University of Nottingham

Doctoral Thesis

Price dependency and spillover effects in global crude oil markets

Author: *Han Zhang*

Supervisor:

Prof. Monica Giulietti

Dr. Ye Bai

A thesis submitted in fulfilment of the requirements

for the degree of Doctor of Philosophy

in the

Finance and Industrial Economics Division

Business School

March 2017

Abstract

The content of this thesis is the result of a comprehensive study about global spot crude oil markets. Using a large data set including 32 crude varieties, this thesis analyzes price dependency, return and volatility spillover effects, and explores the driving forces behind such spillover effects.

The first major aim of the thesis is to detect the presence of structural breaks in the price dependency relationship found in the literature (Wlazlowski, Hagströmer, & Giulietti, 2011). Tests allowing for structural breaks are applied to re-examine unit root test, cointegration test and causality relationships. The results show significant structural breaks in all tests. However, the basic conclusions of unit root tests and cointegration tests are still valid in accounting for structural breaks, while the causality relationship is greatly influenced by the 2008 global crisis, making the conclusion of Wlazlowski et al. (2011) that the Russian Urals could serve as a potential benchmark invalid when using a longer sample period.

The second topic of investigation is the return and volatility spillover effects in the spot crude oil market. By applying a VAR forecast error variance decomposition method (Diebold & Yilmaz, 2012), various spillover measures are constructed. Static analysis shows that the majority of the total variance of the forecast error is explained by shocks across markets rather than by idiosyncratic shocks (87.1% for return and 80.57% for volatility), therefore supporting the integration hypothesis in the global crude oil market. Moreover, benchmark crudes play a key role in terms of return spillovers, possibly due to the pricing formula mechanism in the spot crude oil market. In terms of volatility, WTI behaves as a dominant transmitter. This is attributed to the 2008 global financial crisis, which originated in the United States. Dynamic analysis shows that return and volatility spillover indexes have different patterns. Return spillovers display gradual trends but no bursts, while volatility spillovers display clear bursts that correspond closely to events in the crude oil market. Further dynamic analysis was applied at individual, pairwise and group levels. Generally a time-varying characteristic of spillovers is found.

The third topic of analysis explores the driving forces behind spillover effects which are identified in the second chapter. Five categories of variables were selected to explain the spillover effects. These are international trade variables, fundamental economic variables, country risk variables, global risk factors and time trends. These variables are found to be more relevant for return spillovers than for volatility spillovers, and more relevant for non OPEC countries than for OPEC countries.

Acknowledgement

I would like to express utmost thanks to my supervisors, Professor Monica Giulietti and Dr. Ye Bai, who provided continuous support, encouragement and guidance throughout the course of my research. They guided me to think critically and make logical arguments, which I am sure will benefit me in the future. Besides academic instruction, they also cared about my physical and emotional health. Their comfort supported me through hard times. I would also like to acknowledge Dr. Simona Mateut, my annual review examiner, for her time and effort in giving valuable feedback. My appreciation goes to all of the staff in the Nottingham University Business School, especially Professor David Newton, Dr. Peter Oliver and Andrea Tomlinson for their advice and assistance.

I also thank Nottingham University Business School for financial assistance during my PhD programme. Furthermore, I would like to take this opportunity to thank Dr. Syzmon Wlazlowski and Dr. Stefan Kloessner for their responses to my emails and subsequent discussions.

This thesis is dedicated to my parents for their unconditional love and understanding. I also want to thank Weijia Lu, my husband, who has always been supporting me to pursue my dream.

I also take this opportunity to show my thanks to my PhD. colleagues and friends at Nottingham University. Their company made my research project a colorful and enjoyable journey.

Abbreviations

ADF	Augmented Dicky-Fuller
AIC	Akaike's Information Criterion
API	American Petroleum Institute
bbl	barrel
b/d	Barrels per Day
EIA	Energy Information Administration
EMU	European Monetary Union
FPE	Final Prediction Error criterion
FOB	Free On Board
HQ	Hannan-Quinn information criterion
MBD	Million Barrels per Day
OECD	The Organization for Economic Co-operation and Development
OLS	Ordinary Least Squares
OPEC	The Organization of the Petroleum Exporting Countries
SC	Schwarz Criterion
VIX	Volatility Index calculated by the Chicago Board Options Exchange

Contents

List of Tables

List of Figures

Chapter 1

Introduction

Crude oil is a strategically important commodity. Due to its critical role in both political and economic arenas, research into different varieties of crude oil has received a great deal of attention in the literature. The work is attractive but challenging: there are over 200 different kinds of crude oil in the world (Ghoshray & Trifonova, 2014), and this is far beyond the normal range of analysis. This is because commonly used multivariate time series methods and models (e.g. ARMA and the GARCH-class model) become inefficient when analyzing high-dimensional time series (Tsay, 2013). Therefore, majority of works have focused on only a limited number of so called "benchmark" crude varieties. However, these benchmark crudes have been challenged with regard to their ability to represent the behavior of non-benchmark crudes (Ghoshray & Trifonova, 2014). Therefore, researchers have worked hard to extend the scope of the analyses to include more crudes. For instance, as many as 32 varieties were analyzed in the research of Wlazlowski et al. (2011) and Giulietti, Iregui, and Otero (2014). Their studies are based on price, or price differential, but no one has studied volatility with so many crude varieties. In fact, because of the complexity, there is rarely a comprehensive or systematic analysis of this in the literature.

The main objective of this thesis is to 1) examine the interdependent relationships between 32 oil varieties from various perspectives, and 2) explore the factors that influence the relationships between crude oil in different countries.

In the first empirical chapter (Chapter 3), I extend the analysis of Wlazlowski et al. (2011) to a longer sample period, which includes the 2008 global financial crisis. Tests are applied to examine the existence of structural break in unit root test, cointegration test and causality relationships. The reason and impact of structure breaks are discussed. The importance of structural breaks is that they could change the pattern of price dependency, making the conclusion in tranquil sample periods invalid.

The second empirical chapter (Chapter 4) studies the relationship between crudes from the perspective of both volatility and return spillover effects. A VAR forecast error variance decomposition method is employed to construct various spillover measures. This method provides both static and dynamic results. The dynamic spillover effects are discussed further at different levels i.e. individual directional, pairwise directional and trans-group directional spillovers.

The third empirical chapter (Chapter 5) explores the driving force of spillover effects discussed in Chapter 4. Five categories of variables are selected to explain the spillover effects: international trade variables, fundamental variables, country risk variables, global risk factors and time trend. These variables were found to be more relevant for return spillover than volatility spillover, and more relevant for non-OPEC countries than OPEC countries.

The major contribution to the literature that this thesis makes is that a large data set, including 32 crude varieties is employed, which could provide an overall picture of the crude oil market, therefore enriching the small amount of existing studies which include non-benchmarks as research objects. Another innovation is the application of the VAR forecast error variance decomposition method developed by Diebold and Yilmaz (2012). This method allows the analysis of spillover effects statically and dynamically at different levels. Finally this work is the first attempt to explore the driving forces of spillover on the spot crude oil market, and this will improve the understanding of the crude oil market.

More specifically, this thesis contributes to the following debates in the literature by providing new evidence.

1. Is the "a great pool" hypothesis proposed by Adelman (1984) valid if more crude oil varieties are included? Examples of supporters include AlMadi and Zhang (2011) and Giulietti et al. (2014). The typical example of opponents is Weiner (1991). Recently Y.-J. Zhang and Zhang (2015) give mixed evidence in a dynamic analysis.

2. As an increasing number of low quality crudes joining the market, can the high quality benchmark crudes still represent the market behavior? Ghoshray and Trifonova (2014) challenge the effectiveness of the traditional benchmarks.

3. Although WTI and Brent are both viewed as global benchmark crudes, which one actually plays the dominant role? Kao and Wan (2012) support Brent, while Elder, Miao, and Ramchander (2014) support WTI.

4. Does the market power of OPEC increase or decrease over time? Wlazlowski et al. (2011) and Giulietti et al. (2014) support the effectiveness of OPEC as a price cartel, while Huppmann and Holz (2012) and Fattouh (2007a) challenge it.

The structure of the rest thesis is as follows. Chapter 2 provides a brief literature review with the aim of providing a background and identifying gaps in the literature. More detailed literature reviews are presented in the individual sections in each empirical chapter (Chapters 3, 4 and 5). Chapter 6 concludes.

Chapter 2

Literature Review

In this chapter, a brief literature review is provided, with the aim of providing the background of the research, identifying the gaps in the literature, and introducing the way this thesis will fill these gaps. Two debates in the research are discussed in the first two sections. They also serve as the background of this thesis. Some relevant concepts are clarified in Section 3. Section 4 provides a methodology review, mainly relating to Chapter 4, while Section 5 is a brief literature review relating to Chapter 5. Section 6 concludes.

2.1 Debate over integration and diversification in crude oil market

The price dynamics of crude oil is a topic which has received a great deal of attention due to its political and economic importance. Adelman (1984) first proposed that the crude oil market is "one great pool", implying the integrated nature of the market for crude oil. Based on this hypothesis, he pointed out that the efforts to "secure supply" or "outlets" by importers or exporters is senseless. Weiner (1991) first examined this hypothesis empirically. The results indicated a high degree of market regionalisation rather than unification. After this, various studies were devoted to integration and diversification arguments. The results varied according to the economic methods used, the choice of crude oil varieties, and the sample period.

Kleit (2001) used the improved arbitrage technique to verify the integration of the light crude oil market in the 1990s. AlMadi and Zhang (2011) investigated the cointegrated relationship between four different crude oil prices and concluded that there was a long term market integration, which was more significant than diversification. Giulietti et al. (2014) also supported the integration argument and they found that the majority of relationships between crude oil pairs were stationary. Kleit (2001) applied an arbitrage cost approach to the light crude oil market in the 1990s, and concluded that the support for the market integration hypothesis was "substantial though mixed". Fattouh (2010) used a TAR model with a constant transaction cost to investigate price differentials for seven pairs of crudes. The results only supported integration for crudes with similar physical properties. The above research contributed to the debate by investigating from different perspectives and using different economic methods. In brief, they demonstrate that the world crude oil market did not always exhibit constant integration or diversification, especially when taking into account sudden unexpected oil-related events, which have increased the uncertainty and complexity of the worldwide oil market (Ji & Guo, 2015). Therefore, a dynamic analysis can provide more valuable information than a static analysis. This thesis aims to extend the current literature by applying a dynamic method, and emphasizes the influence of events on the crude oil market.

