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Research on Price Discovery in Major International Crude Oil Futures and Spot Markets

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Abstract: This paper focuses on the price discovery function of the international crude oil futures and spot markets. Against the backdrop of intensified volatility in the global energy market and the gradual rise of Shanghai crude oil futures' influence, it aims to explore the price discovery efficiency and structural breakpoint impact effect of crude oil futures and spot markets in different countries and regions. Selecting data from Shanghai crude oil futures and gasoline, diesel spot markets in 5 countries/regions (China, Singapore, the Netherlands, the United States, and the Mediterranean) from 2018 to 2024, the study employs methods such as dynamic Copula, Bayesian structural breakpoint test, and dynamic Granger causality test. The results show that the price discovery function of crude oil futures is significantly stronger than that of spot markets; the price discovery efficiency of European and American markets (the Netherlands, the United States, the Mediterranean) is far higher than that of Asian markets (China, Singapore); and the intensity of price discovery is highly consistent with structural breakpoints. This research reveals the temporal and spatial characteristics of price discovery in international crude oil futures and spot markets, provides arbitrage references for market participants, and offers a basis for policymakers to optimize the regulatory mechanism of the Asian crude oil market.

Keywords: Crude oil futures and spot, Price discovery, Dynamic Granger.

1. Introduction

Affected by geopolitical, supply and demand factors, the global crude oil market experiences severe price volatility. The price discovery function of futures and spot markets is crucial for resource allocation. As Asia's first crude oil futures product, the linkage effect between Shanghai crude oil futures and domestic and foreign spot markets has attracted much attention. Existing studies mostly focus on a single market or short-term intervals, lacking systematic analysis covering multiple regions, long cycles, and structural breakpoints. The differences in price discovery among different countries/regions and the heterogeneous impact of structural breakpoint shocks remain unclear. The significance of this study lies in revealing the temporal and spatial characteristics of price discovery in international crude oil futures and spot markets, providing references for investors' decisions and policymakers' regulatory improvements. The innovation points are: combining Bayesian structural breakpoint and dynamic test methods, covering two types of crude oil products in 5 countries/regions, and realizing the combination of horizontal regional comparison and vertical structural breakpoint impact test.

2. Literature Review

Domestically, Li Meng et al. (2020) used Granger test based on data from 2018 to 2019 and found that Shanghai crude oil futures have a certain price guiding effect on domestic spot markets but are weaker than international mainstream futures [1]. Wang Ying et al. (2022) adopted the Copula model and pointed out that the correlation between crude oil futures and spot markets has time-varying characteristics, but did not involve structural breakpoint analysis [2]. In foreign studies, Zhang et al. (2019) confirmed the dominant position of U.S. WTI futures in global crude oil spot price discovery through dynamic Granger test [3]. Bouri et al. (2021) found that the price adjustment speed of the European crude oil market is faster than that of Asia by incorporating geopolitical events [4]. Existing studies lack horizontal comparison across multiple regions and systematic impact analysis of structural breakpoints, and insufficiently explore the underlying reasons why price discovery in Asian markets is weaker than in Europe and the United States. This paper takes this as the entry point for research.

3. Research Methods

This study comprehensively uses three types of models, advancing layer by layer in combination with data characteristics and research objectives.

3.1. Dynamic Copula Model

Considering the nonlinearity and tail characteristics of the dependent structure in financial markets, it accurately measures the dynamic correlation between Shanghai crude oil futures and spot markets in 5 countries/regions, laying the foundation for subsequent structural breakpoint analysis. The dynamic Copula evolution equation is:

$$c(F_1(z_{1,t}), F_2(z_{2,t}); \rho_t, n) = \frac{1}{\sqrt{1-\rho^2}} \frac{\Gamma(\frac{n+2}{2})\Gamma(\frac{n}{2})}{[\Gamma(\frac{n+1}{2})]^2} \frac{\left[1+\frac{z_{1,t}^2+z_{2,t}^2-2\rho_t z_{1,t} z_{2,t}}{n(1-\rho^2)}\right]^{-\frac{n+2}{n}}}{\prod_{i=1}^{2}(1+\frac{z_{i,t}^2}{n})^{-\frac{n+1}{2}}} \tag{1}$$

$$Q_t = (1-\beta_1-\beta_2)\bar{Q} + \beta_1 z_{t-1} z_{t-1}' + \beta_2 Q_{t-1} \tag{2}$$

β_1, β_2, n are the estimated parameters of the dynamic Copula model, satisfying the constraint $\beta_1+\beta_2<1$, $\beta_1, \beta_2 \in (0,1)$. $z_{i,t}$ is the standard residual, and $F_i(\cdot)$ denotes the probability integral transformation. ρ_t is the dynamic correlation coefficient. $\bar{Q}$ is the covariance matrix of standard residuals.

