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Price dynamics in refined petroleum spot and futures markets

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Abstract

This article characterizes the spot and futures price dynamics of two important physical commodities, gasoline and heating oil. Using a non-linear error correction model with time-varying volatility, we demonstrate many new results. Specifically, the convergence of spot and futures prices is asymmetric, non-linear, and volatility inducing. Moreover, spreads between spot and futures prices explain virtually all spot return volatility innovations for these two commodities, and spot returns are more volatile when spot prices exceed futures prices than when the reverse is true. Furthermore, there are volatility spillovers from futures to spot markets (but not the reverse), futures volatility shocks are more persistent than spot volatility shocks, and the convergence of spot and futures prices is asymmetric and non-linear.These results have important implications. In particular, since the theory of storage implies that spreads vary with fundamental supply and demand factors, the strong relation between spreads and volatility suggests that these fundamentals – rather than trading induced noise – are the primary determinants of spot price volatility. The volatility spillovers, differences in volatility persistence, and lead-lag relations are consistent with the view that the futures market is the primary locus of informed trading in refined petroleum product markets. Finally, our finding that error correction processes may be non-linear, asymmetric, and volatility inducing suggests that traditional approaches to the study of time series dynamics of variables that follow a common stochastic trend that ignore these complexities may be mis-specified.

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1. Introduction

The contribution of futures trading to the informativeness of commodity prices and to spot commodity price volatility have been subjects of intense academic and policy debate for over a century. From the genesis of futures markets in the 1860s to the present, their supporters have argued that futures trading facilitates the transmission of information while their critics have consistently charged that the low costs of futures trading induce excessive speculation which, in turn, causes commodity prices to vary excessively. As a recent example, some Congressmen and regulators called for the suspension of energy futures trading in the aftermath of the Iraqi invasion of Kuwait and the subsequent increase in oil price levels and volatility because they believed that futures speculation had destabilized the market.

In this article we derive and present new evidence that is highly relevant to this debate by introducing a new empirical approach which can identify several important dynamic relations between spot and futures prices which have not been examined heretofore. We apply this approach to the spot and futures prices of refined petroleum products, which are among the most important of the physical commodity markets.

Advocates of the information role of futures markets typically have focused on the lead-lag relationship between spot and futures returns. For examples, see Kawaller et al. (1987), Ng (1987), Herbst et al. (1987), Stoll and Whaley (1990), Schwarz and Laatsch (1991), Chan (1992), and Schwarz and Szakmary (1994). Conversely, advocates of the excess volatility view have focused on the change in the level of volatility in the spot market after the introduction of the futures markets. Examples of this approach include Cone et al. (1987), Franklin (1988), Harris (1988), and Gerety and Mulherin (1991). Both approaches give only a very limited depiction of the effects of futures trading, and are generally subject to acute statistical problems which render the interpretation of results difficult. For instance, since spot and futures prices of the same commodity are likely to share a common stochastic trend, ignoring this long run relationship and the corresponding error correction mechanism can bias estimates of the lead-lag relationship between spot and futures returns; for examples, see Lai and Lai (1991), Chowdhury (1991), Schroeder and Goodwin (1991), Brenner and Kroner (1991), and Lord (1991). Furthermore, since both spot and futures returns have been found to exhibit time varying volatility, failure to incorporate this effect can invalidate the statistical inferences. In fact, both of these problems, if not properly addressed, can also bias inferences regarding any structural shift in the volatility of spot return following the introduction of the futures market.

Given the statistical problems related to the two common approaches and their "partial" nature (partial in the sense that the information effect and the volatility effect of futures markets on the spot market are related and must be studied together), it is necessary to design a more general approach that can account for the important empirical regularities, and can give a more complete understanding of the dynamic relationship between spot and futures prices which are relevant to the debate. Furthermore, a broad range of theory suggests several heretofore ignored aspects of the dynamic behavior of spot and futures prices. We examine these in detail, and our results permit a more precise determination of the causes of spot volatility and the role of futures markets in facilitating information flows.

First, the theory of storage (see French, 1986, Fama and French, 1988, and Williams and Wright, 1991) implies that the level of inventories affects the volatility of spot and futures returns. Since the spread between spot and futures prices (adjusted for carrying costs and time to expiration) is directly related to the level of beginning of period inventories, the spread (also referred to as the basis) should affect volatility. Hence, a finding that variations in the basis/spread explain most of the variation in volatility is consistent with the hypothesis that the fundamental supply and demand factors which determine the spread, rather than speculative activity, are the primary determinants of volatility.

Second, the existence of volatility spillovers between spot and futures markets provides evidence concerning the direction of information flows. According to Ross (1989), if information arrives first into the futures market, we should see a volatility spillover from the futures market to the spot market but not the reverse. [1]

Third, the relative persistence of spot and futures volatility has implications for the importance of informed trading in the two markets. The theories of Ross (1989), Kyle (1985) and Black (1986) imply that private information flows induce persistent increases in volatility. Thus, higher volatility persistence in the futures market is consistent with the theory that futures markets are the primary locus of informed trading.

In this paper we design and apply a general statistical model that not only takes into account the long run relationship between spot and futures prices and time varying volatility in spot and futures returns, but which also allows us to examine directly the just described dynamic relations between spot and futures returns that are crucial to the understanding of the informational role and volatility effects of the futures markets.

Our results, based on an analysis of daily spot and futures price data for heating oil and gasoline from 1984 to 1990, strikingly show that the interest and storage

[1] Chan et al. (1991) also examine volatility spillovers for the S&P 500 index futures, but do not consider the effects of cointegration and error correction.

cost adjusted basis explain over 96 percent of the innovations of refined petroleum product spot return volatility. Moreover, the effect of the basis is asymmetric; spot prices are more volatile when the spot price exceeds the futures price than when the reverse is true. This is consistent with the theory of storage, and since the relation between the basis and supply and demand conditions is extremely well documented, it is consistent with the hypothesis that fundamentals are the primary cause of spot price volatility for these two important commodities. We also find that volatility shocks are more persistent in futures market than the spot market, and that futures return shocks induce volatility in spot markets, while the reverse is not true. These results are consistent with view that futures markets facilitate the flow of information to the spot market.

In addition to the above economic contribution, our general approach also has important implications which are relevant to the study of time series dynamics in other contexts. When two variables obey a long-term equilibrium relationship, it is typically assumed that the error correction process driving these variables toward the long run equilibrium is linear and symmetric: linear in the sense that the speed of convergence to equilibrium is independent of the size of the deviation; and symmetric in the sense that the speed of convergence is independent of the sign of the deviation. We show that at least for the refined petroleum products spot prices, the error correction mechanism is nonlinear and asymmetric in nature; this evidence is especially strong for heating oil. Hence, inferences obtained from a linear error correction model may be invalid. Specifically, the convergence of spot and futures prices to their long-run relationship is faster: (a) when the futures price exceeds the spot price than when the reverse is true, and (b) the greater the difference between spot and futures prices. These phenomena could reflect asymmetries and indivisibilities in the costs of adjusting production of the commodities studied.

2. Refined petroleum spot and futures markets and price data

The New York Mercantile Exchange's petroleum complex futures are the largest (in terms of contract volume and open interest) futures contracts traded on physical commodities. Contracts are traded on gasoline, heating oil and sweet crude oil on a monthly expiration cycle. Moreover, the spot crude petroleum and refined product markets are among the largest and most important spot commodity markets in the world.

We examine the heating oil (gasoline) futures and spot markets in the period 20 August, 1984 to 31 December, 1990 (4 December, 1984 to 31 December, 1990). The total number of observations studied equals 1582 for heating oil and 1507 for gasoline. The futures contracts call for delivery of 42,000 gallons (1000 barrels) of the relevant product free on board ("f.o.b.") ex barge at the seller's (short's) refinery in New York Harbor.

Daily spot price data on these refined products exist for two important cash markets, New York Harbor and the Gulf of Mexico (i.e., the region in Louisiana and Texas bordering the Gulf of Mexico). As noted above, the former point is the delivery market for heating oil and gasoline. Delivery cannot occur in Gulf. We analyze New York heating oil and Gulf gasoline. Inasmuch as we include both a delivery point and a non-delivery location, the relevance of our results is not limited to deliverable commodities alone. Moreover, these two locations are distinct markets due to the sharply increasing marginal costs of transporting product between them via capacity constrained refined product pipelines, ships, etc.

