Volatility, Storage and Convenience: Evidence from Natural Gas Markets

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INTRODUCTION

The theory of storage literature that begins with Kaldor (1939) holds that processors or consumers of a commodity receive an implicit stream of benefits from holding inventory. This stream of benefits is called convenience. Examples of convenience include the opportunity to benefit from unexpected demand or supply shocks, or the opportunity to reduce costs by smoothing a production process. This theory of storage also implies that commodity forward prices differ from contemporaneous spot prices by the storage and interest costs of holding inventory, less the benefit of convenience.

The theory of storage predicts that marginal convenience value, the benefit of holding inventory, declines as the aggregate level of inventory increases. Theory also predicts that the shape is convex—an additional unit of inventory leads to a larger reduction in marginal convenience value if the current level of inventory is low (see the solid line in Fig. 1). Evidence presented by Working (1948, 1949), Telser (1958), and Brennan (1958, 1991) supports this prediction.

We are grateful to Tom Miller and Rich Pettit for helpful comments.

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The Journal of Futures Markets, Vol. 17, No. 1, 17–43 (1997)

CCC 0270-7314/97/010017-27

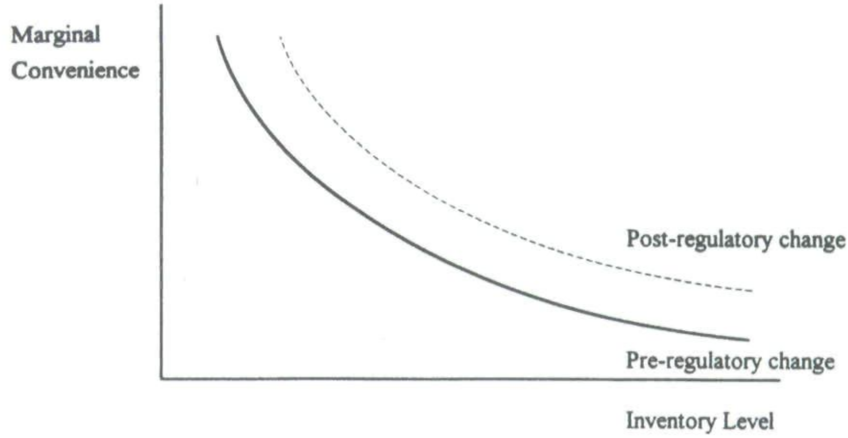

FIGURE 1
Marginal convenience and inventory level.

French (1986), and Fama and French (1987, 1988) derive implications of a convex marginal convenience function in terms of forward and spot price variances and correlations. Suppose that shocks in demand or supply are predominantly either permanent, or current and transitory. French and Fama and French show that if the level of inventory is high, contemporaneous spot and forward prices should have similar variances and exhibit a high correlation. At lower levels of inventory, the variance of the spot price should be greater and the correlation between the spot and forward prices lower. Evidence presented in Cho and McDougall (1990), Siegel and Siegel (1991), and Ng and Pirrong (1994) is consistent with the theory. Convenience, the benefit of holding inventory, is inversely related to the level of inventory. It follows that convenience should be directly related to the variability of the spot price of the commodity and inversely related to the correlation between spot and forward prices. A higher volatility or a lower correlation increases the marginal benefit of holding inventory.

This article analyzes the relationship between commodity price volatility and investment in storage facilities in an industry that went through major changes in market structure. The evidence presented below demonstrates that an increase in volatility was followed by investment in additional storage facilities, as predicted by the theory of storage. During the 1980s, extensive changes in regulations removed entry barriers that increased the feasible frequency of transactions in the U.S. spot market for natural gas. See Stalon (1986), De Canio (1990), and Thompson

(1992).[1] Following the theoretical model of Heinkel, Howe and Hughes (1990), the data is deseasonalized. It is well documented that asset returns and changes in commodity prices have a time-varying variance. As a result, ARCH models are widely used to parameterize these time-varying volatility processes. Given the substantial regulatory changes in the natural gas industry, this article employs the Hamilton and Susmel (1994) switching ARCH model, which also allows a time-varying variance to change in response to structural changes.

The U.S. natural gas industry has some favorable characteristics for this type of analysis. Pipeline quality natural gas is a physically undifferentiated product.[2] At the production area, natural gas is processed to meet standard quality criteria before it can enter the pipeline. The North American market can be considered as independent of the markets in other continents. Imports and exports present few complications. A large change in the North American price level would be required to make it economic to liquify natural gas for import or export. Pipeline imports from Mexico into the U.S. are insignificant. Many of the available data series include both Canadian and U.S. volumes. Natural gas storage is relatively easy to measure in this market. Industry associations and the government gather extensive data on storage activity. In the case of government data, disclosure is required by regulations.

The remainder of this article is organized as follows: First, it motivates the implications of the theory of storage; then discusses the different types of storage; describes the industry structural changes and the evolution of spot natural gas markets; presents evidence from storage capacity surveys; describes the monthly data analyzed; and presents the econometric model and the results.

PRICE VARIANCE AND THE LEVEL OF STORAGE

Let $F(t, T)$ be the forward or futures price at time t for delivery at time T. Let $S(t)$ be the spot price at time t. The theory of storage implies that the forward price differs from the spot price by the marginal cost of storage, $W(t, T)$, plus interest, $S(t)R(t, T)$, minus the marginal minus the marginal convenience yield of holding inventory, $C(t, T)$.[3]

[1]Stalon (1986), an economist and a Commissioner at the Federal Energy Regulatory Commission, offers unique insights on the subject. Also, see Tussing and Barlow (1984), Pierce (1988), Braeutigam (1990), Smith, De Vany, and Michaels (1990) and De Vany and Walls (1994).

[2]As with most commodities, however, there are spot price differences between delivery locations which change over time.

[3]A similar relationship holds between forward (or futures) prices with different maturities.

$$F(t, T) - S(t) = S(t)\,R(t, T) + W(t, T) - C(t, T) \qquad (1)$$

This article makes use of the implications of a convex marginal convenience function (Fig. 1) on variances and correlations of spot and forward prices. Namely, higher marginal convenience values (or lower inventory levels) are associated with greater spot price variance and a lower correlation between spot and forward prices. These implications are derived in French (1986), Fama and French (1987, 1988), and Williams and Wright (1991). The discussion below provides only an intuitive motivation.

Suppose that shocks in demand or supply are either permanent, or current and transitory. Demand and supply elasticities normally increase with the time horizon. As time passes, consumers are increasingly able to switch to substitutes and producers are increasingly able to adjust output. It follows that a permanent shock should have a greater impact on the current spot price than on the expected spot price. The same holds for a current shock.

Storage allows intertemporal shifting of supplies in response to relative scarcity. A convex convenience function implies that if the level of stocks is high, a large change in stocks is associated with a small change in the marginal convenience yield. If the marginal cost of storage is not greatly affected by a change in the level of stocks, the change in the spread between spot and forward prices should be small also. [See eq. (1)]. So, if the level of stocks is high, large quantities can be shifted intertemporally without much change in the spread between spot and forward prices. It follows that at high levels of inventory, shocks should lead to changes in the current spot price that are not much larger than changes in forward prices. Therefore, at high levels of inventory, spot and forward price variance should be similar and exhibit a high correlation.

In contrast, the lower the level of inventory, the greater the effect of a given change in inventory level on the spread between spot and forward prices. At a low level of inventory, the inventory response to a current or permanent shock will be smaller and the impact on the current spot price larger. The spread between spot and forward prices should be more variable. Therefore, at lower levels of inventory, the variance of the spot price should be greater and the correlation between the spot and forward prices lower. Evidence presented in French (1986), Fama and French (1987, 1988), and Ng and Pirrong (1994) is consistent with this theory.