3.2. Bayesian Structural Breakpoint Test

Abandoning the interval division method solely relying on event announcements, it identifies 3 structural breakpoints through structural mutations in dynamic correlation, dividing the sample period into 4 intervals, and overcoming the limitation of inconsistency between event occurrence and announcement time. The Bayesian posterior probability formula is:

$$P(\tau|Y) \propto P(Y|\tau)P(\tau) \quad (3)$$

Y is the observation sequence, $P(Y|\tau)$ is the likelihood function. $P(\tau)$ is the prior probability, usually set as a uniform distribution.

3.3. Granger Causality Test

It includes static and dynamic types: static test analyzes the bidirectional causal relationship of the full sample; dynamic test adopts a daily rolling window method with a window width of 30 (1526 trading days in the full sample, rolled 1496 times) to capture the time-varying characteristics of the price discovery function. Meanwhile, through horizontal comparison of 5 countries/regions and vertical analysis of structural breakpoint impacts, it comprehensively examines the differences in price discovery efficiency. The Granger causality test formulas are:

Unrestricted model:

$$Y_t = \alpha_0 + \sum_{i=1}^{p} \alpha_i Y_{t-i} + \sum_{j=1}^{q} \beta_j X_{t-j} + \epsilon_t \quad (4)$$

Restricted model:

$$Y_t = \alpha_0 + \sum_{i=1}^{p} \alpha_i Y_{t-i} + \epsilon_t \quad (5)$$

F-statistic:

$$F_k = \frac{(SSR_r - SSR_u)/q}{SSR_u/(\omega - p - q - 1)} \quad (6)$$

Y_t and X_t are observation sequences. ω is the window size, and the rolling step is 1. SSR_r is the sum of squared residuals of the restricted model, and SSR_u is the sum of squared residuals of the unrestricted model. p and q are lag orders.

4. Empirical Results

The data is sourced from the Wind database, with the sample period from 2018 to 2024, covering daily trading data of Shanghai crude oil futures and gasoline, diesel spot markets in China, Singapore, the Netherlands, the United States, and the Mediterranean. Shanghai crude oil futures are denoted as SC; gasoline spot markets in China, Singapore, the Netherlands, the United States, and the Mediterranean are respectively denoted as CGAS, SGAS, LGAS, GGAS, EGAS; diesel spot markets in these regions are respectively denoted as CDSL, SDSL, LDSL, GDSL, EDSL.

4.1. Time Series Charts of Prices and Returns

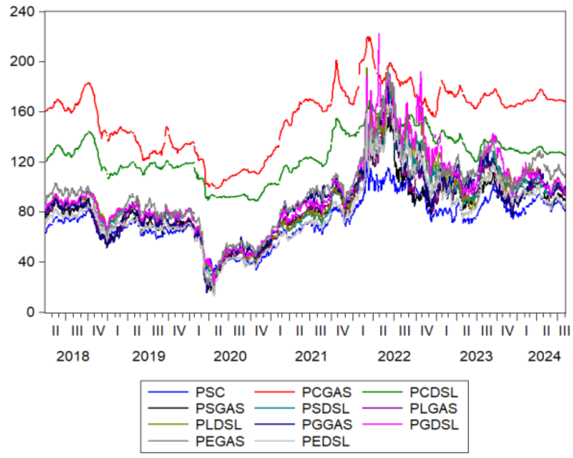

Figure 1. Time Series Chart of Crude Oil Futures and Gasoline, Diesel Spot Prices in 5 Countries and Regions

As shown in figure 1, in terms of products, the price trends of China's gasoline and diesel spot markets are slightly different from others, while the price trends of crude oil futures and gasoline, diesel spot markets in Singapore, the Netherlands, the United States, and the Mediterranean are highly consistent. In terms of time, there were significant declines and increases at the end of 2019 and the beginning of 2022, respectively.