Regarding the choice of crude oil varieties, the overwhelming majority of literature focus only on a limited number of varieties; mainly benchmark crudes, with the implied assumption that benchmark crudes can reliably represent the entire crude oil market. Some exceptions include Fattouh (2010), who investigated price differentials for seven crudes, including benchmark and non-benchmark varieties. Ghoshray and Trifonova (2014) considered all possible 21 pairs of these seven crudes, and therefore extended the analysis of Fattouh (2010). The pairwise approach of Giulietti et al. (2014) allowed them to analyze as many as 496 price differential pairs from 32 crude varieties, most of which were non-benchmarks. These investigations significantly contributed to the literature because they provided evidence of an integrated world oil market on the basis of an analysis which included both benchmarks and non-benchmarks. This evidence is therefore strong than that provided by studies which only included benchmark crudes. This thesis utilizes a data set incorporating 32 crude varieties and includes non-benchmark crudes in order to give a comprehensive empirical analysis.

2.2 Debate over the effectiveness of benchmark crudes

As discussed above, majority of literature has only studied benchmark crudes. Although the analyses of Fattouh (2010) and Ghoshray and Trifonova (2014) extends to non-benchmark crudes, it relies on the distinction between benchmark and non-benchmark crudes. However, benchmark crudes are increasingly challenged because they fail to correctly reflect the market conditions, mainly due to decline in production levels and a shrinking share in the global trade. According to figures from consultants Energy Aspects, loadings of the four blends that make up Brent fell to 930,000 barrels per day in January 2014, down from 1.1 million b/d in the same month three years previously. Critics therefore contend that Brent is “broken” as a marker for global oil prices (Hume, 2014). As for WTI, whose price is supposed to reflect supply-demand conditions in the US, the largest consumer of oil in the world, it disconnects from other benchmarks from time to time. This leads to the debate on whether the WTI benchmark has been "broken" and whether oil market participants should adopt an alternative benchmark which could better reflect the supply-demand balance in the oil market (Fattouh, 2007b). Dubai faces a similar problem to Brent. Its production shrunk from a peak of around 383,000 b/d in 1991 to 68,600 b/d in 2008. The market participants have therefore begun to allocate an increasing proportion of their pricing exposure to other benchmarks (Platts, 2014).

Wlazlowski et al. (2011) applied Granger causality tests to 32 crudes in order to establish which ones drive other prices and which ones simply follow general market trends. Their empirical results confirmed that the traditional benchmarks of Brent and WTI were the global price setters. They also found a third global price setter in Russian Urals crude. However, Dubai Fateh, which is used in practice as benchmark, does not appear to be a price setter, and was suggested that it should be given a lower weight in the assessment of market trends. Candelon, Joëts, and Tokpavi (2013) also adopted the 32 crude dataset, but they extend the univariate Granger causality test in extreme risk with the method developed by Hong, Liu, and Wang (2009). The focus of Candelon et al. (2013) was the pattern in periods of extreme price movements. In both downside and upside price movements, WTI and Brent are price setters due to the fundamental and speculative components of each market. Mediterranean Russian Urals and Europe Forcados act as benchmarks in the periods of extreme downside price movements, while Ecuador Oriente act as benchmarks in extreme upside price movements. Asia Dubai Fateh and Oman Blend, which serve together as benchmarks, act as followers rather than leaders. Candelon et al. (2013) also observe that the integration level between crude oil markets tends to decrease during extreme periods.

Kao and Wan (2012) provide evidence that the benchmark status of WTI has changed over time, because its value no longer reflects underlying market conditions. Therefore WTI has become less reliable as a tool for hedging against price changes in other markets.

Because of the current complexity of the global oil market, in most part of this thesis, benchmark and non-benchmark crudes are not distinguished in advance, but rather analyzed together, unless the empirical method limits the number of crudes analyzed.

2.3 Definition of interdependence, spillover and contagion

In the researches which study the interaction of economic variables, the definition of terms like "interdependence", "spillover" and "contagion", are used intensively, and sometimes interchangeably. This section aims to clarify these concepts.

Interdependence is a stable and elevated two-way link between markets, during tranquil and stress periods. It is generally associated with fundamentals (Xie, 2014), for example, Pretorius (2002) investigated the economic determinants of emerging stock market interdependence. He found a substantial proportion of the interdependence among emerging stock markets could be explained by fundamentals like bilateral trade and industrial production growth differentials.

Spillover could be broadly defined as changes in one financial market in response to changes in factors in other markets, no matter whether during a crisis or a tranquil periods. It reflects co-movement of market returns. Spillover effects are transmissions due to links between markets. Moreover, spillover causes contagion, or, in other words, contagion is the consequence of extreme spillover (Allen & Gale, 2000; Alter & Beyer, 2014). Therefore, spillover is necessary, but not sufficient for, contagion.

Contagion, as opposed to interdependence, suggests that the international propagation mechanisms are different during times of crisis. There is no agreement on the definition of contagion, and many definitions have been proposed. According to K. Forbes and Rigobon (2001), three levels of definitions can be distinguished:

Broad definition: Contagion is identified with the general process of shock transmission across countries. It works in both tranquil and crisis periods and refers to general cross-country spillover effects.

Restrictive definition: Contagion is the propagation of shocks between two markets in excess of what should be expected from the fundamentals and considering the co-movements triggered by the common shocks. The fundamentals needs to be investigated when applying this definition, so that to appraise whether excess co-movements have occurred and whether contagion is displayed. This definition is probably the most controversial one, because there is no agreement on the proper set of fundamentals.

Very restrictive definition: Contagion is interpreted as the change in the cross-country correlation/covariance that takes place during a period of turmoil. This definition is more neutral because it leaves out the problem of identifying the transmission mechanism and the fundamentals. This definition implies that contagious effects are to be differentiated from the "normal" transmissions of shocks across countries, also known as "interdependence". Following this definition, the task of empirical contagion is to investigate whether or not interdependence and causality across countries are changed in certain crisis periods (Alter & Beyer, 2014).

This thesis generally applies the term "spillover" in Chapter 4 and Chapter 5, because it is a concept regardless of crisis or tranquil periods. When there is extreme spillover, both fundamentals and transmission mechanisms are examined. However, the literature review section follows the corresponding authors' usage of terms, without distinguishing.

2.4 Methodology review

Six main methodologies have been used in the literature to analyze interrelations between financial markets: cross-correlations, VAR models, cointegration models, GARCH models, regime switching models and stochastic volatility models (Soriano & Climent, 2005). The first empirical chapter of this thesis applies the approaches of cointegration and VAR models to analyze the price relationship between crudes. The second empirical chapter examines return and volatility spillover using an index constructed under the framework of VAR models.

In the literature of cross market studies in the crude oil market, the most commonly used method are GARCH-class models, especially multivariate GARCH models. For example, Brunetti and Gilbert (2000) used cointegrated bivariate FIGARCH models to study volatility spillover effect in the New York Mercantile Exchange (NYMEX) and International Petroleum Exchange (IPE) crude oil markets. Using GARCH and VAR models Lin and Tamvakis (2001) observed substantial spillover effects between the NYMEX and IPE when both markets were trading simultaneously. Lu, Hong, Wang, Lai, and Liu (2014) proposed a new time-varying Granger causality test based on the rolling Hong test and DCC-MGARCH Hong tests. The GARCH models, first proposed by Bollerslev (1986), have the benefit of allowing the differentiation between the heat waves effect and meteor showers effect described by Engle III, Ito, and Lin (1988). The hypothesis of heat waves is that most of the volatility sources are country specific. On the contrary, the meteor shower hypothesis is consistent with the idea of shock transmission between different markets, countries or regions. In a multi-variate GARCH estimation, the relative importance of own and cross coefficients allows the existence or not of such effects to be determined.

However, the main problem shared by multivariate GARCH models is the great number of parameters to be estimated i.e. the curse of dimensionality. In theory, as long as there is a sufficiently large sample size, this should not be a problem. But, the efficient estimation of these models is done by Maximum Likelihood and it is difficult to achieve the convergence of the optimization algorithms involved in the process. Furthermore, restrictions must be imposed upon the parameters of the model in order to guarantee the non-negativity of conditional variances in individual series. This implies a guarantee that the conditional variance matrix is positive and definite, but in practice, this is not easy to accomplish (Soriano & Climent, 2005).

In this thesis, the data set used has 32 crude varieties. As discussed in Section 2.1 and Section 2.2, a large data set is used in order to allow a comprehensive analysis and avoid the controversy of benchmark, but the large data set also brings the curse of dimensionality. In fact, it is the methodology that limits the number of crude varieties analyzed, as the example of Ghoshray and Trifonova (2014) discussed in Section 2.1 demonstrates. In order to overcome this I use the methodology developed by Diebold and Yilmaz (2009b). They constructed spillover measures by forecast error variance decomposition, and illustrated its wide and flexible application to various markets in a series of papers (see Diebold & Yilmaz, 2009a, 2012, 2013 and 2014). The major advantage of this methodology is that it is not restricted by the number of dimensions and it allows the clear decomposition of total shocks to a given market into domestic market generated and spillover components across all markets. It also enables the researcher to study spillovers in both crisis and non-crisis periods. Some researchers have also followed this methodology. McMillan and Speight (2010) apply it to analyze return and volatility spillovers in different exchange rates; arguing that this method can give hints as regards market interdependence, financial integration and the potential for contagion effects. They found that euro-dollar exchange rate dominates other euro exchange rates in terms of return and volatility spillovers. Bubák, Kočenda, and Žikeš (2011) also used this approach to study the dynamics of volatility spillovers between quotes of some non-euro currencies and EUR/USD quotes. They found specific volatility transmission patterns for each currency, and interpret differences in pre- and post-crisis patterns as increased short-term interrelationships, indicating "a generally faster reaction of the market to volatility dynamics". Fujiwara and Takahashi (2012) uses this method to assess the interlinkages between Asian financial markets and their links to other developed markets. They found some regularity in international spillover dynamics and stressed the importance of US and China as the main drivers of market fluctuations. B. Zhang and Wang (2014) were the first to apply this method to the crude oil market, but they only studied three crudes: WTI, Brent and China Daqing. A comprehensive analysis including more crudes is therefore needed to investigate the patterns in the crude oil market.

Besides the ability of dealing with large dimension data, the methodology developed by Diebold and Yilmaz (2009b) could provide richer information than GARCH-class models. It allows the examination of the relative importance of both within- and cross-market information in explaining the return and volatility movement in each market. It also allows the evaluation of total spillover of return and volatility across markets, the computation of net directional spillover index by summarizing information about how much each market contributes to return or volatility in other markets, and the production of dynamic indexes of total and net directional spillovers to illustrate how markets evolved over time and reacted to the specific events that took place during sample period. Moreover, the pairwise spillover indexes can be aggregated into groups to reflect the spillover characteristics at the group level.