Natural gas is a convenience asset.[4] Only those who receive a benefit from physical services in addition to expected capital gains hold inventory

[4]Empirical evidence indicates convenience yield is an important factor for natural gas. For example,

in storage. According to the theory of storage, a change in market structure that increases the variance of spot prices should increase the use of storage. This article tests the following hypothesis: structural change has increased natural gas price volatility, which has led to an increase in the use of storage.

THREE TYPES OF STORAGE

Natural gas storage can be divided into three types: deferred production, seasonal storage, and high deliverability storage. All of these methods use an underground geologic trap, or reservoir. Removal of natural gas from a deposit requires drilling wells. The maximum rate of flow from the wells declines with time as depletion of the deposit reduces the pressure in the deposit. Deferred production storage refers to slowing down the current rate of flow, to enable larger rates of flow at a later time. Geologic characteristics determine the maximum rate of flow and, therefore, the minimum term for this type of storage. The minimum term is typically a number of years.[5] Once removed from the original deposit, natural gas can be stored by injecting it into other suitable reservoirs called storage reservoirs. Storage reservoirs are chosen on the basis of favorable logistics and injection and withdrawal rate characteristics. Storage reservoirs can be divided into two types: seasonal and high deliverability. Seasonal facilities typically require an injection period of about 200 days and complete withdrawal requires 60 to 100 days. The fastest injection withdrawal cycle is effectively one heating season. In contrast, high deliverability facilities (e.g., salt caverns and salt domes) typically require an injection period of about 20 days and complete withdrawal requires 10 to 15 days.[6] Many injection and withdrawal cycles can be completed over one year.

Seasonal storage facilities have been important assets in natural gas markets for over 50 years. Advances in technology allowed pipeline and distribution companies to invest in numerous seasonal facilities by the late 1930s. Consumption of natural gas has a strong seasonal pattern due

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Brinkmann and Rabinovitch (1994) find that the correlation of daily price changes between the nearby futures contract and more distant maturities is lower than for oil products. For the second and third nearest maturities they report correlations of: .698 and .287 for natural gas, verses .903 and .902 for crude oil. They also find that the correlation of spot price changes to nearby futures price changes is lower for natural gas than for oil products.

[5]For example, for a water pressure driven reservoir, the deferred volume cannot be recovered until the end of the reservoir production life, frequently a decade or longer. For a gas pressure driven reservoir with a rapid production rate of 20% of remaining reserves each year, the deferred volume can be recovered spread out over the life of the reservoir with an average production delay of around 5 years.

[6]See *Natural Gas 1994: Issues and Trends,* U.S. Energy Information Administration, pp. 82–86.

to large winter heating demand. Market-area storage is often the lowest cost method to meet the winter demand peaks in urban markets which are often hundreds of miles from major production areas. Seasonal storage facilities greatly reduce the need for peak-day capacity in both long distance transmission lines and producing wells.[7]

STRUCTURAL CHANGE AND THE EVOLUTION OF SPOT MARKETS

During the 1970s, few buyers and sellers entered into short-term transactions. The interstate pipeline companies that connected reserves to most markets were regulated monopolists in the purchase and resale of gas. Most consumers were captive customers of regulated utilities and were charged regulated rates.[8] Some interstate pipeline companies were allowed to sell gas to large industrial and electric utility customers at unregulated prices. These customers typically had alternative fuel capability. Price series for these unregulated sales provide the only readily available measure of the spot price in this period.

During the 1970s, storage decisions were made primarily by regulated utilities. Most owners of reserves had no choice but to sell under long-term contracts to regulated pipelines. These contracts typically lasted ten or more years and gave the pipeline company the right to choose the rate of production from a well, subject to an annual minimum purchase volume. In other words, these contracts provided pipeline companies large quantities of deferred production storage. Seasonal storage facilities were also widely used by regulated utilities, especially near major markets.

The regulated interstate natural gas markets did not adapt well to the rapid oil price changes of the 1970s and early 1980s. This led to a restructuring of the industry. When oil prices increased in the 1970s, demand for natural gas increased. Most new supplies not subject to existing contracts went to customers in the gas producing states, since these customers were not bound by federal regulations and they could offer higher prices.[9] Nonprice rationing occurred in some regulated interstate markets. To ease the immediate problem, the Congress and federal regulators allowed interstate pipelines to transport spot gas purchased di-

[7]For a thorough discussion of the role of seasonal storage facilities in serving residential heating markets, see Herbert (1992).

[8]In this article, the term *regulated utility* refers to both interstate pipelines subject to federal regulation and the downstream gas distribution utilities subject to state regulation.

[9]Natural gas produced and consumed within one state was not subject to federal price ceilings when transported by an intrastate pipeline.

rectly by some customers.[10] Most customers were denied access to these early transportation programs. To correct the problem on a longer term basis, Congress also increased the price schedule that interstate pipelines could offer for volume from new wells. Progressively higher prices could be offered for volume delivered in each year through 1984, and no price ceiling applied for the volume delivered thereafter.

Transportation programs and spot markets grew more rapidly after regulated natural gas markets failed to adapt to the rapid oil price declines of the 1980s. Interstate pipelines were committed to purchase large volumes of new gas at prices many of their industrial customers refused to pay. Federal regulators allowed interstate pipelines to transport spot gas purchased by their large industrial customers to keep them from switching to oil.[11] Some of these authorized transportation programs eliminated the need for separate regulatory approval of each transportation transaction. As a result, these programs reduced the time between spot price negotiation and delivery, and facilitated more frequent, shorter-term transactions. These transportation programs also generally denied transportation to customers unable to switch fuels.

In May, 1985 the Courts ruled that the existing transportation programs illegally discriminated between customers.[12] In October of 1985 federal regulators responded with a program that allowed interstate pipelines to provide transportation to all customers.[13] However, allocation of rights to transportation capacity and allocation of financial obligations associated with existing gas purchase contracts required a comprehensive regulatory hearing for each pipeline. As a result, transportation rights were extended at different times on different systems.[14] In addition there were almost immediate legal challenges to the new federal regulations, which created uncertainty about the transportation rights that would ultimately exist. In June of 1987, the Courts affirmed the transportation provisions of the federal regulations, but required a few changes effecting the cost of buying out existing gas purchase contracts and the allocation of these costs between customers. Federal regulators issued their revised regulations in August of 1987.[15] Uncertainty about the ultimate form of

[10]Specific Regulatory Orders include: Federal Power Commission (FPC) Order 533 issued 8/28/75, FPC Order 2 issued 2/1/78, and FPC Order 27 issued 4/27/79. Section 311 of the Natural Gas Policy Act (NGPA) of 1976 increased the ability of regulators to authorize transportation service.

[11]Specific regulatory orders include: Federal Energy Regulatory Commission (FERC) Order 319 issued 8/83, FERC Order 234-B issued 8/83, and approval of numerous Special Marketing Programs (SMP's).

[12]Maryland Peoples Counsel v. FERC, 761 (D.C. Cir., 1985) and 758 (D.C. Cir., 1985).

[13]FERC Order No. 436.

[14]For summary data on the rate of adoption of transportation regulations by pipelines over the late 1980s see De Vany and Walls (1994).

[15]FERC Order No. 500.

transportation rights on pipeline systems was reduced further in 1989 when Congress passed the Natural Gas Decontrol Act.[16]

By 1990, transportation service was widely available. However, it was inferior to the transportation that pipelines bundled with the commodity to provide sales service. For example, sales customers alone benefitted from storage fields and the contractual rights that pipelines owned to use upstream pipelines. Transportation customers also were subject to daily scheduling, volume balancing requirements, and penalties that did not apply to sales service.