The available spot price data report refiner offers to sell heating oil and gasoline f.o.b. ex barge on a daily basis. Refiners and traders make bids and offers to buy and sell refined products on a spot basis in an over-the-counter/telephone search market. Price data from this market are collected by telephoning several oil traders near the close of futures trading and report a range of seller offers. Studies that have compared spot price quotations of the type used here with actual transactions prices found, however, that the quotations track the transactions prices closely. Moreover, massive volumes of refined products are bought and sold under term contracts that link the transactions price to the published spot price quotes; the fact that traders use the quotes to price bona fide arms-length transactions strongly suggests that they are reliable measures of spot prices. [2]

For the futures price data we employ the settlement prices from the next to expire futures contract provided by the Commodity Futures Trading Commission. Thus for spot price observations from March we utilize the April futures price, as delivery on this contract occurs in the seven day period starting with the first business day in April. The choice of the next expiring contract is intended to achieve the closest possible match between the timing of the transaction specified in the futures contract and the relevant spot transaction. This contract also tends to have large volume throughout the sample period. We therefore shift futures contracts monthly. [3]

Several studies of spot-futures relations use daily data, and calculate daily

[2] Razavi and Fesharaki (1991), pp. 54–59.

[3] In our empirical work we are careful to take contract switching into account. All futures returns for a given contract are calculated using prices from that contract. For example, when we shift from the July to the August contract on August 1, the futures return for August 1 is equal to the log difference of the August 1 and July 31 August-delivery futures prices. Moreover, we include dummy variables equal to one on contract switch dates and equal to zero otherwise in the cointegration and error correction models in order to correct for potential discontinuities attributable to switching contracts. These dummies are never significant, however, so we suppress them in our reporting of the results.

returns as we do. These include Baillie and Bollerslev (1989), Baillie and Myers (1991), Bessler and Covey (1991), Copeland (1992), and Schroeder and Goodwin (1991).

3. Spot-futures spreads, information and price dynamics: Theoretical considerations and model specification

In this section we examine the determinants of spot and futures price dynamics. We identify certain economic considerations that affect the behavior of spot and futures returns, and use these considerations to motivate models of the mean (in Section 3.1) and variance (in Section 3.2) of these returns.

3.1. Convenience yield, the basis, and error correction in the mean

The textbook cost of carry expression relating spot and futures prices is:

$$F_t = S_t e^{(r_t + w)(T-t)}, \tag{1}$$

where t is the current date, T is the futures contract expiration date, w a proportional warehousing cost, r_t is the riskless money rate of interest at t (we use the 90 day Eurodollar rate in the empirical work), F_t is the futures price at t, and S_t is the spot price at t. This expression implies:

$$\ln F_t - \ln S_t - r_t(T-t) - w(T-t) = 0. \tag{2}$$

In words, (2) states that the interest and storage adjusted basis/spread should equal 0 in equilibrium.

It is well known that this expression may not hold in commodity markets due to the existence of a so-called convenience yield, as expounded by Working (1948), Working (1949) and Telser (1958). [4] According to the theory of storage, inventories provide a stream of benefits – the convenience yield – to processors because they can operate more efficiently with stocks on hand. Hence, processors may want to retain inventory and abstain from sales in the spot market even when the spot price exceeds the futures price. Thus, it is more likely that $\ln F_t - \ln S_t - r_t(T - t) - w(T-t) < 0$.

[4] See Telser (1958), Working (1948), Working (1949), Bresnahan and Suslow (1985), Bresnahan and Spiller (1986), Williams (1986), French (1986), Fama and French (1988), Brennan (1986), Pindyck (1990), and Williams and Wright (1991) for extensive documentation and theoretical analysis of the relation between inventories and spreads.

Working (1948), Working (1949), Telser (1958), and Fama and French (1988) show that there is an inverse relation between the inventory level and the convenience yield. If there is an equilibrium level of inventory and inventory is mean reverting (i.e., stationary), then the convenience yield is mean reverting as well. [5] Define l to be the long run equilibrium level of the convenience yield (which corresponds to the long run level of inventory). And, define the interest, storage cost and long run convenience yield-adjusted spread as:

$$z_t \equiv \ln F_t - \ln S_t - r_t(T-t) - w(T-t) + l(T-t). \tag{2'}$$

Then, z_t captures the deviation of inventory from its long run level as well as temporary disequilibria (i.e., temporary deviations of prices from the equilibrium relation). A negative z_t occurs when inventory is abnormally low, while a positive z_t occurs when inventory is abnormally high.

In either case, agents have an incentive to adjust production and consumption decisions. When inventories are very large, agents reduce current production and increase current consumption, thereby reducing stocks and causing the convenience yield to rise. Conversely, when inventories are very small, they increase production and reduce consumption. This leads to increased stocks and a fall in the convenience yield.

Together, these considerations imply that non-zero values of z_t should be transitory as real adjustments tend to drive spot and futures prices (adjusting for the time value of money) back together. Thus, spot and futures prices should follow an error correction mechanism (''ECM'').

An example of an ECM is the following system of equations:

$$\Delta \ln S_t = \alpha_o + \sum_{i=1}^{n} \alpha_i \Delta \ln S_{t-i} + \sum_{i=1}^{n} \beta_i \Delta \ln F_{t-i} + \sum_{i=1}^{n} \delta_i \Delta y_{t-i} + \theta z_{t-1} + v_t \tag{3}$$

$$\Delta \ln F_t = \gamma_o + \sum_{i=1}^{n} \gamma_i \Delta \ln S_{t-i} + \sum_{i=1}^{n} \phi_i \Delta \ln F_{t-i} + \sum_{i=1}^{n} \lambda_i \Delta y_{t-i} + \psi z_{t-1} + e_t \tag{4}$$

with $-1 \leq \psi \leq 0$ and $1 \geq \theta \geq 0$ (with a strict inequality for at least one coefficient), and where v_t and e_t are random disturbances. Moreover, to ensure stationarity (i.e., to preclude overshooting), $\psi - \theta \leq 1$. In (3) and (4) $\Delta \ln S_t$ is the

[5] In fact, this is a necessary condition for a stable equilibrium.

spot return and $\Delta \ln F_t$ is the futures return, and $\Delta y_{t-i} \equiv r_t(T-t) - r_{t-i}(T-t+i)$. [6]

If $\theta > 0$ and $\psi < 0$, then when $z_{t-1} < 0$ the spot price falls and the futures price rises during the process of convergence. Conversely, if $z_{t-1} > 0$ the futures price falls and the spot price rises to ensure convergence. If $\theta > 0$ and $\psi = 0$, then the burden of convergence falls on the spot market. The opposite is true if $\theta = 0$ and $\psi < 0$.

The specification of (3) and (4) implicitly assumes that the adjustment process is symmetric and linear, as the speed of adjustment to equilibrium is assumed to be the same regardless of whether $z_{t-1} > 0$ or $z_{t-1} < 0$, and to be independent of the size of z_{t-1}. These assumptions, which are standard in the literature, may be incorrect in the present context. As Granger and Terasvirta (1993) suggest, the error correction process may be asymmetric and non-linear. (Escribano, 1987 uses a non-linear error correction mechanism in a study of U.K. money demand, and Granger and Lee, 1989 postulate an asymmetric adjustment mechanism for industrial sales, production, and inventories.)

Cost conditions may make this particularly relevant in refining. For example, the costs of adjusting production and consumption may also lead to a non-linear and/or asymmetric error correction mechanism. Capacity constraints can create backwards "L" shaped marginal costs curves which make it extremely costly for producers to increase output significantly and rapidly when the convenience yield is large and positive in order to take advantage of the relatively high spot price.

[6] The results we present below are not dependent upon whether the lagged $\Delta r_t(T-t)$ terms are included or excluded from the estimation. The p-values for F-tests of the hypothesis that the coefficients on the lagged $\Delta r_t(T-t)$ are jointly equal to zero are above 0.99 for both the futures return equations and the spot return equations. Moreover, the estimates of the volatility equations are virtually unchanged when lagged interest rate changes are included in the ECMs; the correlation between the ECM residuals generated by the two different models exceeds 0.999 for both spot and futures for both commodities.

If $r_t(T-t)$ were integrated of order one, it would also be necessary to include a third equation that regresses the change in $r_t(T-t)$ on lagged values of this variable, and lagged spot and futures returns. We reject the hypothesis that $r_t(T-t)$ is non-stationary. The t-statistic in an augmented Dickey–Fuller regression for this variable is -17.09 in our heating oil sample and -17.25 in our gasoline sample. Indeed, we can reject the hypothesis that r_t itself is non-stationary. The ADF test value is -3.48 from the heating oil sample and -3.52 from the gasoline sample. Moreover, the residuals from estimates of this interest rate equation are uncorrelated with the residuals from the futures return and spot return equations. The point estimates of these correlations are less than 0.01 for both equations and both commodities, and one cannot reject the hypothesis that the correlation is different from zero; the relevant p-values exceed 0.9. Given these results, dropping the third equation affects neither the consistency nor the efficiency of the estimates. These results are economically sensible inasmuch as it is implausible that changes in futures and spot prices for a single commodity affect interest rates. Moreover, since we are primarily interested in the behavior of spot and futures return variances, and since residuals from the third equation do not influence our estimates of the variance processes, we do not discuss this equation hereafter.