However, the methodology of Diebold and Yilmaz (2009b) has a deficit that the forecast error variance decomposition is dependent on the variable ordering. Although Diebold and Yilmaz (2012) proposed to apply a generalized vector autoregressive framework to overcome this problem, this framework was criticized by Klößner and Wagner (2012) and Klößner and Wagner (2014), who demonstrated and illustrated that the generalized approach tends to overestimate the spillover index. A better approach is therefore to explore all VAR orderings, or at least calculate using a considerably large number of randomly created ordering permutations. Chapter 4 will give evidence of different results under various variable orderings and base an analysis on the average values of the spillover table over these permutations.

2.5 Transmission channels

There are various channels linking different markets. According to Dornbusch, Park, and Claessens (2000), there are two categories of causes of contagion transmission. The first category emphasizes the spillovers that result from normal interdependence among markets. This interdependence means that shocks, whether global or regional, can be transmitted across countries because of real and financial linkages. Calvo and Reinhart (1996) called such spillover "fundamentals-based". This type of causes includes macroeconomic shocks that have impact on an international scale, local shocks transmitted through trade links, competitive devaluations, and financial links. Regarding trade links, Diebold and Yilmaz (2015a) point out that trade flows play a key role in the transmission of shocks across countries. If the demand of one country takes hit, its import demand is affected as well, and the domestic shock is transmitted to its exporters via trade links. With respect to currency devaluation, an example is Corsetti, Pesenti, and Roubini (1999) who found that the strengthening of the US dollar against the yen in 1995-96 was an important factor in the export downturn in East Asia and caused subsequent financial difficulties there. A common effect of macroeconomic shock is generally a co-movement in asset prices or capital flows.

The other category of causes of contagion is investor's behavior. Dornbusch et al. (2000) point out that crisis in one country may cause investors to sell off equity in several other markets at the same time in order to reduce the overall exposure of portfolios. In particular, leveraged investors may have to sell their asset holdings in other markets when confronting liquidity problems. Investors' panics, herd behavior and loss of confidence are all reasons why crisis in one market can spread to other markets. For example, Fernández-Rodríguez, Gómez-Puig, and Sosvilla-Rivero (2015) use consumer confidence indicator to gauge economic agent's perceptions of future economic activity. This market sentiment proxy is found to be more significant in peripheral EMU countries (Greece, Ireland, Italy, Portugal and Spain) rather than central countries (Austria, Belgium, Finland, Germany and the Netherlands), indicating that market participants' perceptions seem to be more relevant in peripheral countries.

Although various studies examine the cross-border spillover of financial shocks, most of them focus on the stock and bond markets, with little attention being given to the spot crude oil market. Chapter 5 fills this gap in the literature by examining the factors that could explain spillovers in the spot crude oil market, taking account of these two types of transmission channel.

2.6 Conclusion

The recent debate over the effectiveness of benchmark crudes in the global oil market inspires research to reexamine the role of benchmarks and extend the scope of the analysis to include non-benchmark crude oils. The old hypothesis of "One great pool" regarding the integrated nature of the global oil market also calls for new evidence as more and more crude varieties join the market. In order to give a comprehensive analysis, a large data set including both benchmark and non-benchmark crudes is necessary. However, the methodology commonly used in the literature is not able to deal with large multi-dimension data sets. This chapter gives a brief literature review, clarifies some relevant concepts, identifies the gaps in the literature, and proposes a way to fill them. The following empirical chapters will investigate the connections between 32 varieties of crude from the perspectives of price cointegration and causality (Chapter 3), return and volatility spillover (Chapter 4), and finally examine the factors that influence the linkages (Chapter 5).

Chapter 3

The impact of structural breaks on crude oil prices and price dependency

3.1 Introduction

In the past, three crudes - Brent, West Texas Intermediate (WTI) and Dubai Fateh - were established as price benchmarks/markers and have been viewed as representing the price behavior in the markets. However, their relevance has recently been questioned. For Brent, industry concern grows because this global crude oil benchmark is backed by a declining supply. While future Brent volumes are climbing, the physical oil production from the North Sea that forms the basis of the benchmark has fallen sharply. According to figures from consultants Energy Aspects, loadings of the four blends that make up Brent fell to 930,000 barrels a day in January 2014, down from 1.1 million b/d in the same month three years previously. Critics therefore contend Brent is "broken" as a marker for global oil prices (Hume, 2014). Furthermore, Consilience, an energy advisory group, releases a report (Consilience, 2014) which studied the future prospects of Brent oil as a price marker. They analyzed the production forecasts of all major blends in the Brent basket, including the production from future fields that have not yet come on-stream, and concluded that the current benchmark basket production would only be maintained at around 1 million b/d until 2020. As pointed out by Fattouh (2007a), declining supply and liquidity of the benchmark crudes cannot accurately reflect the price at the margin of the physical barrel of oil. First, thin and illiquid markets are more susceptible to distortions and squeeze. Second, in illiquid markets actual deals are infrequent and irregular and the number of price quotations for actual transactions is quite small. However, for benchmark crudes, price quotations should be generated on a regular basis.

WTI, whose price is supposed to reflect supply-demand conditions in the US, the largest oil consumer in the world, disconnects from other benchmarks from time to time. This leads to the debate on whether the WTI benchmark has been "broken" and whether oil market participants should adopt an alternative benchmarks which could better reflect the supply-demand balance in the oil market (Fattouh, 2007b). Dubai faces the similar problem to Brent. Its production has shrunk from a peak of around 383,000 b/d in 1991 to 68,600 b/d in 2008. The market participants have therefore begun to allocate an increasing proportion of their pricing exposure to other benchmarks (Platts, 2014).

These challenges to established benchmarks stress the necessity to review relationships between crudes prices to see if these benchmarks can still represent the overall price behavior in the market. In this paper, I try to assess the performance of benchmarks across time after taking into account the impact of structural breaks on the crude oil price and price dependency between crudes. The analysis is not limited to benchmarks used in practice, but also 'potential' benchmarks proposed by previous studies.

This research investigates not only the structural breaks in price series, but also the structural breaks in price dependency relationships in crude oil markets. For each test, I locate the structural breaks through tests, and then analyze the corresponding economic environments around the structural breaks. Such analysis will help to deepen the understanding of the impact of economic and geo-political events on crude oil markets. Specifically, this chapter will answer the following questions:

1. Have there been any significant structural breaks in crude oil prices and price dependency relationships since 1997?
2. If so, what was the reason for these breaks?
3. And if so, what was the impact of these breaks?
4. What was the performance of benchmarks after taking account of any structural breaks, and do they still behave as price leaders?

This study contributes to the literature in several ways. First, this research provides evidence of the presence of structural breaks in crude oil markets. The application of various tests allowing for structural breaks provides a whole picture of the price behavior. For example, the cointegration test on structural breaks enables us to analyze the breaks in long-run relationships, while Granger causality tests on sub-periods provide a short-term view of the price relationship. Second, this analysis is based on dynamic view i.e. the model is not assumed to be stable over time, as was assumed by Wlazlowski et al. (2011). Instead, I check the effect of structural breaks on the model. Finally, this empirical analysis uses a broad dataset of 32 crudes in total, which makes this investigation more robust. Moreover, the analysis not only consists of the benchmarks in practice, but also "potential" benchmarks proposed in the literature.

The outline of this study is organised as follows. The following section will give a review of the relevant literature. Section 3 describes the data and classification methodology. In sections 4, 5 and 6, we apply and analyze the unit root test, cointegration test and Granger causality test with structural breaks. The conclusion and discussion will be reported in section 7.

3.2 Literature Review

Price dependency among global crude oil markets have been extensively studied using various models in the literature. Brunetti and Gilbert (2000) found that the New York Mercantile Exchange (NYMEX) dominated the International Petroleum Exchange (IPE) in the crude oil markets through the use of cointegrated bivariate FIGARCH models. Lin and Tamvakis (2001) observed substantial spillover effects between the NYMEX and IPE when both markets were trading simultaneously through the use of GARCH and VAR models. Their later paper (Lin & Tamvakis, 2004) applied an autoregressive conditional duration (ACD) model to examine the information spillover between Brent and WTI futures, and found that the NYMEX had a dominant effect on Brent. Feng-bin, Yi, Shuan-hong, and Shou-yang (2008) analyzed information spillover among the WTI, Brent, Dubai, Tapis and Minas crudes. They applied Hong (2001) tests and found that WTI and Brent were dominant, and that WTI futures had a slight edge over those of Brent. Hong (2001) tests were also applied by Fan, Zhang, Tsai, and Wei (2008) to study spillover in value-at-risks between WTI and Brent, and two-way risk spillover effects were found. Besides linear causal linkages, Bekiros and Diks (2008) also considered the nonlinear causal relationships between daily spot and futures prices of WTI crude oil.

Most of the above studies are based on a static view i.e. one that assumes that the parameters in the model are constant over the period being studied. Only a small number of studies take account of a change of parameters in some periods. Hammoudeh and Li (2004) examined the impact of the Asian crisis on the behaviour of U.S. and international petroleum prices under the VECM framework. They found evidence that the causal relationships in the post-crisis period had either changed direction or weakened. In a recent paper, Lu et al. (2014) proposed a new time-varying Granger causality test based on the rolling Hong test and DCC-MGARCH Hong tests. They used these methods on the daily WTI and Brent futures prices and Dubai and Tapis crude spot prices to investigate time-varying information spillover effects. In particular, they studied the impact of significant events on the causal effects. Such events included the Iraq War in March 2003, OPEC's announcement of a record production cut in December 2008, and the Libyan civil war in early 2011. They found that the causal effects of Dubai and Tapis crudes on Brent and WTI became stronger when such events occurred in major oil-producing countries, when in normal times the Dubai and Tapis crudes play subordinate roles. They concluded that the time-varying causal relationships between global markets indicated that the roles played by crude benchmarks may change over time, so oil pricing mechanisms should be adjusted gradually.

As stated above, benchmarks have been challenged in recent years. Wlazlowski et al. (2011) tried to find new price indicators in the crude oil market. They used 32 crudes in their sample and applied Granger causality tests to establish which crudes drove other prices and which ones simply followed general market trends. Their empirical results confirmed the traditional benchmarks of Brent and WTI as global price setters. They also found a third global setter, Russian Urals crude, because it exhibits significant global price setting behaviour. However, Dubai Fateh, which is used in practice as benchmark, did not appear to be a price setter, and the authors therefore suggested that it be given a lower weighting in the assessment of market trends. Candelon et al. (2013) followed the similar method, but extended the univariate Granger causality test in extreme risk with the method developed by Hong et al. (2009). They also used 32 crude oil prices, but focused on pattern in periods of extreme price movements. In both downside and upside price movements, WTI and Brent are price setters due to the fundamental and speculative components of each market. Mediterranean Russian Urals and Europe Forcados acted as benchmarks in the periods of extreme downside price movements, while Ecuador Oriente acted as a benchmark in extreme upside price movements. Asia Dubai Fateh and Oman Blend, which serve together as benchmarks, acted as followers rather than leaders. The authors also observed that the integration level between crude oil markets tends to decrease during extreme periods.