In 1992 federal regulators issued Order 636 which required interstate pipelines to offer transportation service comparable in quality to that embedded in sales service.[17] Order 636 also required pipelines to release all storage and transportation capacity not needed to maintain operational control of their systems. This improved transportation flexibility made shorter term spot transactions possible. As of 1995, both transportation and storage services are widely available on a flexible basis. The numerous legislative, regulatory, and judicial events described above suggest that this shift towards regulated transportation and unregulated spot commodity markets took place in numerous, unevenly spaced, temporal stages.

EVIDENCE FROM STORAGE CAPACITY SURVEYS

The discussion above suggests that regulatory change during the 1980s led to growth in the spot natural gas market and an increase in the frequency of transactions. The empirical evidence presented in "Empirical Results" supports the hypothesis that this structural change led to an increase in spot price volatility. This finding has the theory of storage implications. According to the theory of storage, an increase in volatility should increase the marginal benefit of holding inventory. An increase in the feasible frequency of transactions should enhance this effect. Figure 1 illustrates these effects with an upward shift in the marginal convenience yield schedule. As a result of this shift, additional storage facilities are expected to be built (especially high deliverability facilities). In "Empirical Results", this hypothesis is tested using a monthly proxy for storage capacity. In this section, less frequent but more detailed storage capacity

[16]This legislation endorsed the transportation program already put in place by federal regulators, and repealed some remaining price controls that affected a few old purchase contracts.

[17]FERC Order 600 was proposed in July, 1991, issued in April, 1992, and took effect on November 1, 1993.

TABLE I

Storage Development by Reservoir Type and Date

	Reservoir	*Aquifer*	*Salt Cavern*	*Total*
EIA data				
Working gas capacity (BCF)				
Existing 1990				3550
Existing 1993	3170 (85.8%)	443 (12.0%)	82 (2.2%)	3695
Proposed 1994–1995	280 (73.1%)	8 (2.1%)	95 (24.8%)	383
Proposed 1994–1999	322 (65.1%)	9 (1.8%)	164 (33.1%)	495
Daily deliverability (MMcf)				
Existing 1990				61718
Existing 1993	53380 (78.8%)	7306 (10.8%)	7041 (10.4%)	67729
Proposed 1994–1995	5345 (39.0%)	110 (0.8%)	8235 (60.2%)	13690
Proposed 1994–1999	6521 (31.4%)	110 (0.5%)	14115 (68.0%)	20746
Number of projects				
Existing 1990				357
Existing 1993	316 (84.3%)	38 (10.1%)	21 (5.6%)	375
Proposed 1994–1995	24 (44.4%)	2 (3.7%)	28 (51.9%)	54
Proposed 1994–1999	31 (38.3%)	3 (3.7%)	47 (58.0%)	81
Pace/GRI data:				
Working gas capacity (BCF)				
Pre-'86	2371 (85.8%)	361 (13.1%)	29 (1.1%)	2761
1986–1993	173 (68.6%)	2 (0.8%)	77 (30.6%)	252
1993–2000	120 (39.7%)	20 (6.6%)	162 (53.6%)	302
Number of projects				
Pre-'86	360 (84.5%)	54 (12.7%)	12 (2.8%)	426
1986–1993	13 (48.2%)	1 (3.7%)	13 (48.2%)	27
1993–2000	8 (50.0%)	2 (12.5%)	6 (37.5%)	16

Sources: U.S. Energy Information Administration (EIA), *The Value of Underground Storage in Today's Natural Gas Industry*, March 1995. This data is based upon Federal Energy Regulatory Commission Filings and information from various news sources. Proposed projects are those announced as of Feb. 28, 1994. Daily deliverability is the maximum amount of gas that can be withdrawn in one day if the facility is filled to capacity. Pace/GRI is a 1992 survey by Pace Consultants commissioned by the Gas Research Institute (GRI), Chicago.

data is examined. The data supports the hypothesis of an increase in storage activity.

Table I describes storage capacity over time. The upper half of Table I presents working gas capacity and deliverability data (the maximum rate of withdrawal) from a 1995 EIA government report.[18] The lower half of Table I presents working gas capacity from a 1992 investment survey conducted by Pace Consultants. Breaks in the time intervals in the Pace survey coincide with major regulatory events. In October of 1985, federal regulators issued the order that allowed and encouraged interstate pipe-

[18]see *The Value of Underground Storage in Today's Natural Gas Industry*, U.S. Energy Information Administration, 1995.

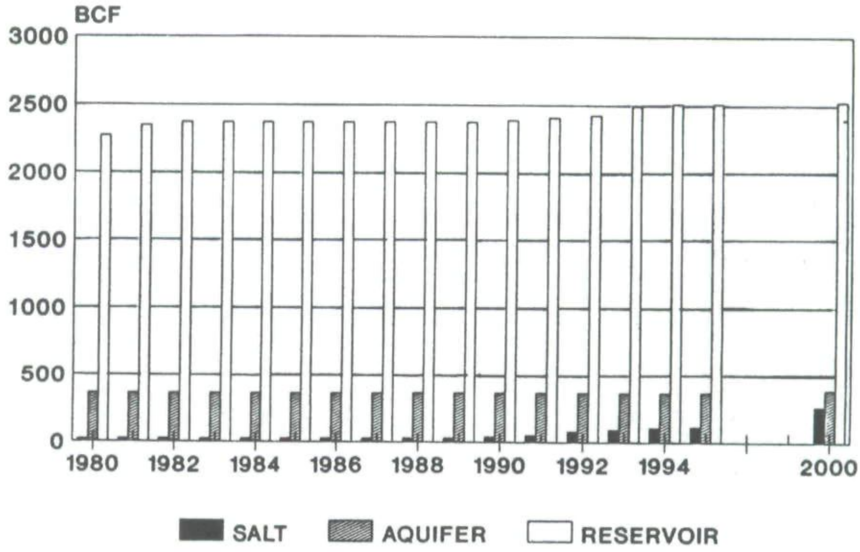

FIGURE 2
Storage capacity by formation type. Notes: The source is a 1992 study by Pace Consultants commissioned by the Gas Research Institute, Chicago. Data points beyond 1992 reflect planned projects and projects under construction.

lines to extend transportation service to all customers (FERC Order No. 436). This order also conveyed the direction that FERC intended to move the market. November of 1993 was the date FERC Order 636 went into effect. This order mandated that pipelines release all transportation and storage capacity not needed to maintain operational control of their systems.

The data in Table I show that large investments in storage capacity occurred during this period of regulatory change. It typically takes 18 to 36 months to plan and build a storage facility.[19] The Pace survey of completed and planned projects indicates that additions to working gas capacity of over 9% were scheduled to be placed in service from 1986 through 1993. Approximately 10% more working gas capacity was scheduled for later years. Figure 2 presents a graph of the Pace working gas capacity data by year and type. The EIA working gas capacity data in Table I also indicate large additions to capacity in the 1990s, with much of the expansion becoming available after 1993. The EIA study shows a 13% increase in capacity for 1994–1999. These large increases in storage ca-

[19]According to the EIA (1995) report, it takes about 18 to 24 months to develop a salt reservoir and about 24 to 36 months to develop a gas or oil field reservoir. Out of the 18 responses that provided planning lead time in the Pace/GRI survey, 13 indicated two years or longer, and 17 indicated one and a half years or longer.

pacity are not attributable to growth in the level of aggregate demand. U.S. natural gas consumption has yet to recover to the levels of the early 1970s.[20] Furthermore, as explained in the next section, it is likely that excess storage capacity was placed in service during the late 1970s and early 1980s.