Given such cost conditions, producers may face few constraints on reducing output when the convenience yield is negative. Under these circumstances, spot prices rise rapidly when z_{t-1} is large and positive, while they decline slowly when z_{t-1} is negative and large in absolute value. Moreover, production cost indivisibilities may induce non-linearities in the speed of adjustment. Such indivisibilities make it profitable to activate (idle) capacity only when the spot price is very high (low). The adjustment may be more rapid, therefore, when the difference between spot and futures prices is large, as it is unprofitable to adjust capacity when price differences are small.

To explore these possibilities, we can rewrite the error correction model as follows:

$$\Delta \ln S_t = \alpha_o + \sum_{i=1}^{n} \alpha_i \Delta \ln S_{t-i} + \sum_{i=1}^{n} \beta_i \Delta \ln F_{t-i} + \sum_{i=1}^{n} \delta_i \Delta y_{t-i} + \theta_1 z_{t-1}^{+} + \theta_2 z_{t-1}^{-} + \theta_3 (z_{t-1}^{+})^2 + \theta_4 (z_{t-1}^{-})^2 + \epsilon_t \quad (5)$$

$$\Delta \ln F_t = \gamma_o + \sum_{i=1}^{n} \gamma_i \Delta \ln S_{t-i} + \sum_{i=1}^{n} \phi_i \Delta \ln F_{t-i} + \sum_{i=1}^{n} \lambda_i \Delta y_{t-i} + \psi_1 z_{t-1}^{+} + \psi_2 z_{t-1}^{-} + \psi_3 (z_{t-1}^{+})^2 + \psi_4 (z_{t-1}^{-})^2 + \eta_t, \quad (6)$$

where $z_{t-1}^{+} = z_{t-1}$ if $z_{t-1} > 0$ and $z_{t-1}^{+} = 0$ if $z_{t-1} \le 0$, and $z_{t-1}^{-} = -z_{t-1}$ if $z_{t-1} < 0$ and $z_{t-1}^{-} = 0$ if $z_{t-1} \ge 0$. In this specification ψ_1 and ψ_3 (θ_1 and θ_3) measure the speed of adjustment of the futures (spot) price to positive adjusted spreads. Similarly, ψ_2 and ψ_4 (θ_2 and θ_4) measure the speed of adjustment of the futures (spot) price to negative adjusted spreads. The quadratic terms allow more rapid convergence for large values of the basis. The η_t, ϵ_t and u_t are random error terms. [7]

If due to production adjustment costs the futures (spot) price converges to equilibrium more rapidly when $z_{t-1} > 0$ than when $z_{t-1} < 0$, then $|\psi_1| < |\psi_2|$, $|\psi_3| < |\psi_4|$, $|\theta_1| < |\theta_2|$, and $|\theta_3| < |\theta_4|$. Or, if due to the nature of arbitrage and

[7] Futures and spot prices for a related *non-deliverable* commodity (e.g., heating oil futures and Gulf spot heating oil prices) may follow an error correction/partial adjustment process as well. If, for example, fundamental supply and demand forces are highly (but imperfectly) correlated (especially in the long run) across spatially separate locations, one would also expect the two series to follow an error correction process (Engle and Granger, 1987 and Brenner and Kroner, 1991). In this case, z_{t-1} varies with the value of inventories, pricing errors, and factors that affect relative prices at the two points (e.g., a supply shock at the non-delivery point). Even though the existence of transportation, transactions and adjustment costs imply that localized, idiosyncratic variations in supply and demand conditions may cause temporary divergences between non-deliverable spot and futures prices, these divergences should diminish over time as demanders shift to the cheaper market and productive capacity shifts to the more expensive point.

production, the futures (spot) price converges more rapidly when $|z_{t-1}|$ is large, then $|\psi_1| < |\psi_3|$, $|\psi_2| < |\psi_4|$, $|\theta_1| < |\theta_3|$, and $|\theta_2| < |\theta_4|$. [8]

This specification allows us to investigate whether information flows from the futures market to the spot market, or the reverse. Individuals in possession of information may trade upon this knowledge in either the spot or the futures market. Prices will respond in the market where the trading occurs, and these price changes will induce subsequent price changes in other markets. The price discovery hypothesis of futures markets states that futures prices should lead spot prices due to the low transactions costs of dealing on futures markets. The response to new information revealed by price changes may be gradual. This is especially likely to be the case in the refined products spot market due to the nature of the price setting mechanism there. [9] The estimation of significant coefficients on lagged futures (spot) percentage price changes in the spot (futures) equations is consistent with the existence of information flows from the futures (spot) to the spot (futures) market. (For brevity, hereafter we refer to percentage price changes as returns.) It should be noted that previous studies of the lead-lag relation that have ignored the error correction term are mis-specified. As a result, any inferences concerning the direction of information flow in spot and futures markets based on the resulting biased coefficients are suspect.

The summary own-and cross-autocorrelations presented in Tables 1 and 2 suggest that futures shocks are only gradually reflected in spot price changes, as the contemporaneous spot-futures correlation is small, while correlations between spot returns and lagged futures returns are large for the first two lags. Lagged spot returns have a far smaller correlation with contemporaneous futures returns. Together these correlations are consistent with the hypothesis that futures prices lead spot prices.

3.2. Time varying volatility in spot and forward returns: The basis, informed trading, and information spillovers

There are strong reasons to believe that the variances of ϵ_t and η_t from (5) and (6) are time varying. First, the theory of storage implies a relation between these variances and z_{t-1}. Second, informed trading may induce persistent changes in volatility. Third, differential rates of information flow to spot and futures markets may cause volatility spillovers between markets. We examine each point in turn.

[8] As noted in Section 2, the spot market is a dealer search market, rather than an auction market. Thus, it is plausible that transactions costs are higher in the spot market than in the continuous auction futures market, and that spot prices adjust more gradually as a result.

[9] Our results do not change substantively if we allow z_t to vary seasonally by allowing the effect of time to expiration to differ by month. The z_t are stationary, and the relations between spreads, spillovers, and volatility hold, when we use seasonally adjusted z_t.

Table 1
Gulf gasoline spot/futures summary statistics

SPOT AND FUTURES RETURNS

Basic statistics

	Mean	Std.dev.	Skewness	Kurtosis
Spot	−1E−05	0.0298	0.0217	12.1320
Futures	0.0009	0.0235	−0.2149	8.9799

Own and cross autocorrelations

Lag	Current Spot, Lagged Spot	Current Spot, Lagged Futures	Current Futures, Lagged Futures	Current Futures, Lagged Spot
0	1.000	0.051	1.000	0.051
1	−0.014	0.701	0.094	0.010
2	−0.067	0.151	0.010	−0.024
3	−0.061	−0.018	−0.033	0.035
4	0.013	−0.029	0.036	−0.079
5	−0.018	0.015	−0.072	0.029
6	0.039	−0.062	−0.009	−0.003
7	−0.033	0.030	0.034	−0.040
8	−0.008	0.023	−0.028	0.025
9	0.039	−0.020	−0.024	0.051
10	0.043	−0.027	0.084	0.062

SQUARED SPOT AND FUTURES RETURNS

Basic statistics

	Mean	Std.dev.	Skewness	Kurtosis
Spot	0.0009	0.0030	10.2883	149.2106
Futures	0.0006	0.0014	9.3878	141.1262

Own and cross autocorrelations

Lag	Current Spot, Lagged Spot	Current Spot, Lagged Futures	Current Futures, Lagged Futures	Current Futures, Lagged Spot
0	1.000	0.130	1.000	0.130
1	0.090	0.526	0.232	0.116
2	0.187	0.124	0.180	0.099
3	0.245	0.101	0.178	0.086
4	0.062	0.112	0.145	0.121
5	0.211	0.104	0.195	0.132
6	0.055	0.107	0.186	0.070
7	0.070	0.078	0.124	0.059
8	0.016	0.039	0.140	0.046
9	0.011	0.057	0.116	0.074
10	0.063	0.062	0.116	0.032

Table 2
New York heating oil spot/futures summary statistics

SPOT AND FUTURES RETURNS

Basic statistics

	Mean	Std.dev.	Skewness	Kurtosis
Spot	3.2E−05	0.0281	−1.2448	42.8975
Futures	0.0009	0.0242	−0.1969	8.7467

Own and cross autocorrelations

Lag	Current Spot, Lagged Spot	Current Spot, Lagged Futures	Current Futures, Lagged Futures	Current Futures, Lagged Spot
0	1.000	0.110	1.000	0.110
1	0.001	0.763	0.045	0.018
2	−0.021	0.091	−0.011	−0.028
3	0.065	−0.041	−0.047	−0.007
4	0.022	0.023	0.023	−0.044
5	−0.063	0.018	−0.082	−0.052
6	−0.028	−0.103	−0.052	0.038
7	0.012	−0.028	0.034	−0.004
8	0.019	0.011	−0.048	0.014
9	0.008	−0.047	0.011	0.059
10	0.031	0.004	0.044	0.036