My analysis extends the work of Wlazlowski et al. (2011) by including structural breaks, and also complements the analysis of Candelon et al. (2013), which only focuses on extreme upside or downside price movement, by examining the general patterns over the whole period. My focus is the impact of structural breaks on the time series properties of price, on the long run price relationship (cointegration) and the evolution of benchmarks as price indicators.

3.3 Data description and time series properties

I obtained the weekly FOB spot prices per barrel of crude oil for 32 crudes for the period January 1997 to November 2011 from Thomas Reuters Datastream. I used this data because they are comparable in terms of payment (with the exception of Suez Blend crude prices, which include a 60 day credit) and shipment (all prices are FOB and the destination ports do not change). This ensures that contractual factors such as time differentials do not affect the results. Each crude has 776 observations. The descriptive statistics of these series are in Table 3.1.

TABLE 3.1: Descriptive Statistics of weekly crude oil prices for 32 crudes

Symbol	Label	Obs	Mean	Std.Dev.	Min	Max	skewness	kurtosis
x_1	WTI Cushing	776	48.88	28.9	11	142.52	0.75	2.74
x_2	Europe Brent	776	48.54	31.04	9.44	141.07	0.83	2.75
x_3	Europe Norwegian Ekofisk	776	48.91	31.57	9.55	143.94	0.84	2.78
x_4	Canadian Par	776	47.79	28.83	10.06	144.93	0.81	2.94
x_5	Canada Lloyd Blend	776	37.54	26.45	5.4	128	1.03	3.23
x_6	Mexico Isthmus	776	46.27	29.73	8.78	137.87	0.86	2.83
x_7	Mexico Maya	776	40.35	27.78	5.8	126.58	0.91	2.88
x_8	Colombia Cano Limon	776	47.32	30.98	8.45	141.44	0.84	2.77
x_9	Ecuador Oriente	776	42.4	27.7	7.9	126.14	0.95	2.96
x_{10}	Angola Cabinda	776	47.07	30.46	8.95	137.09	0.86	2.78
x_{11}	Cameroon Kole	776	47.19	30.63	8.95	141.91	0.86	2.8
x_{12}	Egypt Suez Blend	776	44.39	29.88	7.6	133.15	0.88	2.8
x_{13}	Oman Blend	776	46.43	30.07	9.5	137.45	0.84	2.74
x_{14}	Australia Gippsland	776	50.21	31.97	10.25	145.95	0.82	2.74
x_{15}	Malaysia Tapis	776	51.44	32.77	10.95	151.97	0.83	2.78
x_{16}	Mediterranean Russian Urals	776	46.49	30.36	8.73	137.61	0.87	2.78
x_{17}	China Daqing	776	47.78	30.5	9.5	139.45	0.87	2.86
x_{18}	Saudi Arabia Saudi Light	776	46	30.24	9.65	136.02	0.89	2.81
x_{19}	Saudi Arabia Arab Medium	776	44.59	29.62	9.25	131.77	0.91	2.81
x_{20}	Saudi Arabia Saudi Heavy	776	43.34	29.14	8.5	128.72	0.92	2.81
x_{21}	Asia Murban	776	48.52	31.12	9.83	143.4	0.82	2.74
x_{22}	Asia Dubai Fateh	776	46.02	29.92	9.6	136.82	0.85	2.76
x_{23}	Qatar Dukhan	776	47.89	30.97	10.11	142.8	0.83	2.74
x_{24}	Mediterranean Seri K Iran Light	776	46.42	30.35	9.45	136.03	0.85	2.72
x_{25}	Mediterranean Seri K Iran Heavy	776	45.26	29.68	9.2	132.73	0.86	2.71
x_{26}	Kuwait Blend	776	45.02	29.46	9	133.04	0.87	2.77
x_{27}	Algeria Saharan Blend	776	49.07	31.4	9.75	142.51	0.83	2.73
x_{28}	Europe Nigerian Bonny Light	776	49.53	32	9.45	146.15	0.82	2.73
x_{29}	Europe Forcados	776	49.43	32.07	9.55	146.21	0.83	2.75
x_{30}	Europe Libyan Es Sider	776	47.92	30.59	9.65	138.14	0.84	2.73
x_{31}	Indonesia Minas	776	49.52	32.19	9.65	145.51	0.83	2.74
x_{32}	Venezuela Tia Juana	776	46.45	29.67	8.85	137.98	0.86	2.83

Oil is a heterogeneous product varying in two crucial dimensions: quality and location of production. Each dimension could affect the use and price of the oil, therefore I classify crudes accordingly. Chemically and physically, crude oil is differentiated in terms of API gravity[1], acidity and sulfur content (Bacon & Tordo, 2004). These variations

[1]American Petroleum Institute(API) gravity is a measure of density of petroleum liquids, usually given in degrees and placed between 10° and 70°.

lead to differences in the refining processes and in the products obtained from that processing. Specifically, the higher the degree of API of a crude, the lighter it is, and the higher the quality. This is because light crude usually yield a higher proportion of more valuable final petroleum products, such as gasoline and other light petroleum products, by a simple refining process of distillation. In contrast, heavy crude oils have a low share of light hydrocarbons and require more severe refining processes than distillation, such as coking and cracking, to produce similar proportions of more valuable petroleum products. Sweet and sour refer to the sulphur content of the crude. Sulphur causes pollution and refiners have to make heavy investments to remove it. Hence its content should ideally be low. Low-sulphur content crudes are defined as sweet, while high-sulphur crudes are sour. The criteria of definition is displayed in Table 3.2.

TABLE 3.2: Definition of quality

Criteria	Defined as	Criteria	Defined as
API $> 35°$	Light	Sulphur content $\leq 0.5°$	Sweet
$26° < API < 35°$	Medium	Sulphur content$> 0.5°$	Sour
$API < 26°$	Heavy		

Location is also important, because crude oil must be transported to a refinery and the output must be shipped to final users. Following Wlazlowski et al. (2011), I label the crudes according to their geographical origin (i.e. Europe, America, Sub-Saharan African, Asia & Australia, Middle East and North Africa). The details for the dataset is shown in Table A.1, while Table 3.3 gives a summary.

Table 3.3: Summary of crudes analyzed

By quality	Number of crudes	By Region	Number of crudes
Light & sweet	9	Europe	3
Medium & sour	13	America	8
Medium & sweet	6	Middle East	10
Heavy & sour	2	North Africa	3
Light & sour	2	Sub-Saharan Africa	4
		Asia & Australia	4

Note: This table presents the classification of crudes by quality and by regions, with the corresponding number of crudes in each group.

3.4 Unit root test with structural breaks: Clemente-Montanes-Reyes unit root tests

3.4.1 Methodology

To determine whether the data series are stationary or not is critical in the estimation of economic relationships and modeling fluctuations in economic activity. This is because the estimation method of standard regression, the Ordinary Least Squares (OLS) method, is based on the assumption that series fluctuate around a constant long-run mean, and the variance does not depend on time i.e. the series is stationary. In other words, if the series has no tendency to return to a long-run deterministic path and its variance is time-dependent, OLS estimation would give spurious results, with the only exception of cointegration, in which case the model eliminates the stochastic trends to produce stationary residuals. Therefore the testing of stationarity is a precondition to the existence of cointegration relationships.

Normally, the Augmented Dickey-Fuller (Dickey & Fuller, 1979) test is widely used to test for stationarity (the absence of a unit root). In the traditional view of unit root hypothesis, current shocks only have a temporary effect, which cannot be persistent in the series. However, Nelson and Plosser (1982) found that almost all macroeconomic time series have a unit root, which implies that the random shocks have permanent effects on the long-run level of macroeconomics i.e. the fluctuations are not transitory. Perron (1989) challenged their findings and argued that in the presence of structural breaks, the standard ADF tests are biased towards the non-rejection of the null hypothesis. In other words, for the series that are found to be I(1), there may be a possibility that they are in fact stationary around the structural break(s) I(0), but are erroneously classified as I(1). Therefore, most macroeconomic series are not characterized by a unit root, but rather that only large and infrequent shocks are persistent; so that after small and frequent shocks, the economy will return to a deterministic trend. Perron (1989) points out that "Fluctuations are indeed stationary around a deterministic trend function. The only shocks which have had persistent effects are the 1929 crash and the 1973 oil price shock". He then improves the traditional unit root test by including dummy variables to account for a single exogenous structural break.

However Christiano (1992) criticized Perron's known assumption of the break date, arguing that in practice, the break date is chosen based on a pre-test examination of the data, and this "data mining" procedure invalidates the distribution theory underlying conventional testing. The following studies have developed methodologies for endogenously determining break date rather than applying an exogenous one; they include Banerjee, Lumsdaine, and Stock (1992), Perron and Vogelsang (1992), Perron (1997), Lumsdaine and Papell (1997) and Zivot and Andrews (2002). These studies have shown that bias in the usual unit root tests can be reduced by endogenously determining the time of structural breaks. The representative studies are Perron and Vogelsang (1992) and Zivot and Andrews (2002) whose unit root tests allow for one structural break, and the Clemente, Montañes, and Reyes (1998) unit root test which allows for two structural breaks in the mean of the series. The advantage of these tests is that they do not require a priori knowledge of the structural break dates. Also, since these procedures can identify the date of the structural break, this facilitates the analysis of whether a structural break on a certain variable is associated with a particular event such as a change in government policy, a currency crisis, or war etc.

Ben-David, Lumsdaine, and Papell (2003) caution that "just as failure to allow one break can cause non-rejection of the unit root null by the Augmented Dickey–Fuller test, failure to allow for two breaks, if they exist, can cause non-rejection of the unit root null by the tests which only incorporate one break". Therefore a superior way to apply unit root tests in time series that may have structural breaks is to use the Clemente-Montanes-Reyes unit root tests if the two structural breaks indicated by the respective tests are statistically significant. If the results of the Clemente-Montanes-Reyes unit root tests show no evidence of two significant breaks in the series, the results from the Perron–Vogelsang unit root tests with one structural break are considered. If these tests show no evidence of a structural break, the ADF and PP tests can be considered. Through this method, we can avoid the problem pointed out by Baum (2004): if the estimates of the Perron-Vogelsang and Clemente-Montanes-Reyes unit root tests provide evidence of significant additive or innovational outliers in the time series, the results derived from ADF and PP tests are doubtful, because this is evidence that the model excluding structural breaks is mis-specified.