These working gas capacity numbers greatly understate the increase in storage capability. Prior to 1986, salt caverns accounted for only 1 or 2% of working gas capacity. The Pace study found that salt caverns accounted for over 30% of gas capacity additions from 1986 through 1993. This has increased to over 50% for scheduled capacity additions after 1993. According to the EIA study, more than one-third of the 21 existing salt cavern facilities at the end of 1993 were placed in service after 1991. This trend is important since salt cavern facilities have a deliverability-to-capacity ratio about five times greater than the average reservoir or aquifer facility.[21] The EIA data in Table I show that if all proposed facilities are completed, working gas capacity will increase by 13% by 1999. In contrast, deliverability will increase by 31% due to the shift to salt caverns. Even these higher deliverability figures ignore the fact that salt caverns allow five to ten injection and withdrawal cycles per year versus only one cycle in seasonal facilities.[22] Table II presents evidence that the frequency of cycles is increasing. Comparing the 1982–1986 period to the 1989–1993 period, the average monthly injections and withdrawals per storage field have increased in both the heating and nonheating seasons. The fact that the percentage increase in withdrawals is largest during the nonheating season and the percentage increase injections is largest during the heating season suggests that intraseasonal storage is growing relatively rapidly.

In summary, the data presented above shows large additions to storage capacity over this period of regulatory change and spot market growth. In addition, according to the EIA and Pace studies, most of the new storage facilities are being built in producing areas and most will have access to multiple pipeline systems. These characteristics are consistent with the theory of storage since they maximize the ability to react to short-term price changes.

MONTHLY DATA

In the remainder of this article, monthly data series for price and storage capacity are analyzed. Figure 3 shows the average cost of natural gas

[20]see *Monthly Energy Review,* U.S. Department of Energy.

[21]Thirteen salt caverns, fourteen reservoirs, and two aquifer facilities provided deliverability data in the Pace survey. The deliverability to working gas ratios (MMcfd/Bcf) were 52.8 for salt caverns, 9.7 for reservoirs, and 8.3 for aquifer facilities.

[22]See p. 33 of the EIA (1995) study.

TABLE II

Average Monthly Injections, Withdrawals, and Working Gas Levels (MMcf)

	Nonheating Season	*Heating Season*	*Heating Year*
Average injections per field			
1982–1983 through 1986–1987	757	187	520
1989–1990 through 1993–1994	906	257	642
Percentage change	20	37	23
Average withdrawals per field			
1982–1983 through 1986–1987	126	1099	531
1989–1990 through 1993–1994	185	1217	644
Percentage change	47	11	21
Average working gas per field			
1982–1983 through 1986–1987	5891	5247	5623
1989–1990 through 1993–1994	6451	5734	6160
Percentage change	10	9	10

Source: Energy Information Administration (EIA), *The Value of Underground Storage in Today's Natural Gas Industry,* March, 1995.

purchased by electrical utility plants in the U.S. from January, 1974 through March, 1994. Electric utilities and some large industrial plants were the only interstate customers in the 1970s that purchased gas at unregulated prices. Because these customers often had alternative fuel capability, they provide the best available measure of the market value of gas in this period.

Figure 4 shows base gas volume in storage from September, 1975 through March 1994. This series is used as a measure of storage capacity. The greater the volume of gas in a storage reservoir, the greater the pressure and the greater the possible rate of withdrawal. To maintain a minimum rate of withdrawal, gas volume in a storage reservoir is never reduced below a specified level called base gas volume. Since much of the capacity added over the last decade is salt cavern storage, use of base gas as a proxy for capacity weakens the test results below. This follows because a unit of base gas supports more working gas capacity if it is in a salt cavern.[23] Also, as discussed earlier, salt caverns have deliverability to capacity ratios about five times greater than seasonal facilities. Clearly, the increase in base gas volume over the period understates the increase in storage capability. An additional problem with this series is that accounting adjustments may exist due to reactions to FERC Order 636.

[23]According to the EIA (1995) study, salt caverns require base gas of about 25% of working gas capacity verses 50% for depleted reservoirs and 80–90% for aquifer facilities (see pp. 46–51).

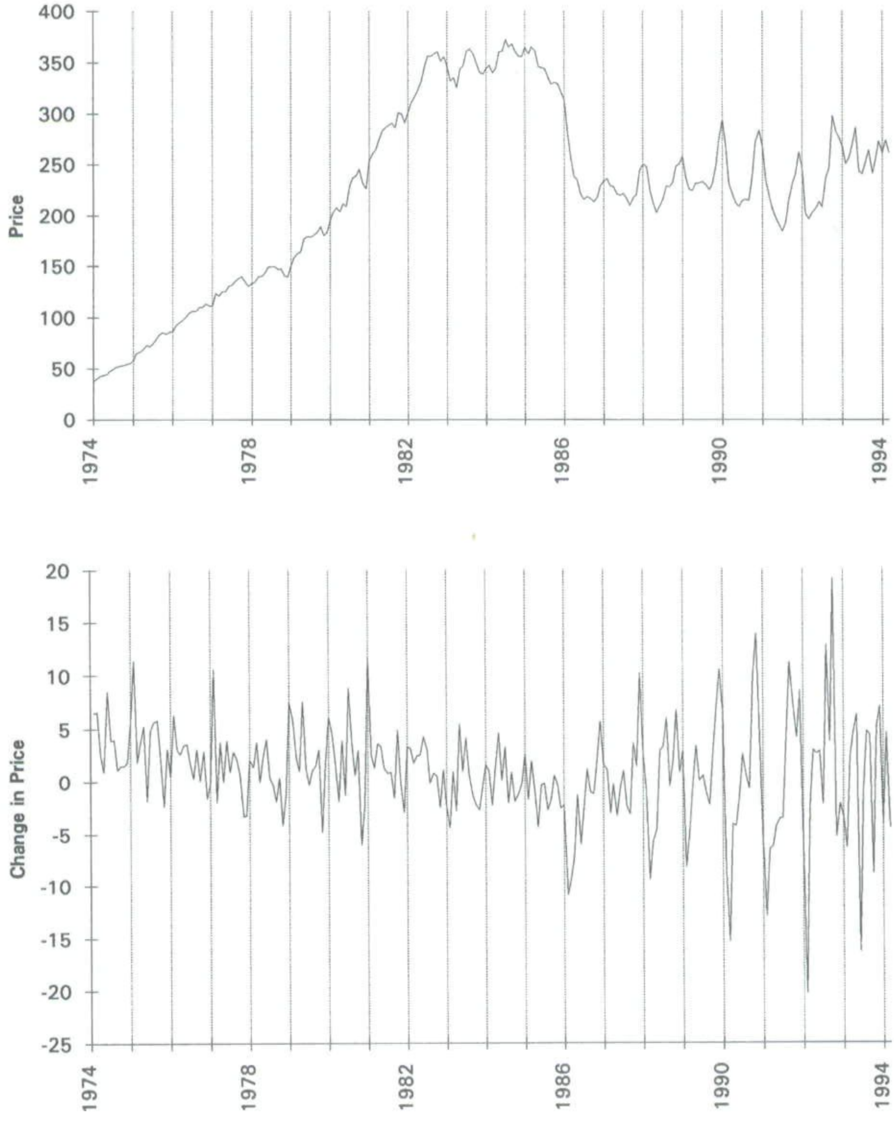

FIGURE 3

Natural gas prices. Notes: Average cost of natural gas purchased by electric utility plants in the U.S. from January, 1974 through March, 1994. The source is Monthly Energy Review, U.S. Department of Energy.