SQUARED SPOT AND FUTURES RETURNS

Basic statistics

	Mean	Std.dev.	Skewness	Kurtosis
Spot	0.0008	0.0051	25.4065	754.9578
Futures	0.0006	0.0017	7.2765	75.0381

Own and cross autocorrelations

Lag	Current Spot, Lagged Spot	Current Spot, Lagged Futures	Current Futures, Lagged Futures	Current Futures, Lagged Spot
0	1.000	0.136	1.000	0.136
1	0.426	0.299	0.312	0.173
2	0.067	0.141	0.257	0.137
3	0.114	0.128	0.240	0.050
4	0.102	0.116	0.131	0.073
5	0.100	0.203	0.205	0.073
6	0.035	0.242	0.153	0.062
7	0.023	0.057	0.157	0.099
8	0.052	0.066	0.126	0.067
9	0.044	0.043	0.116	0.070
10	0.059	0.054	0.152	0.061

Since z_t is strongly and positively related to deviations between current inventories and their long run level, when stocks are small the spread is negative and large in absolute value, and the short run elasticity of supply is very low; the long run supply elasticity is greater due to the ability to adjust production over time. Thus, as z_t decreases and becomes negative and large in absolute value, one expects spot price volatility to increase, as prices are more variable when supply is relatively inelastic. Moreover, futures return volatility should not be affected as acutely by inventory shortages due to the ability to adjust in the longer run. In addition, Brennan (1991) argues that z_t is positive and large when storage capacity constraints bind. Under these circumstances it is more difficult to use inventory adjustments to cushion supply and demand shocks, so again prices become more volatile.

There is no a priori reason to believe that the effects of large inventories and small inventories (and thus positive and negative values of the basis) on price variances are symmetric. Thus, it is possible that the relation between the basis and volatility depends upon its sign. Indeed, it is plausible that scarcity of supplies (and therefore a negative adjusted spread) has a more pronounced effect on volatility than an abundance.

Trading on private information also induces time varying volatility. The model of Kyle (1985) and the reasoning of Black (1986) imply that private information is embedded in prices gradually. The release of new private information (and the associated large price moves) should therefore cause persistent increases in volatility.

Ross (1989) and Tauchen and Pitts (1983) also argue that increases in the rate of flow of information to markets should increase volatility.

A preliminary analysis of the data strongly suggests the existence of such effects. The results in Tables 1 and 2 demonstrate that lagged squared spot returns in refined product markets are correlated with contemporaneous squared spot returns even at relatively long lags. Similarly, lagged squared futures returns are strongly correlated with contemporaneous squared futures returns, even at long lags. The ARCH and GARCH models now commonplace in the economics and finance literatures can capture any such effects.

It is also necessary to consider the possibility that since information based trading may occur in either the cash or the futures market, volatility can spill over from one market to the other. Since information may flow between markets, a shock in the futures market may cause a persistent change in the volatility in the spot market or vice versa if volatility changes in response to information flows. The interesting work of Chan et al. (1991) documents the existence of such spillovers between the S&P 500 index futures market and the market for the stocks underlying that index. Again, the summary data in Tables 1 and 2 points to the existence of such effects. Lagged squared futures returns are very strongly correlated with current squared spot returns; this effect is especially pronounced for Gulf gasoline. There is some evidence of spot to futures spillovers, as there is a positive correlation between contemporaneous squared futures returns and lagged squared spot returns. The correlation coefficients are uniformly smaller than that found for current spot-lagged futures squared returns, however.

We formally test for the existence of these various relations between volatility, shocks, and spreads with the following equations for spot and futures return variance:

$$h_{s,t} = \omega + \lambda h_{s,t-1} + \mu_1 \epsilon_{t-1}^2 + \mu_2 \eta_{t-1}^2 + \mu_3 (z_{t-1}^+)^2 + \mu_4 (z_{t-1}^-)^2 \tag{7}$$

$$h_{f,t} = \sigma + \kappa h_{f,t-1} + \upsilon_1 \epsilon_{t-1}^2 + \upsilon_2 \eta_{t-1}^2 + \upsilon_3 (z_{t-1}^+)^2 + \upsilon_4 (z_{t-1}^-)^2, \tag{8}$$

where $h_{s,t}$ and $h_{f,t}$ are the variances of ϵ_t and η_t, respectively, conditional on all information available up to and including $t-1$. The parameter κ is a measure of the persistence of futures return volatility shocks, while the parameter λ is a measure of the persistence of spot return volatility shocks. The larger the values of these parameters, the longer volatility shocks persist. Since private information based trading induces persistent volatility shocks, κ and λ can be interpreted as measures of the importance of informed trading in the futures and spot markets, respectively.

The presence of η_{t-1}^2 in the spot return variance equation and ϵ_{t-1}^2 in the futures return variance equation capture the effect of volatility spillovers between spot and futures markets. If $\upsilon_1 > 0$, spot price shocks induce increased volatility in the futures market. Again, since volatility increases in response to the entry of informed traders into the market such a finding is consistent with the hypothesis that information flows from the spot to the futures market. If $\mu_2 > 0$, futures price shocks induce increased spot volatility. This is consistent with the hypothesis that information flows from the futures to the spot market. The presence of the error correction terms $(z_{t-1}^+)^2$ and $(z_{t-1}^-)^2$ permits spreads to affect volatility in an asymmetric fashion.

If spreads affect volatility, then the failure to include the $(z_{t-1}^+)^2$ and $(z_{t-1}^-)^2$ terms in the $h_{s,t}$ or $h_{f,t}$ equations implies the resulting estimates of the importance of volatility spillovers and GARCH effects may be biased. This in turn implies that inferences about a) the dynamics of volatility, b) and the nature of information flows, based upon such models are suspect. Furthermore, since the theory of storage implies that fundamental supply and demand conditions drive the spread, a comparison of the relative importance of the ARCH terms and the spread terms can potentially reveal whether fundamental factors are the primary sources of volatility.

In summary, the analysis in this section argues that a variety of factors influence spot and futures price dynamics. First, the costs of adjusting production and consumption over time imply that expected spot and futures returns should depend upon the spot-futures spread. These adjustment costs may induce an asymmetric and non-linear relation between the spread and returns; i.e., the speed of convergence may depend upon the size and sign of the spread. Second, the relation between spreads, stocks, and supply elasticity suggests that spreads should affect volatility in an asymmetric fashion. Third, informed trading induces price shocks, persistent volatility increases, and volatility spillovers. The remainder of this paper tests these hypotheses using data from refined petroleum spot and futures markets.

4. Estimation procedure and results

The analysis of the model and data described above proceeds in three steps.

First, we examine whether $\ln S_t$ and $\ln F_t$ are non-stationary, and if so, whether the z_t are stationary. If the latter result holds, then $\ln F_t$ and $\ln S_t$ are cointegrated (Brenner and Kroner, 1991). We find that both spot and futures prices are indeed non-stationary and cointegrated.

We use an augmented five lag Dickey–Fuller test to determine the existence of a unit root in the logs of the various price series. For Gulf gasoline, the t-statistic on the relevant coefficient in the augmented Dickey–Fuller ("ADF") regression equals -2.08, which is smaller (in absolute value) than the 5 percent level critical value of the augmented Dickey–Fuller test of -2.57 for sample sizes greater than 500. Similarly, the t-statistic from the relevant coefficient from the ADF regression equals -2.09 for gasoline futures, -2.24 for spot New York heating oil, and -2.00 for heating oil futures. We therefore cannot reject the null hypothesis that each of these series has a unit root.

The theory discussed in Section 3 suggests the z_t terms should be stationary. To estimate the z_t term we consider the following regression:

$$\ln F_t - \ln S_t - r_t(T-t) = \hat{b}(T-t) + u_t. \tag{9}$$

(Note that t changes as time passes, and T changes when we switch contracts. Thus, $T-t$ is a variable.) We observe directly neither physical storage costs nor the long run level of inventory, so $\hat{b}$ is an empirical estimate of the w and l from (2′), while u_t is a random error term.

This regression imposes the restriction that the spot-futures cointegrating vector equals $[1,-1]$. It also imposes the restriction that the coefficient on $r_t(T-t)$ equals one. Since $r_t(T-t)$ is stationary in our sample, it is not properly cointegrated with $\ln F_t$ and $\ln S_t$. However, theory implies that it is necessary to include this variable in the analysis to adjust for the effect of the time value of money on the relation between spot and futures prices. The restrictions imposed are implied by the equilibrium relationship between the spot and futures prices. Imposing this theoretically implied restriction can generally improve the efficiency of our estimates. In any event, the practical effects are virtually nil. In an unrestricted regression of $\ln F_t$ on $\ln S_t$, $r_t(T-t)$ and $(T-t)$ the coefficient on the log spot price equals 0.9776 for Gulf gasoline and 0.9919 for New York heating oil. As a result, the unrestricted regression produces virtually identical values for u_t (and thus for z_t) as the theoretically-inspired restricted regression. [10] Moreover, the R^2's from the heating oil and gasoline regressions are 0.959 and 0.970, respectively. These high R^2's suggest that the coefficients are not biased.