Based on the above arguments, I apply the Clemente-Montanes-Reyes unit root test to see if there are two significant breaks in the series. This test offers two models:

1. an additive outliers (AO) model, which captures a sudden change in the mean of a series; and

2. an innovational outliers (IO) model, which allows for a gradual shift in the mean of the series.

3.4.2 Empirical results

Tables 3.4 and 3.5 display the empirical results of the Clemente-Montanes-Reyes unit root test on the crude oil prices. Despite the breaks in the prices, the null hypothesis of unit root cannot be rejected in either the AO or IO model. The AO model picks mid-2005 and early 2011 as optimal break points in most series, while the IO model chooses late 2004 and mid-2010. Note that the t-statistics in the AO model are much larger than those in the IO model. This indicates that the AO model is significantly better at explaining the price series than the IO model. This in turn implies that the series is more likely to exhibit structural breaks that take place rapidly rather than gradually.

According to Chai, Wang, and Xiao (2013), the abrupt change of oil price in 2005 was not caused by supply-demand factors because supply-demand unbalance did not occur. At that moment, oil demand was in decline while supply was slowly increasing. Meanwhile, the US dollar index was relatively stable. However, there were a lot of breaking-out events in 2005 which changed the market expectation, shocked the weak and sensitive oil market and added fuel to the flames in world oil price rise. These events included: hurricane Katrina, which made a surprise landfall on the Gulf of Mexico, where 30% of American crude oil production and 24% refining capacity is based; fire hazards at refineries in America; the death of King Fahd of Saudi Arabia; the kidnapping of oil operators in Nigeria; the explosion in Iran in mid-February; and the ongoing turbulent

TABLE 3.4: Results of Clemente-Montanes-Reyes unit root tests: AO model

Symbol	Label	t-statistic	Breakdate1	t-statistic of break1	Breakdate2	t-statistic of break2
x_1	WTI Cushing	-4.45	5/11/2004	29.17***	30/11/2007	13.96***
x_2	Europe Brent	-4.48	1/4/2005	44.51***	6/5/2011	12.50***
x_3	Europe Norwegian Ekofisk	-4.42	1/4/2005	44.75***	6/5/2011	12.43***
x_4	Canadian Par	-5.57	5/11/2004	29.81***	28/03/2008	9.213***
x_5	Canada Lloyd Blend	-4.1	7/12/2007	28.57***	28/11/2008	-8.84***
x_6	Mexico Isthmus	-4.59	9/9/2005	41.64***	6/5/2011	10.40***
x_7	Mexico Maya	-4.61	7/10/2005	42.07***	6/5/2011	12.00***
x_8	Colombia Cano Limon	-4.2	1/4/2005	46.19***	18/03/2011	14.39***
x_9	Ecuador Oriente	-4.32	1/4/2005	41.92***	18/03/2011	15.83***
x_{10}	Angola Cabinda	-4.51	1/4/2005	44.70***	6/5/2011	12.95***
x_{11}	Cameroon Kole	-4.1	1/4/2005	44.02***	6/5/2011	12.64***
x_{12}	Egypt Suez Blend	-3.91	6/5/2005	45.51***	11/3/2011	16.11***
x_{13}	Oman Blend	-4.33	1/4/2005	46.39***	13/05/2011	11.65***
x_{14}	Australia Gippsland	-4.27	6/5/2005	44.12***	6/5/2011	11.64***
x_{15}	Malaysia Tapis	-4.35	6/5/2005	44.69***	6/5/2011	11.86***
x_{16}	Mediterranean Russian Urals	-4.32	1/4/2005	44.72***	6/5/2011	12.97***
x_{17}	China Daqing	-4.24	29/10/2004	40.96***	13/05/2011	12.35***
x_{18}	Saudi Arabia Saudi Light	-4.56	6/5/2005	44.10***	6/5/2011	12.28***
x_{19}	Saudi Arabia Arab Medium	-4.53	6/5/2005	43.90***	6/5/2011	12.46***
x_{20}	Saudi Arabia Saudi Heavy	-4.46	6/5/2005	43.43***	6/5/2011	12.36***
x_{21}	Asia Murban	-4.21	15/04/2005	46.73***	6/5/2011	11.66***
x_{22}	Asia Dubai Fateh	-4.72	9/9/2005	45.05***	13/05/2011	10.94***
x_{23}	Qatar Dukhan	-4.4	1/4/2005	46.69***	13/05/2011	11.35***
x_{24}	Mediterranean Seri K Iran Light	-4.54	1/4/2005	45.17***	6/5/2011	12.48***
x_{25}	Mediterranean Seri K Iran Heavy	-4.52	1/4/2005	44.99***	6/5/2011	12.46***
x_{26}	Kuwait Blend	-4.14	22/07/2005	45.00***	6/5/2011	12.01***
x_{27}	Algeria Saharan Blend	-4.46	1/4/2005	45.09***	6/5/2011	12.15***
x_{28}	Europe Nigerian Bonny Light	-4.43	1/4/2005	45.90***	6/5/2011	11.97***
x_{29}	Europe Forcados	-4.45	1/4/2005	45.88***	6/5/2011	12.19***
x_{30}	Europe Libyan Es Sider	-4.44	1/4/2005	45.30***	6/5/2011	12.65***
x_{31}	Indonesia Minas	-4.61	29/10/2004	43.26***	6/5/2011	12.83***
x_{32}	Venezuela Tia Juana	-4.46	6/5/2005	43.07***	6/5/2011	11.06***

Note: This table presents the results of Clemente-Montanes-Reyes unit root tests for the price series with AO model. The date in the table is in format "dd/mm/yyyy". *** significant at 1%

TABLE 3.5: Results of Clemente-Montanes-Reyes unit root tests: IO model

Symbol	Label	t-statistic	Breakdate1	t-statistic of break1	Breakdate2	t-statistic of break2
x_1	WTI Cushing	-4.59	28/11/2003	3.11^{***}	12/1/2007	2.89^{***}
x_2	Europe Brent	-4.51	3/12/2004	3.95^{***}	20/08/2010	3.23^{***}
x_3	Europe Norwegian Ekofisk	-4.8	24/12/2004	4.21^{***}	20/08/2010	4.21^{***}
x_4	Canadian Par	-4.57	25/06/2004	3.48^{***}	19/12/2008	3.48^{*}
x_5	Canada Lloyd Blend	-5.42	10/12/2004	3.21^{***}	20/04/2007	3.21^{***}
x_6	Mexico Isthmus	-4.83	24/12/2004	4.25^{***}	17/09/2010	4.25^{***}
x_7	Mexico Maya	-4.79	3/12/2004	4.22^{***}	20/08/2010	4.22^{***}
x_8	Colombia Cano Limon	-5.01	3/12/2004	4.49^{***}	19/11/2010	4.49^{***}
x_9	Ecuador Oriente	-5.08	24/12/2004	4.41^{***}	20/08/2010	4.41^{***}
x_{10}	Angola Cabinda	-5	24/12/2004	4.44^{***}	20/08/2010	4.44^{***}
x_{11}	Cameroon Kole	-5.04	3/12/2004	4.45^{***}	20/08/2010	4.45^{***}
x_{12}	Egypt Suez Blend	-4.85	24/12/2004	4.25^{***}	20/08/2010	4.25^{***}
x_{13}	Oman Blend	-4.76	31/12/2004	4.17^{***}	20/08/2010	4.17^{***}
x_{14}	Australia Gippsland	-4.81	10/12/2004	4.26^{***}	20/08/2010	4.26^{***}
x_{15}	Malaysia Tapis	-4.91	10/12/2004	4.37^{***}	20/08/2010	4.37^{***}
x_{16}	Mediterranean Russian Urals	-4.31	24/12/2004	3.78^{***}	20/08/2010	3.78^{***}
x_{17}	China Daqing	-5	3/12/2004	4.43^{***}	20/08/2010	4.43^{***}
x_{18}	Saudi Arabia Saudi Light	-4.85	24/12/2004	4.29^{***}	20/08/2010	4.29^{***}
x_{19}	Saudi Arabia Arab Medium	-4.42	24/12/2004	3.92^{***}	20/08/2010	3.92^{***}
x_{20}	Saudi Arabia Saudi Heavy	-4.4	24/12/2004	3.91^{***}	20/08/2010	3.91^{***}
x_{21}	Asia Murban	-4.63	31/12/2004	4.05^{***}	20/08/2010	4.05^{***}
x_{22}	Asia Dubai Fateh	-4.56	24/12/2004	3.99^{***}	20/08/2010	3.99^{***}
x_{23}	Qatar Dukhan	-4.63	31/12/2004	4.05^{***}	20/08/2010	4.05^{***}
x_{24}	Mediterranean Seri K Iran Light	-4.92	24/12/2004	4.35^{***}	20/08/2010	4.35^{***}
x_{25}	Mediterranean Seri K Iran Heavy	-4.91	24/12/2004	4.35^{***}	20/08/2010	4.35^{***}
x_{26}	Kuwait Blend	-4.53	24/12/2004	3.96^{***}	20/08/2010	3.96^{***}
x_{27}	Algeria Saharan Blend	-4.33	25/06/2004	3.78^{***}	20/08/2010	3.78^{***}
x_{28}	Europe Nigerian Bonny Light	-5.12	3/12/2004	4.58^{***}	20/08/2010	4.58^{***}
x_{29}	Europe Forcados	-4.83	10/12/2004	4.29^{***}	20/08/2010	4.29^{***}
x_{30}	Europe Libyan Es Sider	-4.42	10/12/2004	3.89^{***}	20/08/2010	3.89^{***}
x_{31}	Indonesia Minas	-4.74	3/12/2004	4.33^{***}	19/11/2010	4.33^{***}
x_{32}	Venezuela Tia Juana	-4.86	24/12/2004	4.28^{***}	17/09/2010	4.28^{***}

Note: This table presents the results of Clemente-Montanes-Reyes unit root tests for the price series with IO model. The date in the table is in format "dd/mm/yyyy". *** significant at 1%; * significant at 10%

situation in Iraq. The declining relationship between the US and Iran, as well as the Iranian nuclear issue also disrupted the global oil market.