However, the authors know of no better monthly proxy for storage capacity.

There is a second problem in the data that is likely to weaken the test results below. Excess underground storage capacity may have been placed in service in the late 1970s and early 1980s due to regulatory incentives. This would artificially reduce additions to storage capacity in

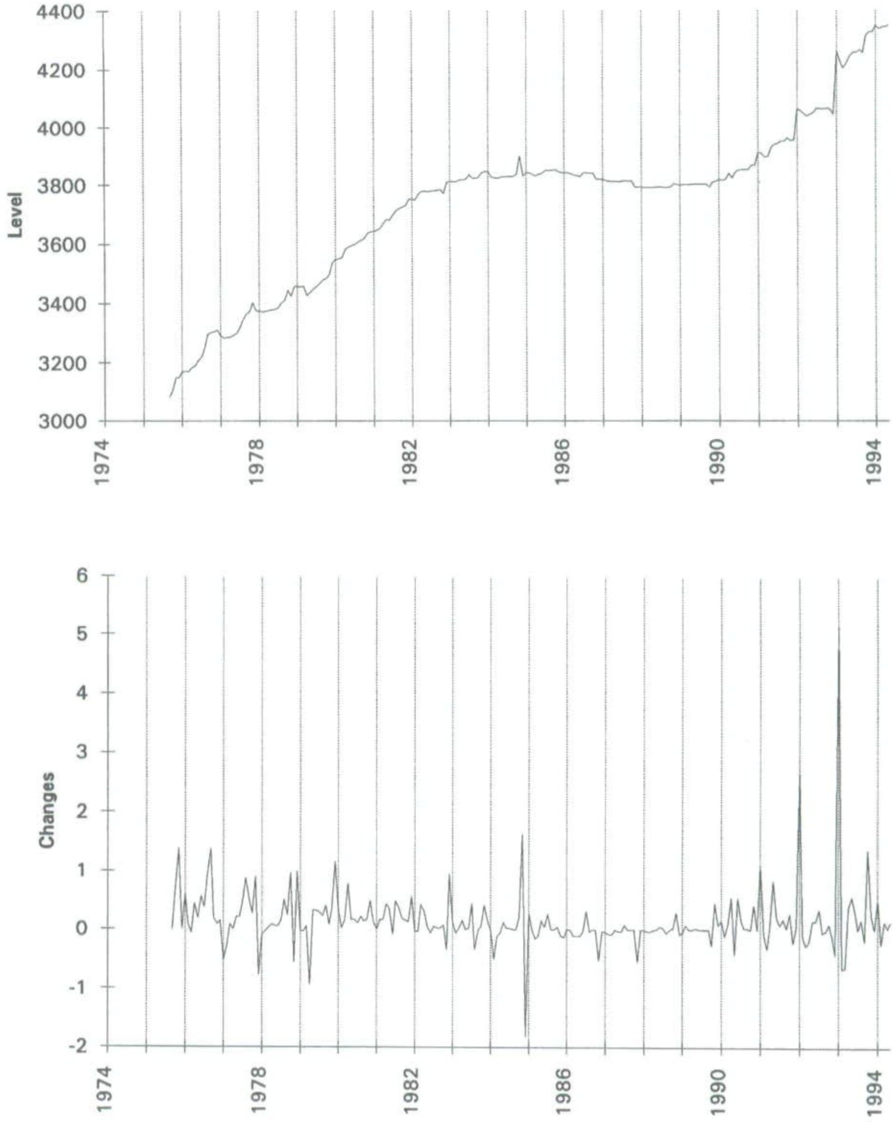

FIGURE 4

Base gas. Notes: Base gas volume in underground storage from September, 1975 to March, 1994. The source is Monthly Energy Review, U.S. Department of Energy. *The large increase from December, 1992 to January, 1993 is due to an accounting change.

the period analyzed. According to Herbert (1992), excess underground storage capacity may have been built in this period due to a rate base incentive to invest combined with underestimation of the effect of large price increases on consumption per heating customer. This overinvestment may have been intensified by differences in wellhead regulation between the interstate and intrastate markets prior to passage of the Natural Gas Policy Act of 1978 (NGPA). Before passage of the NGPA, gas producers were reluctant to sell new supplies to the more heavily regulated interstate market. As a result, gas utilities may have overinvested in storage for interstate markets in an effort to serve as many customers as possible with their scarce contractual supplies from producers. For some or all of these reasons, excess storage capacity is likely to have existed in the early part of the time period analyzed here. This initial excess capacity weakens the test results reported below.

The first panel of Figure 3 shows the level of natural gas prices, and the second panel shows first differences. Figure 4 presents the same analysis for base gas. Table III reports univariate statistics for both series and their log differences: mean, standard deviation, skewness, kurtosis, Dickey–Fuller unit root tests (DF), and the Ljung–Box (1978) Q statistic.

The Dickey–Fuller tests are used to check the stationarity of a given time series. If the null hypothesis of nonstationarity cannot be rejected, the data is said to have a unit root. That is, the first-order autocorrelation coefficient is equal to one. The DF test cannot reject the null hypothesis of a unit root in the price level and storage capacity level data.[24] Walls (1995), using DF tests, also finds a unit root for monthly natural gas spot prices. Similarly, De Vany and Walls (1994) find that natural gas spot prices have a high degree of first-order autocorrelation and, therefore, work with first differences of the price series. To avoid problems associated with units roots,[25] first differences are used: price changes and storage changes. Based on the skewness and excess kurtosis statistics, there is evidence of non-normality for both series.

The Ljung–Box (1978) Q statistic tests for the joint significance of the first K autocorrelations. The Q statistic test for autocorrelation has a χ^2 distribution with K degrees of freedom. In Table III they are calculated with 12 lags ($K = 12$). There is strong evidence for autocorrelation for both price changes and storage changes. However, Diebold (1987) shows that in the presence of heteroskedasticity the standard chi-squared values lead to rejection of the null hypothesis of no autocorrelation too often. Since the price series here are expected to be heteroskedastic, this is important. The magnitude of the Q statistics in Table III, however, indicate that autocorrelation in both series is so strong that it should be

[24]Augmented Dickey–Fuller tests, with 12 lags, have similar results to the Dickey–Fuller tests.

[25]A unit-root process is a nonstationary process. The coefficients of regression models involving unit roots are typically estimated by OLS. The asymptotic distributions of the coefficients cannot be calculated in the same way as are those for regression models involving stationary variables. To achieve stationary, the series with a unit-root process are typically differentiated, see Hamilton (1994).

TABLE III

Univariate Statistics and Diagnostic Tests

A.	*Price Level*	*Price Changes*	*Storage Level*	*Storage Changes*
Mean	227.54	.80	3742.50	.15
Standard dev.	88.43	4.83	273.96	.53
Skewness	.24	−.40	−0.22	4.28
Excess kurtosis	.07	2.75[a]	−.05	42.80[a]
DF	−2.07	−11.37[b]	−0.96	−17.02[b]
$Q(12)$	2361.19	110.58	1999.11	36.97
	[>1.0E-10]	[>1.0E-10]	[>1.0E-10]	[.0002]
AIC-Lags		23		13
B. Filtered Series (Residuals)				
Mean		3.2E-6		5.5E-7
Standard dev.		3.62		.47
Skewness		.01		3.26
Excess kurtosis		.60		25.50[a]
DF		−14.97[a]		−14.61[b]
$Q(12)$		1.22		1.51
		[.9999]		[.9998]
ARCH(4)		11.20		2.47
		[.0244]		[.6500]

Notes: *p*-values in brackets.
DF: Dickey–Fuller test.
ADF(12): Augmented Dickey–Fuller test with 12 lags.
$Q(K)$: Ljung–Box (1978) portmanteau statistic for the level of the series, with K lags.
AIC-Lags: number of lags selected by AIC criterium for percent changes of each series.
ARCH(4): ARCH tests with four lags of filtered series.
[a]Jarque–Bera test rejects the hypothesis of normality at the 1% level.
[b]Reject Unit-root hypothesis at the 1% level.

modeled. In Figure 3, a seasonal pattern for price changes is also visible.[26] In contrast, Figure 4 shows no clear seasonal pattern for storage changes.