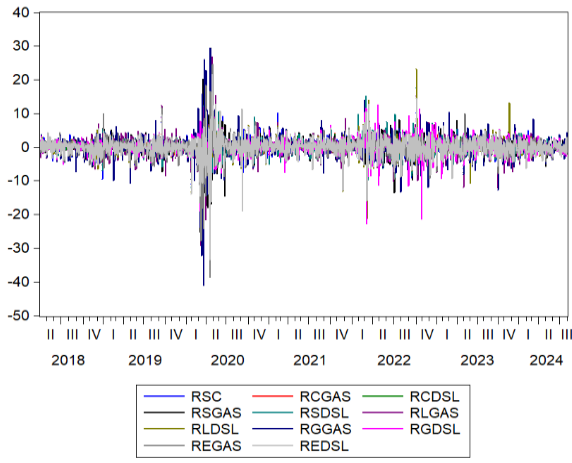

Figure 2. Time Series Chart of Logarithmic Returns of Crude Oil Futures and Gasoline, Diesel Spot Markets in 5 Countries and Regions

As shown in figure 2, the logarithmic returns of crude oil futures and gasoline, diesel spot markets in 5 countries/regions generally fluctuate around zero, showing obvious volatility clustering. From the time perspective, the volatility of logarithmic returns was very severe at the end of 2019 and the beginning of 2020, and also relatively severe in 2022. From the perspective of form, it presents a stable characteristic without an obvious trend.

4.2. Descriptive Statistics

Table 1. Descriptive Statistics of Logarithmic Returns of Crude Oil Futures and Gasoline, Diesel Spot Markets in 5 Countries and Regions

	RSC	RCGAS	RCDSL	RSGAS	RSDSL	RLGAS	RLDSL	RGGAS	RGDSL	REGAS	REDSL
Mean	0.0144	0.0027	0.0028	0.0104	0.0101	0.0118	0.0120	0.0161	0.0110	0.0145	0.0118
Median	0.1133	-0.0137	-0.0081	0.1344	0.0913	0.1840	0.1380	0.1621	0.0988	0.1815	0.1202
Maximum	10.9167	5.1476	4.8292	29.4654	19.5402	26.9377	23.1566	29.4691	15.0787	24.5922	21.6537
Minimum	-9.9650	-7.5245	-6.8512	-27.8020	-22.8051	-32.8895	-21.3849	-41.0799	-22.8287	-38.6047	-33.3633
Std. Dev.	2.0580	0.6512	0.6326	3.2234	2.7871	3.3280	2.7812	3.6244	2.8116	3.1054	2.9359
Skewness	-0.3018	-0.0550	-0.4306	-0.9054	-0.5155	-1.2399	-0.2937	-1.5240	-1.0153	-1.5812	-1.0520
Kurtosis	7.0561	23.3470	20.5875	22.4433	15.1136	23.6905	13.3852	31.2977	13.7434	33.2061	21.3278
Jarque-Bera	1069	26324	19715	24246	9398	27611	6879	51506	7601	58650	21640
Prob.	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ADF	-9.0564	-14.1610	-13.3253	-26.9625	-39.1902	-40.1428	-37.3944	-40.7695	-35.4835	-12.8349	-35.7412
Prob.	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

As shown in table 1, all means are positive, all skewness values are negative, all kurtosis values are greater than 3, and the P-values corresponding to the Jarque-Bera statistics are all 0, indicating that they do not follow a normal distribution and conform to the characteristics of a leptokurtic and skewed distribution. The P-values corresponding to the ADF statistics are all 0, indicating that all logarithmic return sequences are stationary sequences with good statistical properties.

4.3. Structural Breakpoint Test

At present, some literatures mainly determine interval division through announcements or official statements of important events. However, the actual occurrence time of events may be inconsistent with the release date of announcements or statements, so the method of dividing different intervals solely based on the time of event announcements or official statements has limitations. Therefore, with reference to announcements or official statements of important events, this paper comprehensively identifies structural breakpoints by combining the Bayesian structural breakpoint model. Since this paper mainly studies the price discovery function of crude oil futures and spot markets, involving two financial markets (futures and spot), it diagnoses structural breakpoints of the dynamic correlation between crude oil futures and spot markets. For the calculation of dynamic correlation, considering the nonlinearity and tail characteristics of the dependent structure in financial markets, as shown in figure 3, this paper uses the dynamic Copula model to measure the dynamic correlation between crude oil futures and spot markets.