The break detected in early 2011, again, seems not to be caused by market fundamentals, but breaking-out events. Oil supplies remained high at this time, and Saudi Arabia promised an increase in production. Still, the Mideast and North African crisis led to a rise in oil prices to the highest level in two years. Due to the political upheaval, Libyan production also dropped significantly. Despite Saudi promises, the sour type of oil it exports could not replace the more desirable sweet Libyan oil. Although most Libyan oil went to Europe, all oil prices reacted due to the fear of instability.

The above analysis demonstrates that the AO model capture sudden changes in the oil price series. For the IO model, although the structural breaks it detected are not as significant as those detected by the AO model, they still indicate changes in the market, but those which are more related to fundamentals. In 2004, the substantial growth of the global economy, particularly in America, China and India, stimulated the growth of oil demand and boosted world oil prices. American GDP therefore jumped from 2.8% in 2003 to 3.8% in 2004. Meanwhile, China imported more fuel and crude oil due to the shortage of electric power. The overall effect was that the US dollar devaluated further in 2004. In 2003 and 2004, the percentage of US dollar devaluation was over 11 percent, while world oil price increased by 44 percent (Chai et al., 2013).

In 2010, the world economy experienced a significant recovery from the recession. This recovery was mainly due to continued government-led stimulus in the OECD countries, whose oil consumption turned positive after four consecutive years of negative growth. At the same time, developing countries continued their oil consumption. In America a second round of loose quantification policy also provided abundant liquidity and the US dollars index maintained a downward tendency. Hence the world economy recovery and cheap US dollar lead to a gradual change of oil prices in 2010.

Tables A.3 and A.4 show that the 1st difference series of price are stationary with two significant structural breaks. Therefore it can be safely concluded that the price series are I(1) with structural breaks. The estimation model should therefore be based on cointegration models. Moreover, the detected structural breaks are located in the second half of 2008, which is exactly the timing of financial crisis. As 1st difference series measure the change in price level, these structural breaks reflect the switch of price change in 2008, when oil prices increased to record high and then declined sharply afterwards.

Compared with the results of a traditional ADF test (see Table A.2), structural breaks does not change the time series property of crude price series, because both tests indicate they are I(1).

3.5 Cointegration test with structural break: Gregory and Hansen cointegration test

3.5.1 Methodology

The results of the unit root test indicate that the analysis should be based on cointegration models. In the context of crude oil price series, the existence of long run cointegration relationships is the supporting evidence of integration. For example, in the cointegration test for the sweet group, the existence of long run cointegration relationships means that prices for sweet oil from different geographical regions move towards a long run equilibrium. In other words, there are economic forces that drive the prices toward equilibrium if deviation happens.

The conventional cointegration test has the null hypothesis of no cointegration with the alternative hypothesis of the presence of cointegration. This alternative hypothesis implies an assumption that the cointegration long-run relationship is constant over time. However, this assumption may not be valid in practice. The long run cointegration relationship could have shifted on one point. According to Gregory and Hansen (1996), cointegration in the presence of structural breaks can be thought of as holding over some long period of time and then shifting to a new 'long-run' relationship. The break can be a level shift, which is a change in the intercept, a level shift with trend which introduces a time trend into the level shift model, or it can be a regime shift which changes the y-intercept and the slope of the model with a time trend. The standard test procedure is to evaluate modified ADF, Za and Zt statistics in the presence of a one-time regime shift of unknown timing to determine if the null hypothesis of no cointegration can be rejected.

In formulas, these three breaks could be expressed as followings:

Define dummy variable $D_t^\tau = 0$ before the change point and 1 after the change point.

Level shift: $y_t = \alpha_1 + \alpha_2 D_t^\tau + \beta x_t + \varepsilon_{i,t}$, where there is a change in the intercept α after the break point while the slope coefficient is held constant.

Level shift with trend: $y_t = \alpha_1 + \alpha_2 D_t^\tau + \beta_0 t + \beta_1^\tau x_t + \varepsilon_{i,t}, t = 1, \ldots n$. Here the addition of $\beta_0 t$ adds a time trend in the level shift model.

Regime shift: $y_t = \alpha_1 + \alpha_2 D_t^\tau + \beta_1^\tau x_t + \beta_2^\tau x_t D_t^\tau + \varepsilon_{i,t}, t = 1, \ldots n$. Here β_2^τ adds to the slope coefficient after the break.

For all the tests, the null hypothesis is that there is no cointegration in the system. The alternative hypothesis is that there is a cointegration with the presence of a structural shift. The standard statistics calculated are ADF, the Phillips Z_α and the Phillips Z_t.

The disadvantages of this test are

1. It allows only one structural break;
2. The maximum number of independent variables is 4.

The second disadvantage prevents us from applying this test with structural break on more than five variables at one time. Therefore it can only be applied to sub-groups. Within each sub-group, I choose one or two benchmark(s) used in practice or proposed in the literature as dependent variables in the long-run relationship, and then tested if there was a cointegration with a structural break between this benchmark and the rest of the crudes in the sub-group. If there were more than four variables in the sub-group in addition to the benchmark, I applied the test several times to ensure that every crude was covered.

3.5.2 Empirical results

3.5.2.1 Cointegration by quality

In the quality section, I choose WTI Cushing and Europe Brent as benchmarks in the sweet group; and Iran Light as the benchmark in the sour group[2].

Tables 3.6 and 3.7 display the empirical results from the sweet group. From these tables it can be concluded that the null hypothesis of no cointegration can be rejected in every test because the results are significant in almost every test, implying that there is a cointegration relationship with the presence of a structural break. However, we

[2]According to Wlazlowski et al. (2011), Iran Light is a price leader in sour group

Table 3.6: Cointegration test with one structural break for the sweet group, with WTI as the benchmark

With EFK, CPR, GPL & TPS			With SHR, BNL & ESD		
Breaking type	ADF statistic	Breaking date	Breaking type	ADF statistic	Breaking date
level	-12.44***	11/02/2011	level	-7.41***	01/04/2011
trend	-12.73***	11/02/2011	trend	-7.92***	04/03/2011
regime	-11.05***	11/03/2011	regime	-7.53***	11/02/2011
regimetrend	-10.86***	27/08/2010	regimetrend	-7.16***	11/02/2011
	Z_t statistic			Z_t statistic	
level	-16.16***	01/04/2011	level	-9.6***	18/02/2011
trend	-17***	01/04/2011	trend	-9.67***	18/02/2011
regime	-16.74***	18/03/2011	regime	-10.54***	31/12/2010
regimetrend	-17.52***	28/01/2011	regimetrend	-10.15***	18/09/2009
	Z_α statistic			Z_α statistic	
level	-401.23***	01/04/2011	level	-175.54***	18/02/2011
trend	-431.75***	01/04/2011	trend	-178.04***	18/02/2011
regime	-418.94***	18/03/2011	regime	-209.27***	31/12/2010
regimetrend	-446.56***	28/01/2011	regimetrend	-192.89***	18/09/2009
With CLM, CBD & KLE,			With CDQ, FCD & MNS		
Breaking type	ADF statistic	Breaking date	Breaking type	ADF statistic	Breaking date
level	-6.57***	04/03/2011	level	-7.85***	01/04/2011
trend	-6.62***	04/03/2011	trend	-7.84***	01/04/2011
regime	-5.82*	23/10/2009	regime	-8.04***	11/02/2011
regimetrend	-5.62	10/04/2009	regimetrend	-7.94***	12/02/2010
	Z_t statistic			Z_t statistic	
level	-6.83***	07/01/2011	level	-9.7***	18/02/2011
trend	-6.84***	07/01/2011	trend	-9.71***	18/02/2011
regime	-7.36***	18/02/2011	regime	-11***	18/02/2011
regimetrend	-6.61***	07/01/2011	regimetrend	-10.47***	26/02/2010
	Z_α statistic			Z_α statistic	
level	-104.92***	07/01/2011	level	-177.08***	18/02/2011
trend	-105.37***	07/01/2011	trend	-177.8***	18/02/2011
regime	-126.95***	18/02/2011	regime	-224.59***	18/02/2011
regimetrend	-106.84***	07/01/2011	regimetrend	-207.41***	26/02/2010

Note: This table presents the results of the cointegration test with structural breaks for WTI with the other sweet crudes. The format of the dates in the table is "dd/mm/yyyy". *** significant at 1%. Crude names in the tables are abbreviated. See A.1 for full names.

get different break dates with different benchmarks. For WTI, the captured structural break happened mostly in early 2011 whereas for Brent, the captured structural break happened between 2006 and 2009. WTI is lighter and sweeter than Brent and normally traded at +/- 3 USD/bbl compared to Brent. However, in February 2011, WTI was trading at around 85 USD/bbl while Brent was trading at 103 USD/barrel. The reason most cited for this difference was that Cushing had reached capacity, due to a surplus of oil in the interior of North America. At the same time, the price of Brent increased in

TABLE 3.7: Cointegration test with one structural break for the sweet group, with Brent as the benchmark

With EFK,CPR,GPL & TPS			With SHR,BNL & ESD		
Breaking type	ADF statistic	Breaking date	Breaking type	ADF statistic	Breaking date
level	-6.18^{***}	02/03/2007	level	-8.06^{***}	01/09/2006
trend	-6.37^{***}	11/01/2008	trend	-9^{***}	23/06/2006
regime	-19.45^{***}	10/11/2006	regime	-10.52^{***}	11/08/2006
regimetrend	-12.54^{***}	01/02/2008	regimetrend	-19.49^{***}	08/12/2006
	Z_t statistic			Z_t statistic	
level	-19.1^{***}	21/12/2007	level	-17.79^{***}	28/07/2006
trend	-19.25^{***}	21/12/2007	trend	-18.81^{***}	28/07/2006
regime	-20.28^{***}	21/12/2007	regime	-18.68^{***}	28/07/2006
regimetrend	-20.46^{***}	21/12/2007	regimetrend	-20^{***}	18/08/2006
	Z_α statistic			Z_α statistic	
level	-497.45^{***}	21/12/2007	level	-452.72^{***}	28/07/2006
trend	-502.34^{***}	21/12/2007	trend	-487.09^{***}	28/07/2006
regime	-538.74^{***}	21/12/2007	regime	-482.6^{***}	28/07/2006
regimetrend	-544.93^{***}	21/12/2007	regimetrend	-528.2^{***}	18/08/2006
With CLM,CBD & KLE			With CDQ, FCD & MNS		
Breaking type	ADF statistic	Breaking date	Breaking type	ADF statistic	Breaking date
level	-5.23^{*}	21/12/2007	level	-7.28^{***}	06/02/2009
trend	-6.13^{***}	14/11/2008	trend	-7.24^{***}	06/02/2009
regime	-5.16	21/12/2007	regime	-8.5^{***}	02/01/2009
regimetrend	-6.51^{**}	27/08/2004	regimetrend	-8.54^{***}	02/01/2009
	Z_t statistic			Z_t statistic	
level	-13.2^{***}	29/02/2008	level	-14.5^{***}	13/02/2009
trend	-14^{***}	20/06/2008	trend	-14.48^{***}	13/02/2009
regime	-13.29^{***}	29/02/2008	regime	-15.97^{***}	02/01/2009
regimetrend	-16.02^{***}	20/08/2004	regimetrend	-16.31^{***}	27/06/2008
	Z_α statistic			Z_α statistic	
level	-294.04^{***}	29/02/2008	level	-340.54^{***}	13/02/2009
trend	-323.29^{***}	20/06/2008	trend	-339.9^{***}	13/02/2009
regime	-299.16^{***}	29/02/2008	regime	-388.29^{***}	02/01/2009
regimetrend	-390.37^{***}	20/08/2004	regimetrend	-400.31^{***}	27/06/2008