Heinkel, Howe, and Hughes (1990) present a model where the value of holding inventories is related to the unpredictable component of the spot price. This article takes a similar approach. Following Pagan and Schwert (1990) and Engle and Ng (1993), this article concentrates on uncorrelated residuals, free of seasonalities. The appropriate lag structure is chosen according to the Akaike Information Criteria (AIC). The AIC chooses 23 lags for price changes and 13 lags for storage changes. Price changes are also regressed on monthly dummies.[27] The long lag structure

[26]De Vany and Walls (1994) also find evidence of seasonality in natural gas price changes.

[27]The AIC is also used to select seasonal dummies. AIC chooses the formulation with dummy vari-

chosen by the AIC confirms the strong results reported by the Ljung–Box Q tests. As discussed, barriers to spot market transactions were successively reduced over time through a series of regulatory actions. It is likely that entry occurring in stages produced unusual patterns of autocorrelation in these series. It should be noted that the filtered series have lower skewness and kurtosis statistics.

The GARCH(q,p) model, proposed by Bollerslev (1986), has become the standard in modeling a time-varying volatility process for speculative price changes. Kroner, Kneafsy, and Claessens (1993) and Ng and Pirrong (1994) find evidence of a time-varying volatility process in commodity markets. The GARCH(q,p) specification provides a parsimonious autoregressive model to parameterize a time-varying variance.[28] In Table III, panel B, Engle's (1984) ARCH test statistics are reported. The ARCH test follows a χ^2 distribution. The ARCH(4) test rejects the null hypothesis of a constant variance for the price change series only. The next section proposes and estimates a switching ARCH model which allows the variance to be affected also by structural changes.

EMPIRICAL RESULTS FROM THE MONTHLY DATA SERIES

A Switching Volatility Model for Natural Gas

Since the natural gas price change series used are residuals free from seasonalities[29] and autocorrelation, the focus of this section is on the estimation of the variance. Table III presents evidence for a time-varying variance for changes in natural gas prices [see, the ARCH(4) tests]. Lamoureux and Lastrapes (1990) argue that GARCH estimates are seriously affected by structural change. Cai (1994) and Hamilton and Susmel (1994) modified the standard ARCH model to take into account changes in regime. Since the gas industry has undergone extensive structural change in the last ten years and it is hypothesized that these structural

ables for price changes, while it does not favor this formulation for storage changes, which is consistent with the seasonal patterns that appear in Figure 2 and Figure 3.

[28]A popular formulation of the GARCH(q,p) model is the GARCH(1,1) specification, which is parameterized as follows:

$$y_t = a + b'x_t + e_t, \quad e_t|I_t \sim N(0, h_t)$$
$$h_t = \alpha_0 + \alpha_1 e_{t-1}^2 + \beta_1 h_{t-1}.$$

where x_t is a vector of predetermined variables and h_t is the conditional variance. For a detailed discussion, applications, and variations of the ARCH model, see the survey by Bollerslev et al. (1992).

[29]It should be noted that the residuals are free from seasonalities in the mean, not in the variance. Later, in Tables IV and V, it is reported that there is no evidence of seasonalities in the variance either.

changes have had an impact on the variance of price changes, a Switching ARCH model for the variance of price changes is an appropriate choice. The proposed model for natural gas price changes, y_t, is:

$$y_t = a + b' x_t + e_t, \quad e_t | I_t \sim N(0, h_t) \tag{2}$$

$$\frac{h_t}{\gamma_{s_t}} = \alpha_0 + \sum_{i=1}^{q} \alpha_i \frac{e_{t-i}^2}{\gamma_{s_{t-i}}} + \varepsilon \frac{e_{t-1}^2}{\gamma_{s_{t-1}}} L_t \tag{3}$$

where x_t is a vector of predetermined variables (which is not used in this case); h_t is the conditional variance; γ_{s_t} is the switching parameter; and $L_t = 1$ if $e_{T-1} < 0$, and $L_t = 0$, otherwise. The state of the industry, s_t, evolves according to a Markov transition matrix, P, where the typical element, p_{ij}, measures the probability of $s_t = \text{j}$, given that $s_{T-1} = \text{i}$. The values of the switching parameters, the γ's, capture the effect of the state of the industry on the process for the variance. The switching parameter for the first state, γ_1, is normalized at unity with $\gamma_j > 1$ for $j = 2, 3, \ldots, K$. The idea is to model changes in regime as changes in the scale of the process for the variance. Equation (3) describes a SWARCH(K,q) model, which is a switching ARCH model, with K regimes and q lags in variance, augmented with a leverage effect. Equation (3) includes an asymmetric effect, or leverage effect, which allows for negative price change surprises to have a larger impact on volatility.[30] Hamilton and Susmel (1994) describe how to estimate the SWARCH model using maximum likelihood methods.

Hamilton (1989) describes how to make inferences about the particular state the industry was in at date, t, from the observed price change values, y_t. One of these inferences is based on the "smoothed probabilities," $p(s_t = i | y_T, y_{T-1}, \ldots, y_{-3})$, which denote the conditional probability that the date, t, state was $s_t = i$, given the whole history of y_t. The smoothed probabilities produce K numbers for each date, t, one for each regime.

Different values for K and q are specified in the SWARCH(K,q) model for the error term of natural gas price changes. Models with $K =$ 2 to $K = 3$ states and $q = 1$ to $q = 3$ autoregressive terms, with and without leverage effects, are fitted. Randomly generated initial values are used and then the maximum likelihood SWARCH algorithm is run. This

[30]An asymmetric effect is called a leverage effect in the stock market literature. In eq. (3), the asymmetric effect is modeled following Glosten, Jaganathan, and Runkle (1993). The formulation in eq. (3) is called the SWARCH(K,q)-L model. Engle and Ng (1993) compare different ARCH specifications. They show that the Glosten et al. (1993) model and Nelson's (1991) exponential GARCH, or E-GARCH, model are the best models to describe the asymmetric effect of negative news.

TABLE IV

GARCH Estimation

	GARCH(1,1)		*GARCH (1,1)-L*	
	Coeff.	*SE*	*Coeff.*	*SE*
a	.244	.23	.165	.23
$\alpha 0$	4.198	2.88	6.322	4.21
$\alpha 1$	.319	.17	.137	.13
$\beta 1$	.395	.31	.185	.34
ε	...		.492	.35
L:		578.5		576.5
LR-C:		11.6		15.6
		[.0030]		[.0014]
$Q(12)$:		2.74		3.23
		[.9971]		[.9937]
$Q^2(12)$:		5.72		11.32
		[.9295]		[.5017]
LM-S-L:		.86		.86
		[.9999]		[.9999]
LM-S-V:		7.47		6.71
		[.8251]		[.8762]

Notes: *p*-values in brackets.
SE: Standard errors.
L: negative log likelihood for the GARCH(1,1) model.
LR-C: Likelihood Ratio test for no ARCH effects ($\alpha_1 = \beta_1 = 0$).
$Q(K)$: Ljung–Box (1978) portmanteau statistic for the level of the series, with K lags.
$Q^2(K)$: Ljung–Box (1978) portmanteau statistic for the squared of the series, with K lags.
LM-S-L: LM test for monthly seasonality in the level of the residuals.
LM-S-V: LM test for monthly seasonality in the variance of the residuals.

procedure is repeated 25 times. Then, the final parameters of the best model are chosen and used as starting values for the final estimation of the model. For comparison purposes, a GARCH(1,1) model is estimated, since this is usually the benchmark model. In comparing these two models, it is useful to recognize that an ARCH(q) model is equivalent to a SWARCH(1,q) model.

