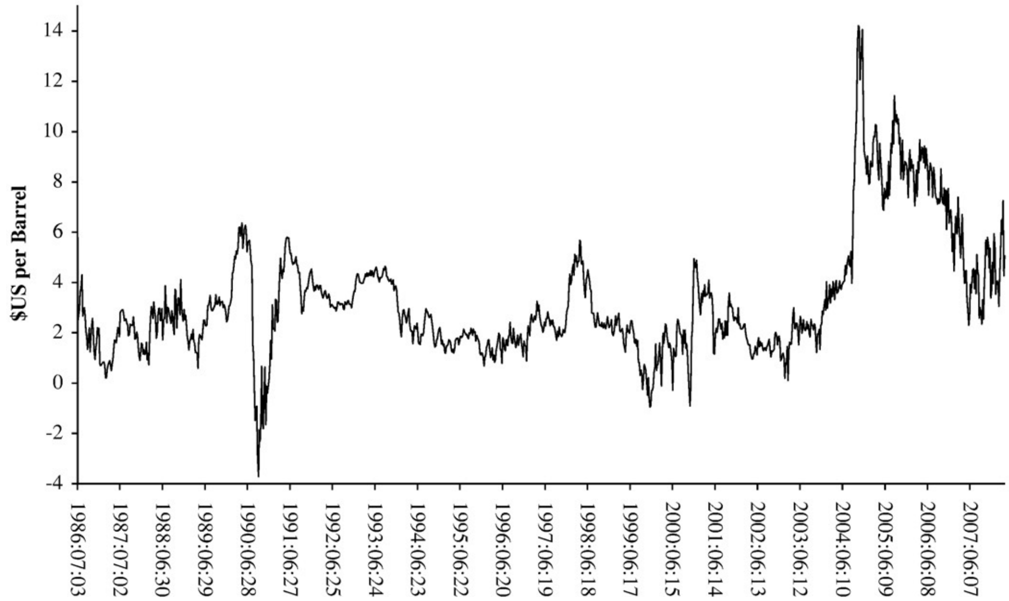

Fig. 2. The difference between the far month contract for WTI and the spot price for Dubai–Fateh (solid line).

financial instruments (US Energy Information Agency, 2008). Beyond speculation, Newberry (1992) argues that futures markets provide opportunities for price manipulation. Conversely, if hypotheses about the importance of market fundamentals are correct, we would expect to see price innovations enter the oil market via spot markets. Spot markets focus on prompt delivery—only small amounts are delivered in the future via a "forward physical market." As such, those that purchase oil on the spot market generally take possession. This is not to say that speculators do not participate in spot markets, but it is more difficult.

The crude oils that serve as gateways for price innovations and the nature of the linkages among prices are consistent with the hypothesis that the rise in crude oil prices through March 2008 is driven in part by market fundamentals. One of the two gateway prices identified by the error correction models is the spot price for Dubai–Fateh, a designation that is confirmed by the tests of weak exogeneity on the VECM.

That the spot price for Dubai–Fateh is a 'gateway' for innovations to crude oil prices is consistent with arguments for the importance of demand growth in developing nations, especially the Asian nations of China and India. Most of Middle East oil is represented by this benchmark, both as oil reserves or exports. A large fraction of the crude oil shipped to Asian nations from the Middle East (more than 10 mbd) uses the spot price for Dubai–Fateh as a benchmark (Montepeque and Stewart, 2005). As such, innovations in the spot price for Dubai–Fateh may reflect increasing demand in Asia.

The role of the spot price for Dubai–Fateh also is consistent with arguments about changes on the supply side. According to the supply side hypothesis, the recent price rise is caused in part by a shift in the source of crude oil from non-OPEC to OPEC nations. Production of crude oil by non-OPEC nations grew from 34.2 mbd in 1993 to 41.01 mbd in 2004—3 years later (2007) it was 41.09 mbd (Annual Energy Review, various years). This stagnation, along with demand growth forced OPEC to increase production, which allowed OPEC to regain control over the marginal supply of oil. In this role, OPEC can influence oil prices by managing production quotas (Wirl and Kujundzic, 2004; Kaufmann et al., 2008a) and/or capacity utilization (Kaufmann et al., 2004, 2008b). Consistent with this hypothesis, changes in OPEC capacity utilization or quotas may enter the market as innovations to spot prices for crude oils that are produced by the OPEC nation the United Arab Emirates, which is the source for Dubai–Fateh. Moreover, this oil lies in an area that witnessed two important wars, lengthy embargos, and chronic potential conflict, which make its price very sensitive to shocks.

Our results also provide support for the role of speculation in the recent rise of crude oil prices. The other gateway price identified by both the error correction models and the VECM is the far month contract for WTI. This crude oil and contract may serve as a gateway for speculative pressures to enter the futures markets. The effect of such innovations may be amplified by asymmetry in the causal relationships in the futures market, which favor price increases. All six bi-variate causal relationships between prices in the futures market are asymmetric—four transmit only price increases and two transmit only price reductions.