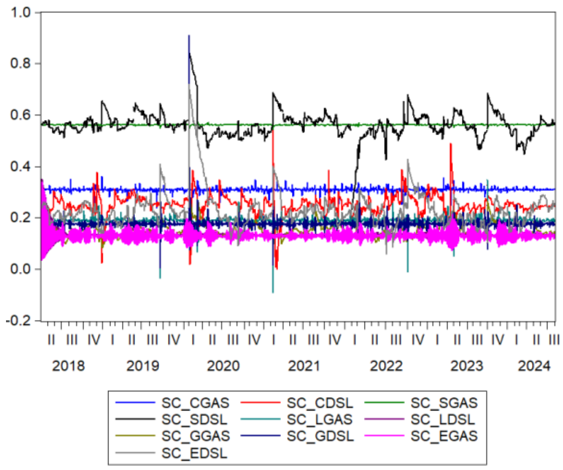

Figure 3. Dynamic Correlation between Crude Oil Futures and Gasoline, Diesel Spot Markets in 5 Countries and Regions

Table 2. Bayesian Structural Breakpoint Diagnosis Results

SC-CGAS	SC-CDSL	SC-SGAS	SC-SDSL	SC-LGAS	SC-LDSL	SC-GGAS	SC-GDSL	SC-EGAS	SC-EDSL
2018-11-19	2020-02-10	2019-03-21	2019-11-14	2018-12-07	2021-02-04	2020-01-16	2019-09-23	2020-02-03	2020-01-13
2019-11-15	2020-06-12	2019-12-10	2019-12-16	2019-10-31	2021-03-08	2022-02-28	2020-12-23	2019-08-06	2022-03-02
2020-02-03	2022-09-07	2022-03-08	2022-06-08	2020-01-22	2022-08-01	2022-03-07	2022-03-01	2020-03-06	2022-03-04
2020-11-25	2023-03-14	2022-07-01	2023-01-03	2020-03-16	2022-09-30	2023-10-12	2023-05-10	2022-07-01	2022-06-08
2021-04-16	2023-10-20	2024-02-19	2023-09-13	2022-02-28	2023-09-28	2023-10-17	2023-08-18		2022-07-04
2021-12-06			2023-10-18	2023-10-13	2023-11-17		2023-11-28		2023-10-16
2022-07-19				2024-04-12					2023-10-30
2024-01-26				2024-07-02					

Table 3. Segmented Statistics of Bayesian Structural Breakpoints by Quarter

Stage	Subtotal	Stage	Subtotal	Stage	Subtotal	Stage	Subtotal
2018Q1	0	2020Q1	8	2022Q1	7	2024Q1	2
2018Q2	0	2020Q2	1	2022Q2	2	2024Q2	2
2018Q3	0	2020Q3	0	2022Q3	7		
2018Q4	2	2020Q4	2	2022Q4	0		
2019Q1	1	2021Q1	2	2023Q1	2		
2019Q2	0	2021Q2	1	2023Q2	1		
2019Q3	2	2021Q3	0	2023Q3	3		
2019Q4	5	2021Q4	1	2023Q4	9		

As shown in table2 and 3, by diagnosing the structural breakpoints of the dynamic correlation between crude oil futures and spot markets and conducting segmented statistics by quarter, it is found that the number of structural breakpoints is 7 or more in Q1 2020, Q1 2022, Q3 2022, and Q4 2023. Considering that the time interval between Q1 2022 and Q3 2022 is too short, only one of them is selected. Therefore, through comprehensive judgment based on the Bayesian structural breakpoint model and actual background, as shown in figure 4, this paper identifies February 3, 2020, February 28, 2022, and October 16, 2023 as structural breakpoints, and divides the sample period into 4 intervals.

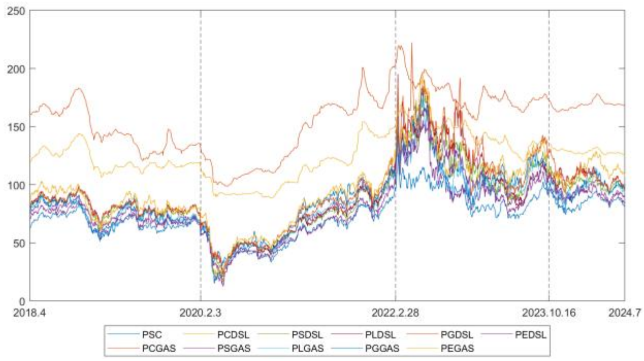

Figure 4. Interval Division of Crude Oil Futures and Gasoline, Diesel Spot Markets in 5 Countries and Regions

4.4. Static Granger Causality Test

Table 4. Static Granger Causality Test of Crude Oil Futures and Spot Markets in 5 Countries and Regions