We define $z_t = u_t$, and run a five lag ADF regression for z_t. The t-statistic on the relevant coefficient from this regression equals -7.26 for Gulf gasoline and gasoline futures, and -8.07 for New York heating oil and heating oil futures. We can therefore reject the null hypothesis of a unit root in the error correction term at a high level of significance. The z_t are therefore stationary.

Recognizing that the z_t may be heteroskedastistic, and that the ADF tests are not robust to weakly dependent error processes, we also implement the more robust Phillips–Perron tests for stationarity. [11] The Phillips–Perron test statistic on z_t equals -19.62 for gasoline and -15.08 for heating oil, both of which are far greater (in absolute value) than the critical value of -2.57. Similarly, Phillips–Perron tests do not reject the null of a unit root in S_t and F_t. For S_t, the test statistic equals -2.26 for gasoline and -2.24 for heating oil. For F_t, it equals -2.22 for gasoline and -2.14 for heating oil. These values are smaller (in absolute value) than the critical value of -2.57. Thus, the Phillips–Perron and Dickey–Fuller tests give the same results: the spot-futures spreads are stationary, but the spot and futures prices are not. If anything, the Phillips–Perron tests provide even stronger evidence for the stationarity of z_t.

The preceding finding is important as some studies (see Brenner and Kroner, 1991 for a summary of several of these) of spot-futures relations reject cointegration. Moreover, the finding of cointegration combined with the results of the Granger representation theorem (Engle and Granger, 1987) implies that it is necessary to include an error correction term in the mean Eqs. (5) and (6).

[10] In the unrestricted heating oil regression, the coefficient on $r_t(T-t)$ equals -3.91 with a heteroskedasticity corrected standard error of 2.16, and the coefficient on $T-t$ equals -0.0535 with a corrected standard error of 0.212. One can reject the null hypothesis that the coefficients on $\ln S_t$ and $r_t(T-t)$ are both equal to one at the 0.005 level. For gasoline, these coefficients (standard errors) are 13.17 (3.50) and -0.134 (0.019) respectively. For gasoline one can also reject the null that the coefficients on $\ln S_t$ and $r_t(T-t)$ are jointly equal to one at the 0.005 level. Although the unrestricted regressions do not satisfy the theoretical restriction, this is of little importance for the empirical work. The residuals from the unrestricted regressions are stationary. For both commodities, the t-statistics on the relevant coefficient in the ADF regression on the unrestricted residuals are the same (to the third decimal place) as the t-statistics from the ADF regression on the restricted residuals. Moreover, for both commodities, the correlation between the restricted and unrestricted residuals exceeds 0.995. Given that the residuals from the restricted and unrestricted regressions are almost identical, the results we present below are not dependent upon which we use.

[11] The reported Phillips–Perron statistics are based on a regression of the first difference of z_t (or $\Delta \ln S_t$ or $\Delta \ln F_t$) on its first five lags (to capture the short term dynamics of the spread or returns series), and z_{t-1} (or $\Delta \ln S_{t-1}$ or $\Delta \ln F_{t-1}$). No deterministic time trend is included. The heteroskedasticity correction is based on a Newey–West approach. Similar results obtain if the lagged values of the difference in z_t are excluded from the regression. The test values from the unaugmented regression (without trend) are -14.31 for heating oil and -18.98 for gasoline.

Using the just calculated z_{t-1} as a pre-determined variable, our second step is to estimate (5) and (6) using OLS; it is necessary to use $n = 10$ in these regressions in order to eliminate all autocorrelation in the residuals. Recognizing the possibility of seasonality for these commodities, we seasonally adjust the spot and futures returns prior to estimating these equations. To do so, we regress spot returns and futures returns against monthly dummy variables, and use the residuals from these regressions as the seasonally adjusted spot and futures return series. Estimating (5) and (6) using these adjusted returns, we obtain the residuals $\hat{\epsilon}_t$ and $\hat{\eta}_t$.

Third, given the residuals from (9) we estimate (7) and (8) as a bivariate system assuming

$$\begin{pmatrix} \hat{\epsilon}_t \\ \hat{\eta}_t \end{pmatrix} | F_{t-1} \sim \text{Student } t \left(\begin{pmatrix} 0 \\ 0 \end{pmatrix} \begin{pmatrix} h_{st} & \sigma_{sft} \\ \sigma_{sft} & h_{ft} \end{pmatrix}, \Theta \right), \tag{10}$$

where

$$\sigma_{s,f,t} = \rho \sqrt{h_{st} h_{ft}} \tag{11}$$

and F_{t-1} is information available as of time t, and Θ is the inverse of the number of degrees of freedom in the Student t-distribution. In (11) (following Chan et al., 1991) we assume a constant correlation-ρ-between spot and futures residuals.

The use of the bivariate conditional t-distribution (where the degrees of freedom $1/\Theta$ is estimated) as opposed to the normal is intended to capture the fat tails of the joint distribution of η_t and ϵ_t; since the t-distribution contains the normal as a limiting case, it is more general than the bivariate normal distribution typically used in related studies of these issues. The use of this distribution represents another advance over traditional analyses of time varying volatility as it generalizes the univariate GARCH-t model of Bollerslev to a bivariate case. The estimation as a bivariate system also improves the efficiency of the parameter estimates. [12]

Four considerations justify this three-step estimation procedure. First, since the cointegrating vector is prespecified based on theory, the first step actually involves the estimation of an average storage cost and/or convenience yield. Such an adjustment in the constant term will not have much effect on the price dynamics which are the focus of this paper. Second, even if the cointegrating vector were to be estimated, Stock (1987) has shown that the cointegrating regression is super-consistent and hence the results in the error correction model will not be much affected. Third, OLS gives consistent estimates of η_t and ϵ_t because the explanatory variables in (5) and (6) are identical. Hence, the separate execution of the

[12] We also estimate the (7) and (8) independently. This has little effect on the point estimates of the coefficients, but robust standard errors of the bivariate estimates are consistently smaller.

second and third steps neither prevents consistency nor reduces the asymptotic efficiency of the estimates in the third step. Fourth, for high-frequency data, it is generally found that the estimation of the mean has minor effects on the estimation of variance and covariance parameters as the mean is typically very small. Our approach of separately estimating the first and second moments follows that of

Table 3
Gulf gasoline spot/futures nonlinear error correction model
(White heteroskedasticity consistent t-statistics in parentheses)

		Spot Mean Equation	Futures Mean Equation
Constant		−0.0016 (−1.46)	0.0011 (0.96)
Disequilibrium:			
z(t) positive		0.0992 (1.48)	−0.0951 (−1.12)
z(t) negative		−0.0583 (−0.69)	−0.0075 (−0.13)
squared z(t) positive		0.9748 (1.69)	1.5250 (1.49)
squared z(t) negative		−0.6264 (−0.82)	0.2070 (0.56)
Lagged spot returns:			
Lag	1	−0.1864 (−3.57)	0.0169 (0.47)
	2	−0.1347 (−2.86)	−0.0144 (−0.30)
	3	−0.1323 (−2.04)	0.0105 (0.27)
	4	−0.0651 (−1.67)	−0.0279 (−0.72)
	5	0.0361 (0.77)	0.0443 (1.16)
	6	0.0177 (0.55)	−0.0330 (−0.94)
	7	−0.0256 (−0.76)	−0.0149 (−0.42)
	8	0.0509 (1.29)	0.0563 (1.63)
	9	0.0766 (2.87)	−0.0111 (−0.30)
	10	0.0196 (0.92)	0.0422 (1.78)
Lagged futures return:			
Lag	1	0.7271 (16.11)	0.0991 (2.19)
	2	0.2666 (4.69)	−0.0137 (−0.27)
	3	0.1029 (1.94)	−0.0356 (−0.69)
	4	0.1159 (1.96)	0.0469 (0.89)
	5	0.0601 (1.20)	−0.0555 (−0.99)
	6	−0.0550 (−1.05)	−0.0336 (−0.65)
	7	0.0278 (0.76)	0.0697 (1.52)
	8	0.0294 (0.75)	−0.0244 (−0.47)
	9	−0.0355 (−0.97)	−0.0628 (−1.32)
	10	−0.0699 (−1.86)	0.0875 (1.79)
R-squared		0.5742	0.0282
Ljung-Box statistics for 12th order serial correlatio in the residual (Chi-sq. 12)		8.46	6.23
White t test for Ho:			
[z(t) neg.] = −[z(t) pos.]		0.31	−0.83
[sq.z(t) neg.] = [sq.z(t) pos.]		2.08	1.29

Table 4
Gulf gasoline spot/futures variance models

Bivariate GARCH-t with spillovers and the basis effect (Asymptotic t-statistics in parentheses)
Log-likelihood: 7986.70

	Spot Conditional Variance	Futures Conditional Variance
Constant	3.2E−05 (4.87)	7E−06 (2.60)
Lagged spot conditional variance	0.4433 (8.86)	
Lagged futures conditional variance	0.8608 (43.92)	
Lagged spot shock	0.2057 (5.24)	0.0140 (1.51)
Lagged futures shock	0.0927 (4.25)	0.1284 (6.27)
squared z(t) positive	0.0151 (2.09)	−0.0018 (−0.56)
squared z(t) negative	0.0408 (4.05)	−0.0004 (−0.20)
Conditional correlation	−0.0214 (−0.68)	
Degree of fat-tailedness 1/(d.f. of conditional-t)	0.1465 (9.85)	
Ljung-Box(12) for: squared normalized residual	10.67	13.96

Pagan and Schwert (1990) and Gallant et al., 1992. Lin (1992) compares the estimates derived from two step procedures with those obtained from full maximum likelihood estimation, and finds they are quite close.