Note: This table presents the results of the cointegration test with structural breaks for Brent and the other sweet crudes. The format of the dates in the table is "dd/mm/yyyy". *** significant at 1%. Crude names in the tables are abbreviated. See A.1 for full names.

reaction to civil unrest in Egypt and across the Middle East. Since WTI-priced stockpiles at Cushing could not easily be transported to the refineries on the Gulf Coast, WTI crude was unable to be arbitraged to bring back the price parity. The detected break in 2011 exactly reflects the disconnection of WTI from other sweet crudes. Moreover, this event had remarkable influence because it not only caused a level shift, but also shifts in trend and regime on the long-run relationship among sweet crudes. "A combination of inflexible pipeline systems, a lack of capacity for shipping crude out of the US Midwest, and a surge in deliveries of both Canadian and US domestic crude from new shale plays means that the WTI dislocation is likely to persist for some time and could get much worse." (Fletcher, 2011). Because this dislocation is specific to WTI, the tests with Brent as a benchmark do not show the same structural breaks in 2011.

However, the breaks detected in the tests with Brent do reflect the continuous tightness in the market from 2006 to 2009. In mid-2006, crude oil prices reached a high level. The increases were attributed to geopolitical tensions resulting from North Korea's missile launch. The ongoing war in Iraq, and Israel and Lebanon going to war were also causative factors. From the last quarter of 2007 to the first half of 2008, Hamilton (2009) is of the opinion that "this episode qualifies as one of the biggest shocks to oil prices on record" and attributes the price increase of 2007-08 to strong demand confronting stagnating world production. At the beginning of 2009, oil prices rose temporarily because of tensions in the Gaza Strip: from 27 December 2008 to 18 January 2009, there was a three week armed conflict in the Gaza Strip between Israel and Palestinian militants (BBC, 2009).

In contrast, although Table 3.8 also confirms the existence of a cointegration relationship with one break in the sour group, the break dates detected do not have a clear pattern. One possible reason could be the choice of benchmark. According to Montepeque (2005), the medium and sour crudes do not have a suitable benchmark. The lack of pattern in Table 3.8 confirms his argument, because a suitable benchmark, as discussed above with regards to WTI and Brent, should be able to reflect market conditions and hence have predictable patterns.

Table 3.8: Cointegration test with structural break for the sour group, with Iran Light as a benchmark

With IMS, ORT, SUZ & OMN			With URL, SSL, SAM & SSH		
Breaking type	ADF statistic	Breaking date	Breaking type	ADF statistic	Breaking date
level	-10.72***	10/10/2003	level	-4.79	06/06/2003
trend	-10.72***	10/10/2003	trend	-5.65*	08/01/2010
regime	-10.11***	15/10/2010	regime	-5.07	06/06/2003
regimetrend	-10.33***	19/11/2010	regimetrend	-5.87	01/05/2009
	Z_t statistic			Z_t statistic	
level	-10.4***	30/07/2004	level	-13.82***	01/08/2003
trend	-10.36***	30/07/2004	trend	-14.34***	27/11/2009
regime	-12.34***	10/09/2004	regime	-14.41***	15/08/2003
regimetrend	-12.35***	10/09/2004	regimetrend	-14.81***	17/12/2004
	Z_α statistic			Z_α statistic	
level	-166***	30/07/2004	level	-290.29***	01/08/2003
trend	-165.87***	30/07/2004	trend	-305.73***	27/11/2009
regime	-234.31***	10/09/2004	regime	-308.14***	15/08/2003
regimetrend	-233.99***	10/09/2004	regimetrend	-322.16***	17/12/2004
With DBF, KWT & TJN			With LYD & MYA		
Breaking type	ADF statistic	Breaking date	Breaking type	ADF statistic	Breaking date
level	-6.24***	05/11/2010	level	-6.34***	18/04/2008
trend	-6.14***	15/10/2010	trend	-6.31***	01/10/2004
regime	-6.37**	05/06/2009	regime	-6.59***	13/02/2009
regimetrend	-6.46**	21/03/2008	regimetrend	-6.89***	10/09/2004
	Z_t statistic			Z_t statistic	
level	-7.75***	13/08/2010	level	-6.09***	10/06/2011
trend	-7.76***	13/08/2010	trend	-6.39***	10/09/2004
regime	-7.91***	25/06/2010	regime	-6.73***	13/06/2008
regimetrend	-8.42***	23/05/2008	regimetrend	-6.79***	27/06/2008
	Z_α statistic			Z_α statistic	
level	-118.51***	13/08/2010	level	-70.23***	10/06/2011
trend	-118.51***	13/08/2010	trend	-74.65***	10/09/2004
regime	-126.67***	25/06/2010	regime	-86.96***	13/06/2008
regimetrend	-135.59***	23/05/2008	regimetrend	-88.53***	27/06/2008

Note: This table presents the results of the cointegration test with structural breaks for Iran Light and other sour crudes. The format of dates in the table is “dd/mm/yyyy”.*** significant at 1%. Crude names in the tables are abbreviated. See A.1 for full names.

3.5.2.2 Cointegration by geography

In the regional groups, only the Middle East and North Africa and the American groups have more than five crudes, which means that these groups will exceed the independent variable limit of the Gregory and Hansen test. For these two groups, cointegration tests with structural breaks are applied several times to make sure that every crude in the group is involved.

Table 3.9: Cointegration test with structural break for the Asian group, with TPS as the benchmark

TPS, GPL, CDQ & MNS		
Breaking type	ADF statistic	Breaking date
level	-7.1***	01/05/1998
trend	-7.09***	01/05/1998
regime	-7.34***	16/01/2009
regimetrend	-10.05***	28/07/2000
	Z_t statistic	
level	-10.19***	13/02/1998
trend	-10.21***	29/09/2000
regime	-10.63***	13/02/2009
regimetrend	-10.84***	13/02/2009
	Z_α statistic	
level	-162.91***	13/02/1998
trend	-163.67***	29/09/2000
regime	-181.85***	13/02/2009
regimetrend	-182.77***	13/02/2009

Note: This table presents the results of the cointegration test with structural breaks for the Asian group. The format of the dates is "dd/mm/yyyy".*** significant at 1%. Crude names in the table are abbreviated. See A.1 for full names.

Table 3.10: Cointegration test with structural break for the European group, with Brent as the benchmark

BRT, EFK & URL		
Breaking type	ADF statistic	Breaking date
level	-7.87***	17/08/2007
trend	-8.27***	08/06/2007
regime	-10.2***	15/06/2007
regimetrend	-20.14***	04/07/2008
	Z_t statistic	
level	-18.08***	04/05/2007
trend	-18.55***	04/05/2007
regime	-19.1***	21/12/2007
regimetrend	-20.13***	20/06/2008
	Z_α statistic	
level	-463.81***	04/05/2007
trend	-479.32***	04/05/2007
regime	-498.73***	21/12/2007
regimetrend	-533.44***	20/06/2008

Note: This table presents the results of the cointegration test with structural breaks for the European group. The format of the dates in the table is "dd/mm/yyyy".*** significant at 1%. Crude names in the tables are abbreviated. See A.1 for full names.

Table 3.11: Cointegration test with structural break for the American group, with WTI as the benchmark

WTI, CPR, LYD, IMS & MYA			WTI, CLM, ORT & TJN		
Breaking type	ADF statistic	Breaking date	Breaking type	ADF statistic	Breaking date
level	-12.06***	18/03/2011	level	-7.44***	11/03/2011
trend	-12.42***	18/03/2011	trend	-7.62***	11/03/2011
regime	-11.18***	04/03/2011	regime	-7.13***	01/04/2011
regimetrend	-12.98***	10/09/2010	regimetrend	-5.79	22/07/2011
	Z_t statistic			Z_t statistic	
level	-15.02***	01/04/2011	level	-8.7***	22/04/2011
trend	-15.66***	01/04/2011	trend	-8.83***	22/04/2011
regime	-16.08***	01/04/2011	regime	-9.54***	18/02/2011
regimetrend	-16.07***	17/09/2010	regimetrend	-8.66***	07/01/2011
	Z_α statistic			Z_α statistic	
level	-361.13***	01/04/2011	level	-157.83***	22/04/2011
trend	-383.05***	01/04/2011	trend	-160.22***	22/04/2011
regime	-397.01***	01/04/2011	regime	-184.48***	18/02/2011
regimetrend	-397.45***	17/09/2010	regimetrend	-162.67***	07/01/2011

Note: This table presents the results of the cointegration test with structural breaks for the American group. The format of the dates in the table is "dd/mm/yyyy".*** significant at 1%. Crude names in the tables are abbreviated. See A.1 for full names.

All of the tests confirm the presence of a structural break in the cointegration relationships between crudes in the same region. Moreover, there are some interesting results in relation to regional features. The test for the Asian group captures the break in the 1998 Asian financial crisis, and shows that this regional financial crisis only induced a shift in the level, not trend or regime (See Table 3.9). The break in trend happens in 2000, when the emerging countries in Asia, especially China, began to develop fast and demand more energy. Table 3.11 shows that the dislocation problem of WTI discussed in last section also caused profound structural breaks in cointegration relationships between local crudes, because almost all detected structural breaks detected happened in early 2011. The test for the European region, as shown in Table 3.10, indicates a structural break taking place between crudes in Europe in 2007, when US dollar successively hit a new low and initiated a concern about inflation in the market, so a large sum of funds was invested into the oil market for appreciation (Chai et al., 2013).