Country/Region	Null Hypothesis	P-value
China	RSC is not the Granger cause of RCGAS	0.0000
	RCGAS is not the Granger cause of RSC	0.1593
	RSC is not the Granger cause of RCDSL	0.0000
	RCDSL is not the Granger cause of RSC	0.5442
Singapore	RSC is not the Granger cause of RSGAS	0.0013
	RSGAS is not the Granger cause of RSC	0.0000
	RSC is not the Granger cause of RSDSL	0.0000
	RSDSL is not the Granger cause of RSC	0.0000
Netherlands	RSC is not the Granger cause of RLGAS	0.0034
	RLGAS is not the Granger cause of RSC	0.0000
	RSC is not the Granger cause of RLDSL	0.0173
	RLDSL is not the Granger cause of RSC	0.0000
United States	RSC is not the Granger cause of RGGAS	0.0011
	RGGAS is not the Granger cause of RSC	0.0000
	RSC is not the Granger cause of RGDSL	0.0556
	RGDSL is not the Granger cause of RSC	0.0000
Mediterranean	RSC is not the Granger cause of REGAS	0.0002
	REGAS is not the Granger cause of RSC	0.0000
	RSC is not the Granger cause of REDSL	0.0006
	REDSL is not the Granger cause of RSC	0.0000

As shown in table 4, The bidirectional static Granger causality of crude oil futures and spot markets in 5 countries/regions is tested respectively. From a static perspective, crude oil futures are the Granger cause of spot markets in all 5 countries/regions; except for China, spot markets are also the Granger cause of futures markets in the other 4 countries/regions.

4.5. Dynamic Granger Causality Test

This paper uses dynamic Granger causality test to examine the price discovery function of crude oil futures and spot markets. The dynamic method adopts the daily rolling window method. To avoid excessive data loss in the rolling window, the window width is set to 30. There are 1526 trading days in the full sample, requiring 1496 rolls.

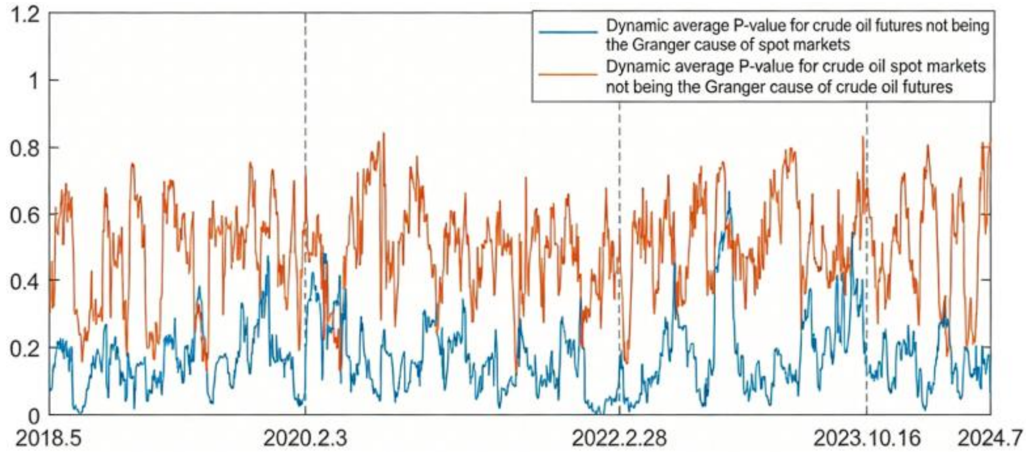

Figure 5. Overall Situation of Price Discovery Function of Crude Oil Futures and Spot Markets

As shown in the figure above, it is obvious that the blue line is below the red line for most of the time, indicating that it is more likely to reject the null hypothesis that "crude oil futures are not the Granger cause of gasoline and diesel spot markets in 5 countries/regions", that is, the price discovery function of crude oil futures on spot markets is significantly stronger than that of crude oil spot markets on futures markets.

4.6. Horizontal Comparison of Price Discovery Function

As shown in the following figures, each Granger test chart of crude oil futures and spot markets in each country/region has 4 curves, which are the P-values of bidirectional dynamic Granger causes between crude oil futures and gasoline, diesel spot markets in each country/region. The P-value fluctuates between 0 and 1, reflecting the changes in the price discovery function between crude oil futures and spot markets in different countries/regions over time.