It is true that joint estimation of (5)–(8) would improve the efficiency of the parameter estimates in (5) and (6). Given the large number of parameters in the system joint estimation is computationally infeasible. While the White heteroskedasticity-consistent standard errors of our parameter estimates in the mean equation are larger than the asymptotic standard errors that would be obtained under joint estimation which accounts explicitly for the form of heteroskedasticity, this is of secondary importance to our results as we are primarily interested in the variance effect. At most, it implies that our conclusions concerning the asymmetry and non-linearity of the error correction mechanism, and the direction of information flow, are conservative.

The results of this analysis are contained in Table 3, Table 4, Table 5, Table 6. (In the interest of brevity, coefficients on the lagged Δ_{yt} are not reported because they are jointly and individually insignificant. The estimates of the interest rate equation are also not reported because they are not relevant to the objective of the study.) An examination of these results reveals several salient points. First, variations in spreads induce variations in spot price volatility. Second, the effect of spreads on spot volatility is strongly asymmetric; z_{t-1}^{-} has a far greater impact on spot volatility than z_{t-1}^{+}. Third, spot (futures) price shocks induce persistent increases in spot (futures) volatility, but spot volatility shocks are less persistent than futures volatility shocks. Fourth, there are volatility spillovers from futures to

Table 5
New York heating oil spot/futures nonlinear error correction model
(White heteroskedasticity consistent t-statistics in parentheses)

		Spot Mean Equation	Futures Mean Equation
Constant		−0.0029 (−3.26)	0.0000 (0.01)
z(t) positive		0.1381 (3.24)	−0.0310 (−0.34)
z(t) negative		0.0574 (1.07)	0.0827 (1.87)
squared z(t) positive		−0.0423 (−0.08)	1.1470 (0.97)
squared z(t) negative		−0.7080 (−2.89)	−0.2747 (−2.77)
Lagged spot returns:			
Lag	1	−0.2678 (−4.71)	0.1103 (1.99)
	2	−0.1513 (−2.74)	0.0262 (0.48)
	3	0.0193 (0.44)	−0.0484 (−0.87)
	4	0.1250 (2.77)	0.0315 (0.48)
	5	0.0913 (1.67)	−0.0046 (−0.08)
	6	0.0644 (1.74)	0.0788 (1.41)
	7	0.0234 (0.70)	0.1132 (1.82)
	8	0.0624 (2.12)	0.0659 (1.36)
	9	0.0352 (1.12)	0.0698 (1.99)
	10	0.0148 (0.91)	0.0183 (0.61)
Lagged futures return:			
Lag	1	0.8299 (14.71)	0.0255 (0.47)
	2	0.3302 (4.87)	−0.1120 (−1.74)
	3	0.1149 (2.48)	−0.0835 (−1.20)
	4	0.0392 (0.72)	0.0822 (1.21)
	5	−0.0740 (−1.89)	−0.1133 (−1.54)
	6	−0.0902 (−1.61)	−0.0495 (−0.80)
	7	−0.0291 (−0.78)	−0.0248 (−0.37)
	8	−0.0263 (−0.65)	−0.1779 (−2.61)
	9	−0.0574 (−1.57)	−0.0574 (−0.97)
	10	−0.0148 (−0.91)	−0.0183 (−0.61)
R-squared		0.717	0.0325
Ljung-Box statistics for 12th order serial correlatio in the residual (Chi-sq. 12)		14.62	7.88
White t test for Ho:			
[z(t) neg.] = −[z(t) pos.]		2.29	0.44
[sq.z(t) neg.] = [sq.z(t) pos.]		1.30	1.22

spot markets, but the reverse is not true. Fifth, the error correction mechanism is asymmetric and non-linear; convergence occurs more rapidly if $z_{t-1} > 0$ than if $z_{t-1} < 0$, and the larger is z_{t-1} (in absolute value). Sixth, lagged futures returns explain current spot returns, but the reverse is not true. We now consider each finding in detail.

Table 6
New York heating oil spot/futures variance models

Bivariate GARCH-t with spillovers and the basis effect (Asymptotic t-statistics in parentheses)
Log-likelihood: 9278.48

	Spot Conditional Variance	Futures Conditional Variance
Constant	8E−06 (4.15)	9E−06 (2.82)
Lagged spot conditional variance	0.4149 (8.35)	
Lagged futures conditional variance		0.8687 (41.53)
Lagged spot shock	0.2554 (5.68)	0.0290 (1.50)
Lagged futures shock	0.0295 (5.05)	0.1300 (5.69)
squared z(t) positive	0.0022 (1.34)	−0.0008 (−0.27)
squared z(t) negative	0.0238 (5.57)	−0.0023 (−1.27)
Conditional correlation	0.0599 (1.90)	
Degree of fat-tailedness 1/(d.f. of conditional-t)	0.1998 (11.05)	
Ljung-Box(12) for: squared normalized residual	4.99	14.42

(1) Spreads induce spot excess return volatility but not futures price volatility. The coefficients on $(z_{t-1}^{+})^2$ and $(z_{t-1}^{-})^2$ are both significant in the gasoline spot variance equations and insignificant in both the futures variance equations. Moreover, the coefficient on $(z_{t-1}^{-})^2$ is significant in the heating oil equation. These results document (for the first time to our knowledge) the important effect of spreads on return variances.

This effect is extremely important. Indeed, the z_{t-1} terms explain virtually all of the innovations in spot excess return volatility in both markets. To see this, consider the following measure of the relative importance of spreads and lagged squared spot and futures shocks in explaining spot volatility innovations:

$$f(z_{t-1},\eta_{t-1},\epsilon_{t-1}) = \frac{g(z_{t-1})}{g(z_{t-1}) + v(\eta_{t-1},\epsilon_{t-1})},$$

where

$$g(z_{t-1}) \equiv \hat{\mu}_3(z_{t-1}^{+})^2 + \hat{\mu}_4(z_{t-1}^{-})^2$$

and

$$v(\eta_{t-1},\epsilon_{t-1}) \equiv \hat{\mu}_1\epsilon_{t-1}^2 + \hat{\mu}_2\eta_{t-1}^2.$$

The function $f(.)$ essentially measures the expected volatility innovation resulting from z_{t-1} alone relative to the expected volatility innovation resulting from both spreads and lagged spot and futures shocks (i.e., the ARCH effects). In the sample for heating oil, the average value of $f(z_{t-1},.,.)$ equals 0.9779 (with a standard deviation of 0.1003), while in the gasoline sample it equals 0.9623 (with a standard deviation of 0.1413). Thus, variations in the spread are responsible for virtually all of the volatility innovations in the spot market. The corresponding statistic for futures volatility is much smaller.

Another measure of the closeness of the relation between spreads and volatility is the correlation between $g(z_{t-1})$ and $h_{s,t}$. This correlation is very high for both commodities, equaling 0.94 for heating oil and 0.89 for gasoline.

Fig. 1a and Fig. 1b provide a striking visual illustration of the relation between z_{t-1} and spot market volatility. The figures plot the fitted values of $h_{s,t}$ and $-5g(z_{t-1})$; we adjust $g(z_{t-1})$ to scale the figures and improve their clarity. These functions are virtual mirror images. It is thus plain that large deviations between spot and futures prices are associated with large spot volatilities for both gasoline and heating oil.

Given the importance of spreads in determining volatility, it is unsurprising that the consequences of ignoring it may be quite severe. For instance, when the spread terms are excluded from the $h_{s,t}$ equation the coefficient on the lagged spot variance $h_{s,t-1}$ in the New York heating oil equation equals 0.616, while if the z_{t-1} terms are included, the coefficient equals 0.441. In this case, the exclusion of the z_{t-1} term leads to a very sizable overestimate of the persistence of spot volatility. Although the disparity is not quite so severe in the Gulf gasoline case – there the coefficient on $h_{s,t-1}$ equals 0.551 if the error correction terms are excluded while it equals 0.443 if they are included – the direction of the bias is the same. Moreover, the coefficients on the lagged spot shocks also fall slightly when the spread term is included.