The potential for speculation to affect oil prices may be enhanced by the nature of causal relationships that run from the futures market to the spot market. Three of the four causal relationships that run from the futures market to the spot market affect the spot price for Maya crude, which is a so-called 'dead-end' crude oil. This structure implies that speculative pressures can enter the futures market and not be transmitted fully to the spot market. If speculative effects were sufficiently large, these weak linkages could allow prices on the futures market to diverge from those on the spot market.

To examine the hypothesis that innovations to the futures markets allow these prices to diverge prices on the spot market, we examine price differences between the two gateway crude oils, the spot price for Dubai–Fateh and the far month contract for WTI. The difference between the two prices seems to shift in August or September of 2004 (Fig. 2). Before this date, the price difference fluctuates between $0 and $5/barrel. The price difference jumps to $5–$10/barrel after August/September 2004. Consistent with a role for speculation in the recent price increase, the greater price differential indicates that prices rise on markets that are used as financial instruments relative to prices on markets where purchasers generally take physical possession.

To evaluate the statistical significance of this seeming shift, we use the Quandt Likelihood statistic to test whether there is a change in the constant (α) or slope (β) of the cointegrating relationship (Eqs. (1) and (2)) between the two gateway prices. The Sup *F* test strongly rejects the null hypothesis that the cointegrating relationship is stable over the sample period (Table 3). To evaluate whether the law of one price maintains a long-run relationship between future and spot prices, we

Table 3
Tests of stability of cointegrating relationships.

	Sup F	Date of maximum value	ADF
Dubai-Fateh spot = $\alpha+\beta$ *WTI_far_month			
Change in intercept (α)	1243.9**	2004:08:26	−3.50*
Change in slope (β)	739.1**	2004:02:12	−2.50
WTI_far_month = $\alpha+\beta$ * Dubai-Fateh spot			
Change in intercept (α)	614.0**	2004:08:26	−3.32*
Change in slope (β)	334.1***	2004:02:05	−2.35

**Value exceeds $p<.01$, *$p<.05$, and $+p<.10$.

use an ADF statistic to test whether prices cointegrate during the period that starts with the largest value of Quandt Likelihood Ratio (as determined by a test for a change in the slope or intercept) and ends with the most recent observation, March 28, 2008. ADF statistics suggest that the prices of the two 'gateway' crudes cointegrate before the break point identified by the Quandt Likelihood Ratio, but not after the break point (Table 3).

The timing of the change may offer some clues about the role of speculation and market fundamentals. For the test of a change in the intercept (the Sup F for this change always is greater than the Sup F test for a change in slope) the largest value for the Quandt Likelihood ratio occurs for the week of August 26, 2004. A cursory glance at the oil market chronology maintained by the US Energy Information Agency (2004) identifies two events near this time that could change the relationship between spot and futures prices. One event is Hurricane Ivan, which reduced oil production in the US Gulf of Mexico by several hundred thousand barrels/day. But a one-time event is unlikely to shift the long-run relationship between prices on the spot and futures market.

The other item in the chronology is an announcement by OPEC of an increase in their production ceiling. This increase is important because it reversed on-going declines in OPEC production ceilings and may have signaled a fundamental shift in the supply–demand balance. OPEC production ceilings (minus Iraq) declined from 26.7 in October 2000 to 23.5 mbd on March 31, 2004, when OPEC reconfirmed its existing production quota. On June 3, OPEC raised its quota to 25.5 mbd and on September 15, 2004 they raised the quota to 27 mbd as of November 2004, which was the largest it had been since January 1998, when Iraqi production was included in the OPEC production ceilings.

This increase, and those that followed, were caused by increased demand and little growth in non-OPEC production. Recognition of this fundamental shift may have altered the market's perception of the long-term supply–demand balance and fueled speculation about a longer term increase in oil prices. As OPEC gained control over marginal supply, the probability that oil prices would rise increased. First, increasing demand for oil from OPEC reduced the probability that OPEC cooperation would break down and production would greatly exceed OPEC production ceilings, and this lessened the possibility of a significant price decline. As the world became increasingly reliant on OPEC, this increased the probability that a supply disruption would raise prices. In the longer term, political and economic obstacles to significant increases in OPEC capacity (Gately, 1995, 2007; Dees et al., 2007) increased the probability that supply shortfalls would raise prices.

5. Conclusions

Causal relationships between the prices for the ten crude oils analyzed here suggest that the rise in oil prices towards the end of the sample period (March 2008) was generated by both changes in market fundamentals and speculation. This result should not be too surprising, despite efforts by politicians and the popular press to highlight one or the other. Increasing demand along with stagnant levels of non-OPEC production changed the supply demand balance in a way that required higher prices to clear the market. This change in market fundamentals was recognized by speculators, who reckoned that ongoing changes in fundamentals would raise prices further, and took positions accordingly. The increase anticipated by prices set on the future market was eventually transmitted to the spot market, which drove price prices beyond levels justified by the existing supply/demand balance. This increase slowed demand directly by raising energy prices and indirectly by slowing rates of economic activity. For example, US oil demand declined by nearly 6% during the first 11 months of 2008 compared to the same period in 2007 This may have deflated speculative pressures and allowed prices to decline towards levels that are consistent with market fundamentals.

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