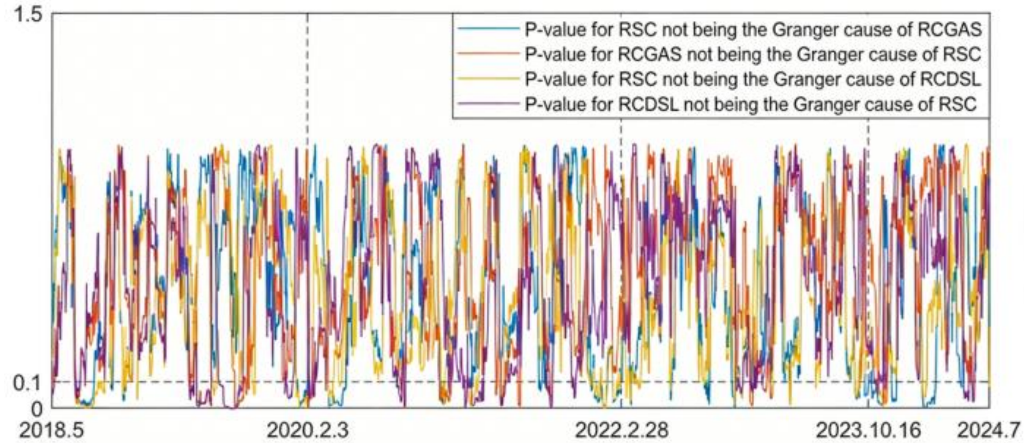

Figure 6. Price Discovery Function of Crude Oil Futures and Spot Markets in China

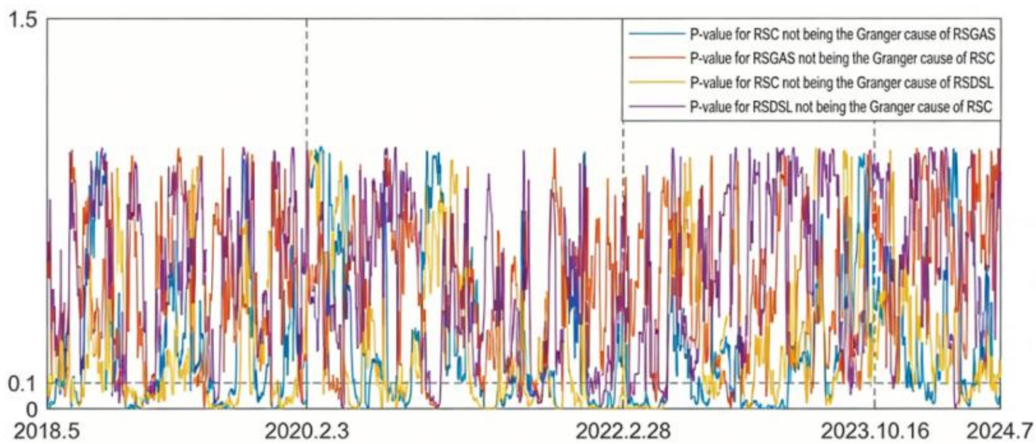

Figure 7. Price Discovery Function of Crude Oil Futures and Spot Markets in Singapore

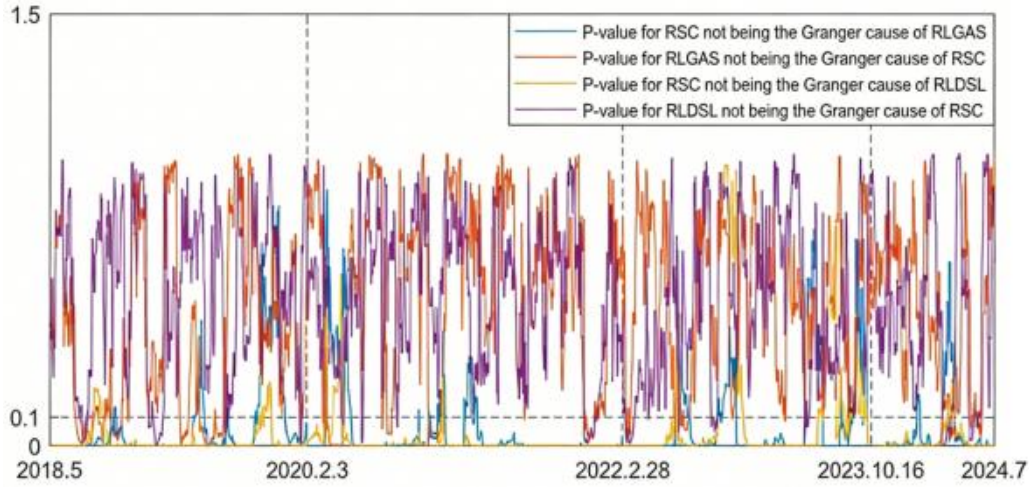

Figure 8. Price Discovery Function of Crude Oil Futures and Spot Markets in the Netherlands