The intuition behind these differences is straightforward. There is some persistence in the error correction term, and z_{t-1} contributes to volatility. When the spread term is omitted, therefore, the $h_{s,t-1}$ term (which measures the persistence of volatility shocks) pick up some of the effect of the omitted error correction term.

(2) There is a pronounced difference between the coefficients on $(z_{t-1}^{+})^2$ and $(z_{t-1}^{-})^2$. In particular, when the spot price is above the futures price, spot return volatility is higher ceteris paribus than when the spot price is below the futures price. This difference is strongly significant. Specifically, the critical χ^2 value of a likelihood ratio test of the null hypothesis that $\mu_3 = \mu_4$ equals 3.84. The test value for Gulf spot gasoline equals 4.44, while that for New York spot heating oil equals 18.25.

This asymmetry in the relation between spreads and volatility is consistent with the theory of storage and suggests that variations in fundamental supply and demand conditions are the major determinant of spot excess return volatility changes. When $z_{t-1} < 0$, the market is in an unusually large backwardation (i.e., the convenience yield is large). This typically occurs when physical stocks of the commodity are very low relative to expected demand. [13] Since it is impossible to increase current consumption with future production (negative inventories are impossible), but future consumption can be augmented by carrying over current stocks, supply is relatively inelastic when stocks are low. Spot prices therefore bear the burden of all adjustments to changes in demand. Ceteris paribus, this leads to a high spot return volatility when $z_{t-1} < 0$. [14]

The fact that there is no statistically significant relation between spreads and futures return volatility is also consistent with the theory of storage. As noted by Fama and French (1988) and French (1986), over longer time horizons real variables (e.g., output or shipments of supplies to a market) adjust to supply and demand shocks. These real responses reduce the magnitude of the futures price response to demand and supply shocks. The coefficients in the mean spot return equations provide direct evidence of such an effect. Specifically, lagged spot return coefficients are consistently negative and significant at the first lag, and sometimes at more distant lags. This overshooting is consistent with the hypothesis that refiners cannot adjust output immediately to demand and supply shocks, but can do so over a several day period because supply is more elastic in the long run immediately in response to a supply or demand shock as output cannot do so. As output adjusts to accommodate the shock the initial price response is reversed in part. This finding is consistent with the finding that futures return volatility does not depend significantly upon spreads, as supply constraints are less pronounced in the longer run, and hence demand shocks have a smaller effect on futures prices.

[13] Brennan (1986) and Pindyck (1990) document a convex and increasing relation between spreads, stocks, and anticipated demand for heating oil, while Telser (1958), Brennan (1958), Working (1947), Working (1948), Williams (1986), Bresnahan and Spiller (1986), and Williams and Wright (1991) provide evidence for other commodities. Fama and French (1988) and French (1986) explore the relation between spreads and volatility in a different framework, and find results consistent with ours. We also estimate a GARCH model of the raw spot return volatility, i.e. we model the variance of seasonally adjusted spot returns without correcting for the effect of past futures and spot returns. The findings of this analysis are also broadly consistent with the theory of storage. Large negative spreads are associated with large spot return variances. Large positive spreads have a statistically significant, but far smaller impact on raw spot return variances. Neither ARCH nor GARCH effects are pronounced, but lagged squared futures returns have a significant effect on raw spot return volatility.

[14] An alternative explanation of the relation between spreads and volatility is related to Keynes' ''normal backwardation'' theory (Keynes, 1930). We reject this interpretation of our results for several reasons. Most importantly, we regress the current spread (z_t) against lagged spreads and lagged squared spot and futures returns. If volatility shocks are persistent (as the data suggest), the lagged squared shocks are measures of expected volatility. Under the no-arbitrage normal backwardation hypothesis, the coefficients on the lagged shocks should be negative as higher volatility (holding other conditions-captured by the lagged spreads) should depress the futures price relative to the spot price. The coefficients on the lagged squared shocks are positive as well as negative, and not always significant, while the lagged spreads are significant for several lags. Thus, there is no evidence that the direction of causation is from volatility to spreads, while there is considerable evidence of a strong relation between spreads, stocks, and volatility.

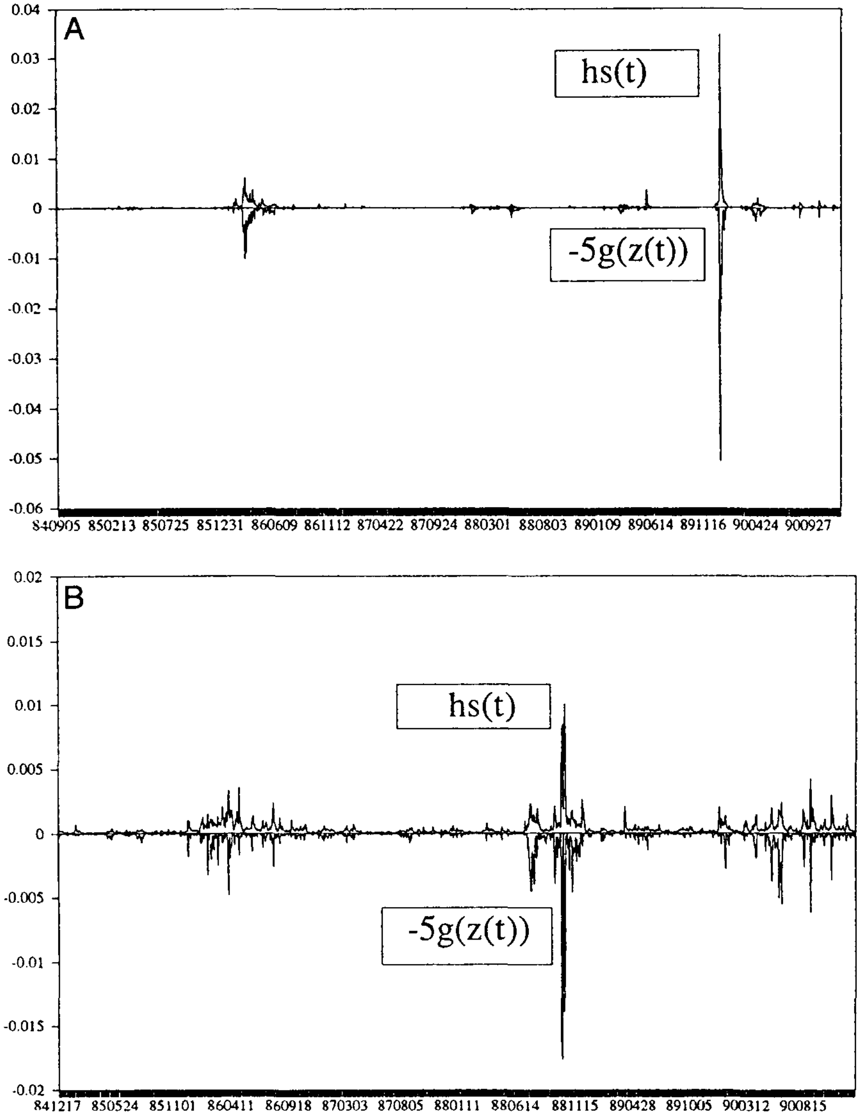

Fig. 1. (a) Heating oil volatility and spread. (b) Gasoline volatility and spread.

The positive relation between $(z_{t-1}^{+})^2$ and h_{st} is also consistent with the theory of storage. According to Brennan's (1991) hypothesis, positive spreads exist when stocks are abnormally large relative to storage capacity. The lack of storage capacity limits the market's ability to make real adjustments to demand and supply shocks. Instead, prices bear the brunt of the response to these shocks. (In the absence of storage capacity constraints, one would expect a negative relation between $(z_{t-1}^{+})^2$ and $h_{s,t}$.)

(3) The volatility of unexplained spot price movements depends on past spot shocks and past spot volatility, and futures volatility depends on past futures shocks and past futures volatility. The coefficients on lagged variance are large and significant in both the spot and futures variance equations. This is consistent with the large body of evidence that now exists for stock cash and futures markets and some commodity futures markets (Baillie and Myers, 1991).

It is of interest to note that volatility shocks are considerably more persistent in the futures markets than the spot markets. In the Gulf gasoline spot variance equations, for instance, the coefficient on $h_{s,t-1}$ equals 0.491 while the coefficient on $h_{f,t-1}$ in the gasoline futures variance equation equals 0.864. The disparity is even more pronounced in the New York heating oil market. There the coefficient on $h_{s,t-1}$ is only 0.441 while the coefficient on $h_{f,t-1}$ equals 0.861.