Table IV presents the GARCH(1,1) estimates. A GARCH(1,1) model with an asymmetric effect is the preferred GARCH model for the price series. There is an asymmetric effect associated with the sign of the residual. Negative price surprises, that is, observed price changes less than expected price changes, increase the volatility of natural gas prices more than positive price surprises. The model passes the Ljung–Box q test for serial autocorrelation and ARCH effects. In addition, Lagrange Multiplier tests for monthly seasonal effects are calculated, for both the level of the residuals (LM-S-L) and the time-varying variance (LM-S-V). The LM

TABLE V

SWARCH(2,2) Estimation

	SWARCH(2,2)		*SWARCH(2,2)-L*	
	Coeff.	*SE*	*Coeff.*	*SE*
a	.214	.21	.110	.21
$\alpha 0$	6.330	1.27	6.294	1.16
α_1	.222	1.12	.004	.07
α_2	.144	.10	.119	.08
γ_2	2.869	.96	2.834	.90
ε	.		.494	.22
	.994	.012	.995	.011
P	.005	.988	.005	.989
L:	575.4			571.9
$L_{2,1}$:	577.2			573.3
$L_{3,2}$:	575.4			571.8
$Q(12)$:	4.14		4.00	
	[.9808]			[.9834]
$Q^2(12)$:	9.64		11.84	
	[.6475]			[.4586]
LM-S-L:	1.42		1.42	
	[.9999]			[.9999]
LM-S-V:	5.51		5.30	
	[.9387]			[.9472]

Notes: see Table IV.
$L_{k,q}$ = negative log likelihood for the SWARCH (k,q) model.

tests are distributed χ^2, with 12 degrees of freedom. None of the test-statistics are significant.

Table V presents the SWARCH(2,2) results. First, as in the GARCH(1,1) formulation, note that the preferred model is SWARCH(2,2)-L, a model with an asymmetric effect in variance. Second, note that the switching parameter, γ_2, is significantly different from one, which is the value under the null hypothesis of no switching. Although the GARCH(1,1)-L specification is not strictly nested within the SWARCH(2,2)-L specification, note that a likelihood ratio test would reject the GARCH(1,1) model with a test-statistic equal to $-2x(571.9–576.5) = 9.2$. Since this likelihood ratio test has a χ^2 distribution with three degrees of freedom, the likelihood ratio test-statistic has an associated p-value of .0267. Under the null hypothesis that there is only one state, the switching parameter, γ_2, is unidentified. Therefore, the regularity conditions do not hold and the usual interpretation of the likelihood ratio test is not strictly correct. However, it seems reasonable to interpret the small p-value of .0267 as an indication of switching. The model passes the Ljung–Box Q tests for serial autocorrelation, ARCH effects, and monthly seasonal effects.

The first panel of Figure 5 plots the monthly price changes. The other panel plots the smoothed probabilities, $\text{Prob}(s_t = 1|y_T, y_{T-1}, \ldots, y_{-3})$, for the change in natural gas prices, that is, the second panel plots the smoothed probability that the economy was at state 1 at time t. The observations are classified following Hamilton's (1989) system, that is, an observation belongs to state i if the smoothed probability, $\text{Prob}(s_t = i|y_T, y_{T-1}, \ldots, y_{-3})$, is higher than .5. Changes in natural gas prices switch to the high volatility state in February, 1990. The smoothed probabilities begin an increasing trend towards the high volatility state in mid 1989. Ruge-Murcia (1995) discusses a different interpretation of these probabilities. Rational economic agents evaluate the credibility of actions undertaken by a government. The smoothed probabilities represent the best ex-post assessment of a rational agent of the credibility of the structural reform undertaken by the government. In this context, the economic agents started to assign a high probability to the event of full deregulation in mid-1989. This coincides with the congressional approval of the Natural Gas Decontrol Act, which endorsed the nondiscriminatory transportation program put in place by FERC and removed the few remaining wellhead price ceilings.[31]

Figure 6 plots the estimated one-step forecast of the variance using the SWARCH(2,2)-L model. From 1990 on, the variance has a positive trend. This period coincides with the increase in underground storage capacity in the last 4 years.

Inventories and Volatility

As discussed, an increase in volatility increases marginal convenience yield (the benefit of holding inventory). In this section a test is proposed for the hypothesis that increases in volatility are associated with increases in storage capacity. This hypothesis seems to hold during the last years of the sample, as Figures 3, 4, and 6 show. The hypothesis can be formally tested with the following equation:

$$\Delta I_t = \mu_0 + \delta \, \Delta h_t + \varepsilon_t \tag{4}$$

where I_t denotes the storage capacity residuals, obtained in Table III, and

[31] Along these lines, from Figure 5, the economic agents started to assign a nonzero probability to the event of full deregulation in mid-1985. This coincides with FERC Order No. 436, which is the first version of the nondiscriminatory transportation program that FERC undertook for the gas industry.