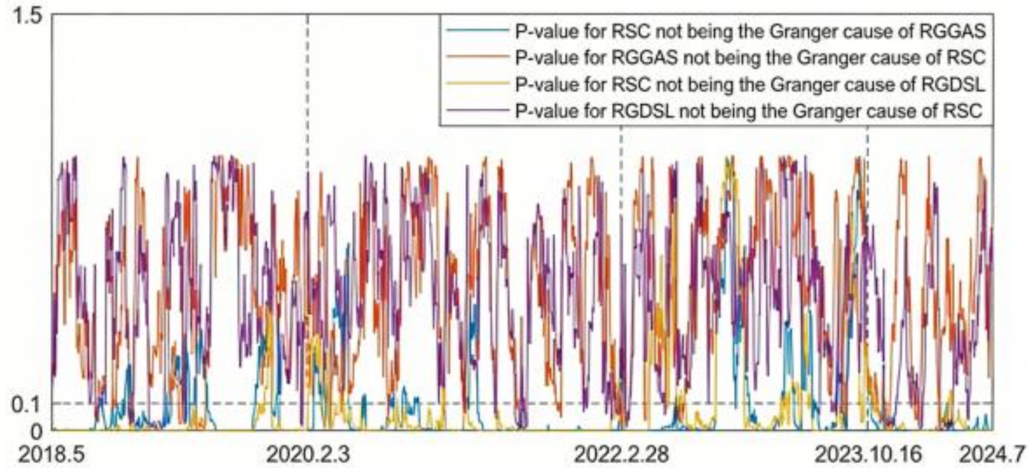

Figure 9. Price Discovery Function of Crude Oil Futures and Spot Markets in the United States

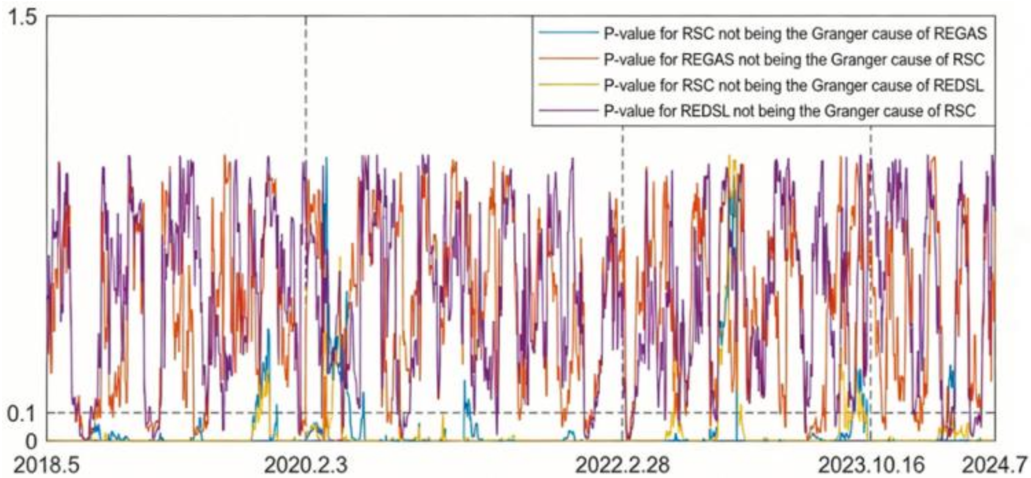

Figure 10. Price Discovery Function of Crude Oil Futures and Spot Markets in the Mediterranean

It can be clearly seen that in the Granger causality test charts of crude oil futures and spot markets in China and Singapore, the curves are rarely below 0.1, while in the Netherlands, the United States, and the Mediterranean, the curves are often below 0.1. This indicates that the price discovery function of crude oil futures and spot markets in Asian markets (such as China and Singapore) is weak, while that in European and American markets (such as the Netherlands, the United States, and the Mediterranean) is strong. The main reasons may be that European and American financial markets are more mature and efficient, and the impact of important events can be quickly reflected in the financial markets; while Asian financial markets are relatively underdeveloped with lower efficiency, and the frequency of national intervention and government regulation is higher, leading to the relatively limited impact of important events on the crude oil futures and spot markets.