The difference in persistence between spot and futures market volatility is consistent with the idea that trading on private information is more prevalent in futures than spot markets. As noted by Kyle (1985), Black (1986), and Masulis and Ng (1992), private information is incorporated in prices only gradually because privately informed individuals release their information over time in order to exploit more effectively the camouflage provided by noise traders. As a result, the introduction of new private information should induce increased volatility for some period of time. Less private information based trading in the spot market, therefore, would produce the observed difference in volatility persistence in the spot market. This again supports the price discovery hypothesis.

(4) The volatility of residual spot returns depends on lagged futures shocks, but futures volatility does not depend on lagged spot shocks. That is, there are volatility spillovers from futures to spot markets, but not the reverse. This finding is again consistent with the price discovery theory of futures markets. As Ross (1989) notes, the rate of information flow should impact volatility. Thus, a simple VAR analysis alone is insufficient to capture completely the effect of the introduction of new information on prices; it is necessary to examine volatility as well. The fact that futures price shocks portend increased spot price volatility is therefore consistent with the idea that information flows from futures markets to spot markets. The lack of a spillover in the opposite direction suggests a minimal (at best) price discovery role for the spot market.

The finding that there are no spot to futures volatility spillovers contrasts with the results for the S&P 500 futures of Chan et al. (1991), who find significant volatility spillovers from spot to future markets as well as from futures to spot markets. The differences in the behavior of these two sets of markets is plausibly due to their quite different micro-structure. In particular, the lack of centralized spot petroleum product trading may make it costlier to trade on private information in that market. Alternatively, it may result from their omission of the z_{t-1} effect.

(5) There is evidence of asymmetry and non-linearity in the error correction mechanism. The evidence is strongest for spot heating oil. The error correction process is statistically significant, nonlinear, and asymmetric in the New York heating oil spot mean equation. In the spot equation, one can reject the hypothesis that all four error correction coefficients are jointly zero at the 0.00194 level. Moreover, one can reject the hypothesis that the a) coefficient on z_{t-1}^{+} equals minus one times that on z_{t-1}^{-} and b) the coefficient on $(z_{t-1}^{+})^2$ equals that on $(z_{t-1}^{-})^2$ at the 0.0044 confidence level. The null hypothesis that the coefficients on the squared deviations are jointly zero is rejected with a p-value of 0.032.

The asymmetry in the error correction coefficients implies that convergence to the long run equilibrium is more rapid when the futures price (adjusting for the time value of money and time to expiration) is high relative to the spot price than when the reverse is true. As noted in Section 3, this is consistent with differential costs of expanding and contracting production. The non-linearity in the error correction mechanism is also consistent with production indivisibilities. When spot-futures deviations are small, the gains from reversing them may not cover the production costs incurred when doing so. Conversely, when deviations are large, potential gains exceed the costs of exploiting them. Thus, large deviations are reversed more rapidly than small ones.

The error correction process in spot Gulf gasoline is statistically significant although no individual term is significant. The p-value for the hypothesis that all four coefficients are jointly zero equals 0.00002. [15] However, the evidence supporting the asymmetry and non-linearity of the error correction mechanism for spot gasoline is less clear-cut than that for spot heating oil. One can reject at the 10-percent level the joint hypothesis that the coefficients on $(z_{t-1}^{+})^2$ and $(z_{t-1}^{-})^2$ are both equal to zero for Gulf gasoline, but one cannot reject that hypothesis at the 5-percent level. The p-value on the relevant test is 0.097. Moreover, one can reject at the 5-percent level the null hypothesis that the coefficients on $(z_{t-1}^{+})^2$ and $(z_{t-1}^{-})^2$ are equal in the spot gasoline equation; the p-value equals 0.0376 in this case. The point values of the coefficients imply that spot prices rise more rapidly when the futures price is high relative to the spot price than they fall when the futures price is low relative to the spot price by a similar amount. Thus, there is

[15] One can decisively reject the hypothesis that all of the error correction term coefficients are equal to zero; the p-value for this test equals 0.00001. ECMs including only z_{t-1}^{+} and z_{t-1}^{-} (and excluding the squared spreads) for Gulf gasoline have virtually identical coefficients on the lagged spot and futures returns. In these regression, the value of the coefficient on z_{t-1}^{+} equals 0.134 with a t-statistic of 3.34, and that on z_t^{-} equals -0.141 with a t-statistic of -2.98. One cannot reject the hypothesis that the absolute values of these coefficients are equal. The relevant p-value equals 0.85. We use residuals from the non-linear and asymmetric ECM model in our volatility equation estimation because a) this specification is more general, and b) the data cannot decisively reject the non-linearity and asymmetry of the error correction mechanism.

evidence for a non-linear and asymmetric error correction mechanism for Gulf gasoline, but that evidence is somewhat weaker than for New York heating oil.

The evidence regarding the significance, linearity, and symmetry of the error correction mechanism is mixed for the futures mean equations. For heating oil futures, the error correction mechanism is statistically significant; the p-value on the test of the hypothesis that all four error correction coefficients equal zero is 0.0267. The joint hypothesis that the a) coefficient on z_{t-1}^{+} equals minus one times that on z_{t-1}^{-} and b) the coefficient on $(z_{t-1}^{+})^2$ equals that on $(z_{t-1}^{-})^2$ for heating oil futures is rejected at the 5 percent level, but just barely; the p-value equals 0.0573 in this case. In addition, the coefficient on $(z_{t-1}^{-})^2$ is statistically significant, providing evidence of non-linearity. In contrast, for gasoline futures, one cannot reject the hypothesis that the error correction terms are jointly zero. The p-value on this test equals 0.448. One cannot reject the hypothesis that the error correction mechanism is linear or symmetric either; the p-values for the relevant tests range between 0.20 and 0.43. The difference between the behavior of the error correction mechanism for gasoline and that of heating oil is plausibly due to the fact that the deliverable spot price is used in the latter regressions, whereas a non-deliverable spot price is used in the former.

(6) Lagged futures returns affect spot returns, but lagged spot returns do not explain much of the variation in futures returns. The first three coefficients on the lagged futures returns in the spot return regressions are large and significant for both commodities. In the gasoline futures return regressions, one cannot reject the hypothesis that the coefficients on lagged spot returns are jointly zero; the p-value equals 0.1395. For heating oil futures, some of the lagged spot coefficients are of borderline significance, and one can reject the hypothesis that all the lagged spot coefficients equal zero with a p-value of 0.0375. However, lagged futures and spot returns together explain little of the variability in futures returns, as the adjusted R^2 in these regressions are less than 0.04 for both commodities. Thus, the economic significance of the relation between futures returns and lagged spot returns is minimal. These findings are also consistent with the hypothesis that the futures market is the primary price discovery mechanism for refined petroleum products, as futures price changes lead spot price changes, but the reverse is not true.

5. Summary and conclusions

This article provides an extensive characterization of the spot and futures price dynamics of two vital commodities, gasoline and heating oil. Using a very general specification of spot and futures returns, we produce many important results heretofore absent from the literature. For example, we show that spreads between spot and futures prices explain virtually all spot return volatility innovations for these two commodities, and that the effect of spreads is asymmetric; spot prices are more volatile when the spot price exceeds the future than when the reverse is true. We also demonstrate the existence of volatility spillovers from futures to spot markets, and show that spot volatility shocks are less persistent than futures volatility shocks. We also demonstrate for the first time that the process of convergence of spot and futures prices – the error correction mechanism – is non-linear and asymmetric; the speed of adjustment is faster (slower) when the difference between spot and futures prices is large (small) in absolute value, and when the futures price exceeds the spot price.

These results are pertinent to both researchers and market participants. The findings that spreads and spillovers affect volatility, and that error correction mechanisms may be non-linear and asymmetric suggests that time series analyses of both spot-futures relations and the relations of other variables that are cointegrated (e.g., stock prices and dividends, income and consumption, short term and long term interest rates) that ignore these features may be mis-specified. Moreover, the strong and asymmetric relation between spreads and volatility documented in this article strongly suggests that fundamental supply and demand conditions (as opposed to extraneous factors such as noise trading) are the prime determinants of refined petroleum spot price variance, while the existence of volatility spillovers, the greater persistence of futures volatility shocks, and the lead-lag relations between futures and spot prices are consistent with the view that the futures market is the primary locus of informed trading of refined petroleum products.

As always, caution is warranted when interpreting these results. Although the results are clearly consistent with a fundamentals-based theory of commodity price dynamics, it may be the case that an ''excess volatility'' model could explain the data as well. However, since existing excess volatility theories are barren of refutable implications, we have not been able to test this alternative using our data. Even given this caveat, however, our results are important inasmuch as they show that a fundamentals-based theory can explain salient aspects of price dynamics for important and heavily traded physical commodities. Indeed, the fact that a variable that is a well-documented proxy for fundamental supply and demand conditions – the spot-futures spread – explains virtually all of the innovations in volatility of refined petroleum spot prices provides stronger evidence of the link between fundamentals and price dynamics than has been documented heretofore.

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