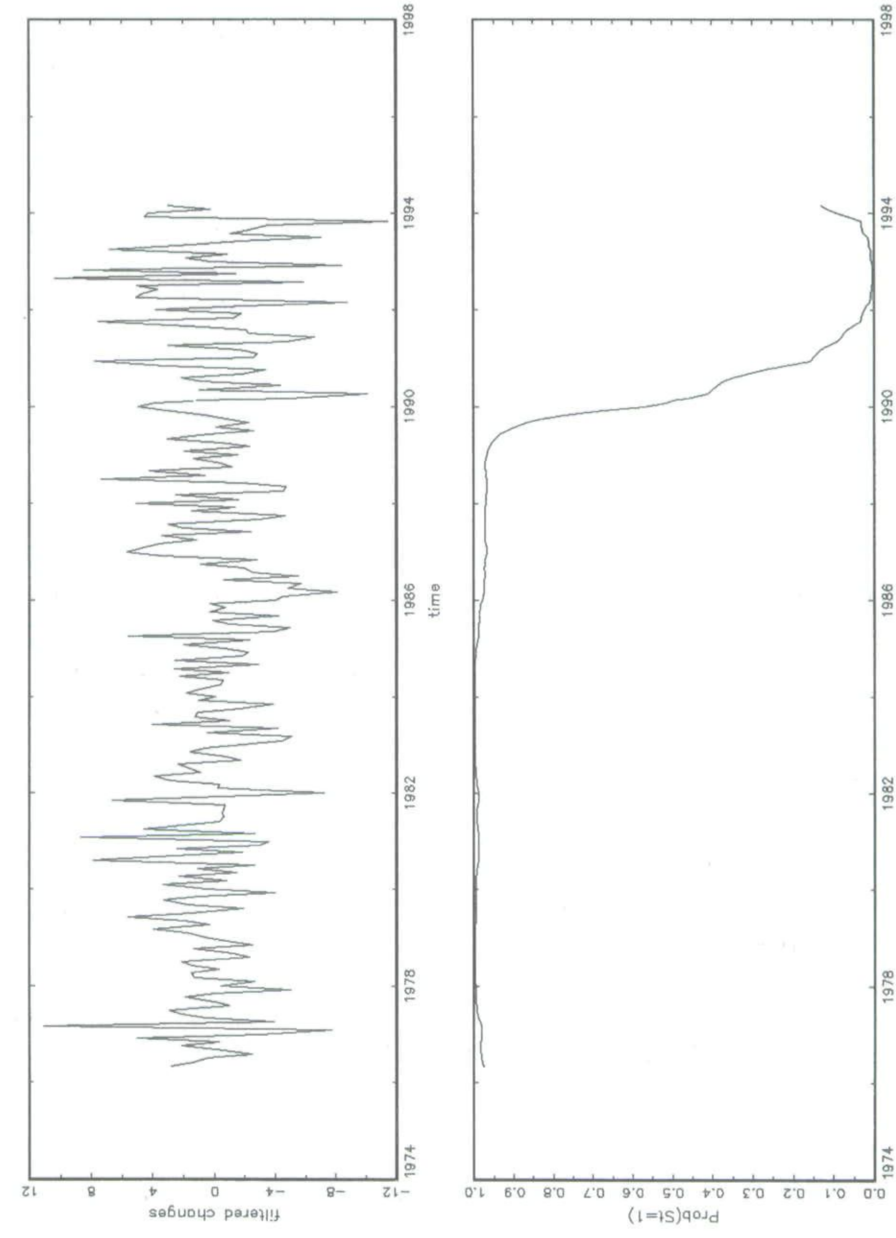

FIGURE 5
Natural gas price changes: SWARCH(2,2)-L.

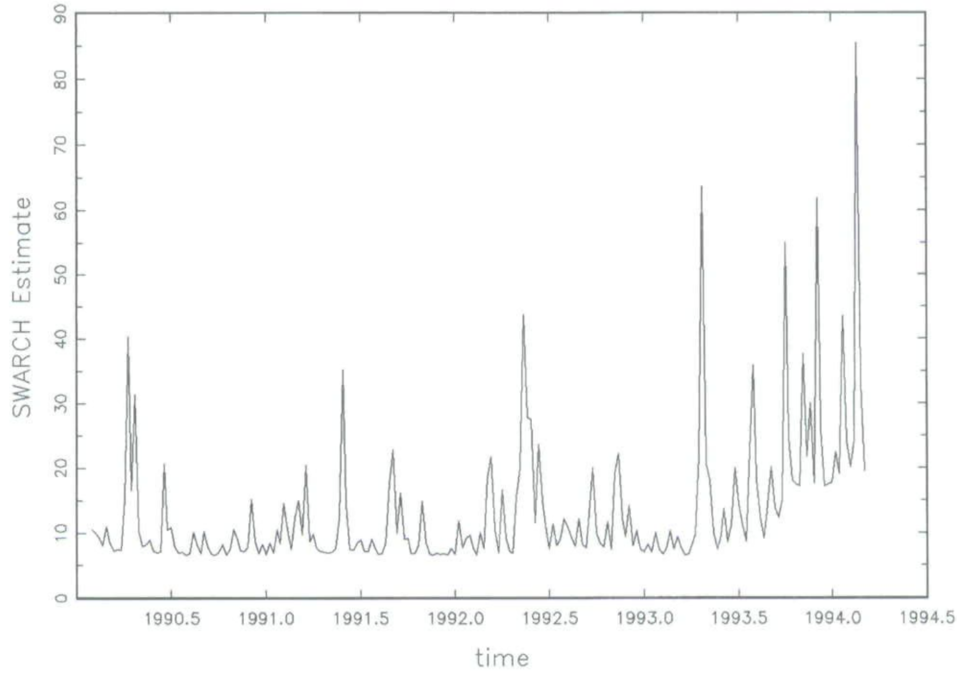

FIGURE 6
Natural gas price changes: Variance estimates.

TABLE VI

Inventories and Changes in Volatility

$$\Delta I_t = \mu_0 + \delta \, \Delta h_t + \varepsilon_t$$

	Coefficient	*SE*
μ_0	.0017	.032
$\delta(\Delta h_t)$	.0630	.031
$R^2 = .02$		
$\sigma = .47$		
$Q(12) = 2.8$		

Notes: ΔI_t: changes in the storage capacity residuals.
Δh_t: changes in the forecast of volatility for period t under the SWARCH(2,2)-L model.
$Q(K)$: Ljung–Box (1978) portmanteau statistic for the level of the series, with K lags.

h_t is the forecast of volatility for period t under the SWARCH model. Under the above hypothesis, δ should be positive.

Table VI reports the OLS estimates of eq. (4). The estimates are consistent with the hypothesis of a positive relationship between changes in forecasted volatility and changes in storage capacity. The coefficient on changes in volatility, δ, is positive with a p-value of .021. The overall fit is low, with an R^2 of only 2%. The low explanatory power of the model should not be a surprise given the shortcomings of the data and the simplifications required to specify the model. Recall that base gas in only a weak proxy for capacity, and that it is likely that excess storage capacity was added in the 1970s and early 1980s. With respect to the model, eq. (4) ignores the unknown project specific lead time required to add capacity. Also, to focus on storage capacity additions, the effect of variation in the current inventory level is not accounted for in this analysis. In terms of Figure 1, the model is designed to focus on vertical shifts in the convenience function, but is deficient in analyzing inventory level movements along the function. In summary, given the data limitations and required simplicity of the model, the low explanatory power of the regression in Table VI should not be surprising. However, the low p-value supports the theory of storage hypothesis along with the more detailed storage capacity survey data presented in "Evidence From Storage Capacity Surveys."

CONCLUSIONS

Extensive regulatory changes through the 1980s and early 1990s increased entry and the feasible frequency of transactions in the U.S. natural gas spot market. This article presents evidence that these regulatory changes led to an increase in the volatility of the price process. Specifically, this article analyzes natural gas prices changes and finds that a switching ARCH model with two states and two autoregressive terms provides a good description of the volatility of the process through this period of regulatory change. This model outperforms standard GARCH models. The switching ARCH model indicates that regulatory changes led to an increase in the volatility of spot natural gas prices.

For convenience assets, the theory of storage implies that an increase in volatility of the spot price should lead to an increase in storage activity and increased inventory levels. An increased level of storage activity for natural gas requires investment in additional specialized facilities. Therefore, the theory of storage implies that investment in additional natural gas storage facilities should be observed.

This article presents two types of evidence consistent with this hypothesis: econometric evidence using monthly data on base gas volume; and evidence from less frequent but more detailed storage capacity surveys. These findings of storage capacity additions are not attributable to demand growth since consumption of natural gas has yet to return to the level of the early 1970s. They are also not attributable to cost-based, regulated rates. Under the new regulations, customers are not obligated to purchase storage service from any specific company. Rates are negotiable, and entry is allowed. The evidence supports the hypothesis that the addition of storage capacity is due to structural changes in the market that led to increased price volatility.

The theory of storage tested in this article has several implications for natural gas markets. First, regional markets should become more integrated as a result of the increased ability to hold natural gas inventories. This follows because storage capacity is, to some extent, a substitute for transportation. Second, the cointegration between natural gas spot and futures prices should become stronger as more capacity is added. That is, changes in natural gas spot and futures prices should track more closely as the ability to shift volumes intertemporally and interspacially increases.

Finally, this article illustrates how the SWARCH technique can be applied to the analysis of markets subject to structural change. For example, the introduction of a natural gas futures contract in April, 1990 suggests another application. The SWARCH model might prove useful in measuring the impact of this contract on the daily volatility of natural gas spot prices.

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