Table 5. Comparison of the Strength of Price Discovery Function of Crude Oil Futures and Spot Markets in 5 Countries and Regions

China		Singapore		Netherlands		United States		Mediterranean	
Price Discovery	Days	Price Discovery	Days	Price Discovery	Days	Price Discovery	Days	Price Discovery	Days
RSC discovers RCGAS	231	RSC discovers RSGAS	624	RSC discovers RLGAS	1237	RSC discovers RGGAS	1176	RSC discovers REGAS	1368
RCGAS discovers RSC	137	RSGAS discovers RSC	136	RLGAS discovers RSC	238	RGGAS discovers RSC	124	REGAS discovers RSC	233
RSC discovers RCDSL	198	RSC discovers RSDSL	597	RSC discovers RLDSL	1330	RSC discovers RGDSL	1260	RSC discovers REDSL	1391
RCDSL discovers RSC	215	RSDSL discovers RSC	142	RLDSL discovers RSC	129	RGDSL discovers RSC	158	REDSL discovers RSC	154
Total	781	Total	1499	Total	2934	Total	2718	Total	3146

Further observing the strength of the price discovery function of crude oil futures and spot markets in different countries and regions, as shown in the table above, the Mediterranean crude oil futures and spot markets have the strongest price discovery function, accumulating 3146 days. The Netherlands and the United States also have strong price discovery functions, accumulating 2934 days and 2718 days respectively. In contrast, the Singapore crude oil futures and spot markets have a relatively low price discovery function, accumulating only 1499 days, and the Chinese crude oil futures and spot markets have the lowest, with only 781 days. In addition, for the Chinese market, the bidirectional price discovery function between crude oil futures and gasoline, diesel spot markets is not much different, both at a relatively low level. For the Singapore, Netherlands, United States, and Mediterranean markets, the price discovery function of crude oil futures on gasoline and diesel spot markets is significantly stronger.

4.7. Vertical Comparison of Price Discovery Function

The Netherlands, United States, and Mediterranean markets, which are more sensitive to the price discovery of crude oil futures and spot markets, are selected for vertical comparison and analysis.

Table 6. Comparison of the Strength of Price Discovery Function of Crude Oil Futures and Spot Markets in the Netherlands, the United States, and the Mediterranean

Structural Break	Price Discovery Type	Market Type	Netherlands	United States	Mediterranean
2020Q1	Price discovery in 10 trading days after the breakpoint	Futures discover gasoline spot	10	10	10
		Futures discover diesel spot	10	1	10
	Average price discovery in 10 trading days of the interval	Futures discover gasoline spot	8	8	8
		Futures discover diesel spot	9	8	9
2022Q1	Price discovery in 10 trading days after the breakpoint	Futures discover gasoline spot	10	9	10
		Futures discover diesel spot	10	10	10
	Average price discovery in 10 trading days of the interval	Futures discover gasoline spot	7	6	8
		Futures discover diesel spot	7	5	8
2023Q4	Price discovery in 10 trading days after the breakpoint	Futures discover gasoline spot	10	6	10
		Futures discover diesel spot	10	5	10
	Average price discovery in 10 trading days of the interval	Futures discover gasoline spot	8	9	9
		Futures discover diesel spot	9	9	10

As shown in the table above, for different countries and regions, the impact of structural breakpoint shocks on the price discovery of crude oil futures and spot markets varies. In the Netherlands and Mediterranean markets, the three structural breakpoints have a very obvious positive impact on the price discovery function of crude oil futures and spot markets. In the 10 trading days after the shock, the price discovery function exists in all cases, which is higher than the average level of the interval. For the U.S. market, in the 10 trading days after the second structural breakpoint, there is a very obvious price discovery function of crude oil futures and spot markets, which is significantly higher than the average level of the interval; while at the first and third structural breakpoints, this enhancement of price discovery is not obvious, lower than the average level of the interval. The main reason may be that with the U.S. shale revolution, it has basically achieved energy independence and has a strong ability to resist shocks.

5. Conclusions

Main findings: Firstly, the price discovery function of crude oil futures on spot markets is significantly stronger than that of spot markets on futures markets. In the dynamic test of the full sample period, the price leadership of futures over spot markets is more obvious. Secondly, there are significant regional differences. The cumulative days of price discovery in European and American markets (the Netherlands, the United States, the Mediterranean) all exceed 2700 days, while Asian markets (China with 781 days, Singapore with 1499 days) are significantly lagging behind. The root cause lies in the high maturity and low government regulation of European and American financial markets, while Asian markets have low efficiency and frequent regulation. Thirdly, price discovery is highly consistent with structural breakpoints. Structural breakpoints are concentrated in Q1 2020, Q1 2022, and Q4 2023, and the impact of structural breakpoints on the

Netherlands and Mediterranean markets is stronger. The United States shows strong shock resistance due to energy independence. The theoretical significance of this paper lies in enriching the multi-dimensional empirical evidence of price discovery in the crude oil market. The practical significance is to provide arbitrage references for investors and a basis for policymakers to optimize the mechanism of the Asian crude oil market and enhance international discourse power.

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