Crudes from the Middle East and North Africa region are all of similar quality (light/medium

Table 3.12: Cointegration test with structural break for the Middle East and North Africa group, with DBF as the benchmark

DBF, SUZ, SSL, SAM & SSH			DBF, MBN,DKN,IRL & IRH		
Breaking type	ADF statistic	Breaking date	Breaking type	ADF statistic	Breaking date
level	-7.12***	01/07/2005	level	-6.42***	08/01/2010
trend	-7.28***	01/07/2005	trend	-6.45***	15/01/2010
regime	-7.27***	11/05/2007	regime	-7.25***	21/03/2008
regimetrend	-7.97***	04/04/2008	regimetrend	-6.95**	30/07/2004
	Z_t statistic			Z_t statistic	
level	-8.43***	15/04/2005	level	-6.34***	26/03/2010
trend	-8.4***	06/08/2010	trend	-6.36***	26/03/2010
regime	-9.15***	08/06/2007	regime	-7.81***	12/09/2008
regimetrend	-9.7***	23/05/2008	regimetrend	-8.47***	28/09/2007
	Z_α statistic			Z_α statistic	
level	-143.76***	15/04/2005	level	-83.34***	26/03/2010
trend	-142.31***	06/08/2010	trend	-84.22***	26/03/2010
regime	-162.51***	08/06/2007	regime	-115.42***	12/09/2008
regimetrend	-179.44***	23/05/2008	regimetrend	-132.93***	28/09/2007
DBF, KWT,SHR & ESD					
Breaking type	ADF statistic	Breaking date			
level	-6.27***	18/02/2011			
trend	-6.23***	18/02/2011			
regime	-6.46**	08/08/2008			
regimetrend	-6.79**	09/05/2008			
	Z_t statistic				
level	-7.53***	04/02/2011			
trend	-7.49***	04/02/2011			
regime	-7.9***	14/11/2008			
regimetrend	-8.18***	25/04/2008			
	Z_α statistic				
level	-106.78***	04/02/2011			
trend	-106.22***	04/02/2011			
regime	-118.21***	14/11/2008			
regimetrend	-125.62***	25/04/2008			

Note: This table presents the results of the cointegration test with structural breaks for the Middle East and North Africa group. The format of the dates in the table is "dd/mm/yyyy".*** significant at 1%. Crude names in the tables are abbreviated. See A.1 for full names.

density and sour), therefore similar conclusion can be drawn as in the sour group as discussed above i.e. that there is no pattern in this group, possibly due to the lack of a price leader among this region's sour crudes. However, an interesting observation can be made: the test involving Europe Libyan Es Sider (ESD) indicates February 2011 as a break point, when Libya was experiencing the worst violence and political upheavals, and its ruler Colonel Muammar Gaddafi used snipers and helicopters to shoot protesters in the capital city of Tripoli and sent fighter jets to fire missiles at rebel forces. This crisis halved the country's oil production (1% of global oil production) according to an estimation by Forbes (Katusa, 2011). From Table 3.12, it can be seen that the Libyan crisis imposed a break on the level and trend of the long-run cointegration relationship.

3.6 Granger causality test with structural breaks

3.6.1 Methodology

For each pair of series, basic Granger causality test is based on the following model:

$$x_{i,t} = \sum_{l=1}^{p} a_l x_{i,t-l} + \sum_{m=1}^{p} b_m x_{j,t-m} \tag{3.1}$$

$$x_{j,t} = \sum_{l=1}^{p} c_l x_{i,t-l} + \sum_{m=1}^{p} d_m x_{j,t-m} \tag{3.2}$$

where $x_{i,t}$ and $x_{i,t}$ are two time series variables. The joint significance of coefficients b_m and c_l, tested by F-statistics, shows if lags of one regressor has useful predictive information of the other. If all the b_m are jointly different from zero, the null hypothesis of x_j does not Granger cause x_i is rejected, implying that x_j Granger causes x_i.

However the coefficients may change over time due to the evolution of the economy, policy changes or other related events. In other words, coefficients may be unstable and depend on events in the time period. For example, Wlazlowski et al. (2011) found that the Mediterranean Russian Urals crude could serve as a potential global price setter, because its past values could predict other crudes' prices in the Granger causality tests for the sample period of 1997 to 2006. However, if the sample period is extended to 2011, its role as a price setter is not evident. To check this, the calculation was repeated by following the same methodology as Wlazlowski et al. (2011) for the sample period up to 2011. The method involves the calculation of the fraction of rejection in the Granger causality tests for a crude with all the other 31 crudes. In Equation 3.2, if x_i Granger causes x_j, x_i is said to be a price setter of x_j, and x_j is said to be a price taker of x_i. For each crude, there are 31 tests for its price setter characteristics and 31 tests for price taker characteristics. The fraction of cases from the 31 tests where a crude is seen to be a price setter is called the price setter factor in Table 3.13, while the fraction where a crude is seen to be a price taker is the price taker factor in the table. If a crude has a high price setter factor which is larger than the price taker factor, this crude is viewed as being able to respond quickly to market changes and having a leading role in price dependency. In contrast, a low price setter factor combined with high price taker factor are viewed as an indication of slow market adaptation behavior, indicating a role as a follower.

Table 3.13 displays the Granger causality tests in different sample periods. The results from a sample period from 1997-2006 are cited from Wlazlowski et al. (2011). Based on these results, Wlazlowski et al. (2011) claim that WTI (x_1) and Brent (x_2) are both global price setters, but Asian Dubai Fateh (x_{22}) and Oman Blend (x_{13}) do not display price setter properties in global market. My analysis with sample period from 1997-2011 shows that WTI (x_1) and Brent (x_2) are well integrated in the market mechanism, because they have high scores on both price setter and price taker factors[3]. There is little evidence to support the position that Asian Dubai Fateh (x_{22}) and Oman Blend (x_{13}) are price setters in this analysis. The most significance change is with Russian Ural's (x_{16}), which was claimed to be a third global price setter by Wlazlowski et al. (2011). Russian Urals' price setter factor decreases from 1 to 0.58, implying that its

[3]The reason for the difference is that Wlazlowski et al. (2011)'s Brent price is slightly different with mine.

price setting role diminished over time; that is, the coefficients of x_{16} as a regressor in Equation 3.2 may be unstable. In order to test if there is any structural break in the coefficients of Russian Urals, the supremum Wald test was applied to them.

The supremum Wald test requires no prior knowledge about the break date. Instead, it constructs a Wald test for each possible break date in the sample, and compares the maximum of sample test with what could be expected under the null hypothesis of no break. If the maximum value of the test statistic exceeds that under the hypothesis of no break, the null hypothesis is rejected and a structural break is said to have happened at the date with the maximum test statistic(Kim & Siegmund, 1989; Quandt, 1960; Andrews, 1993).

3.6.2 Empirical results

Table 3.14 shows the supremum Wald test statistics and the corresponding break date of the Russian Urals' coefficients at predicting other crudes' prices. All of these supremum Wald test statistics are significant at the 1% level, indicating the presence of a structural break. The break dates are generally clustered in the period of the 2008 global financial crisis, although some were carried over to the beginning of 2009.

Table 3.14 only displays the maximum Wald test statistics. In order to observe the dynamics of Wald test statistics, Figure 3.1 displays all of the Wald test statistics instead of just the maximum one. From January 1997 to March 2006, the sample period of Wlazlowski et al. (2011), can be viewed as a peaceful period, the period since 2007 is quite tumultuous, especially in the middle of 2008, when crude oil prices plummeted from a peak. The stability of the relationship between the price of Russian Urals and other crudes was destroyed by the collapse of crude oil prices. Although a structural break in

TABLE 3.13: Granger causality test results in different sample period

overall		1997-2006		1997-2011	
	Label	setter	taker	setter	taker
x_1	WTI Cushing	1	0.13	1	0.97
x_2	Europe Brent	0.97	0.26	1	0.94
x_3	Europe Norwegian Ekofisk	0.71	0.68	0.65	0.39
x_4	Canadian Par	0.65	1	0.52	1
x_5	Canada Lloyd Blend	0.94	1	0.39	1
x_6	Mexico Isthmus	0.87	0.45	0.97	0.81
x_7	Mexico Maya	0.71	0.16	0.97	0.94
x_8	Colombia Cano Limon	0.84	0.26	0.97	0.84
x_9	Ecuador Oriente	0.68	0.87	0.77	0.74
x_{10}	Angola Cabinda	0.65	0.74	0.77	0.48
x_{11}	Cameroon Kole	0.74	0.87	0.55	0.58
x_{12}	Egypt Suez Blend	0.55	0.84	0.55	0.58
x_{13}	Oman Blend	0.77	0.84	1	0.97
x_{14}	Australia Gippsland	0.61	0.77	0.97	0.81
x_{15}	Malaysia Tapis	0.13	1	0.68	0.97
x_{16}	Mediterranean Russian Urals	1	0.42	0.58	0.61
x_{17}	China Daqing	0.35	1	0.45	0.94
x_{18}	Saudi Arabia Saudi Light	0.58	0.48	0.65	0.61
x_{19}	Saudi Arabia Arab Medium	0.65	0.52	0.74	0.68
x_{20}	Saudi Arabia Saudi Heavy	0.61	0.52	0.71	0.65
x_{21}	Asia Murban	0.84	0.81	0.9	0.87
x_{22}	Asia Dubai Fateh	0.68	0.81	0.87	0.84
x_{23}	Qatar Dukhan	0.77	0.84	0.9	0.87
x_{24}	Mediterranean Seri K Iran Light	0.84	0.61	0.77	0.42
x_{25}	Mediterranean Seri K Iran Heavy	0.84	0.77	0.77	0.42
x_{26}	Kuwait Blend	0.87	0.9	0.94	0.87
x_{27}	Algeria Saharan Blend	0.61	0.58	0.52	0.39
x_{28}	Europe Nigerian Bonny Light	0.58	0.81	0.52	0.42
x_{29}	Europe Forcados	0.68	0.71	0.55	0.58
x_{30}	Europe Libyan Es Sider	0.77	0.9	0.52	0.52
x_{31}	Indonesia Minas	0.48	1	0.39	1
x_{32}	Venezuela Tia Juana	0.52	0.94	0.77	0.61

Note: The Granger causality test results for the period 1997-2006 is cited from Wlazlowski et al. (2011) while the test result from 1997-2011 is newly calculated by the same method but with data from a longer time period. A price setting (price taking) factor of 0.9 implies that the crude is Granger causing (is Granger caused by) 90% of the other crudes. The same logic applies to other degrees of price setting/taking factors. If a crude has a high price setting factors combined with a low price taking factor, this interpreted as strong ability to respond quickly to market changes. In contrast, a low price setting factor combined with high price taking factors is viewed as an indication of slow market adaptation.

Table 3.14: Structural break in Russian Urals' coefficients

Name	Supremum Wald Test Statistic	Break Date	Name	Supremum Wald Test Statistic	Break Date
WTI	54.85^{***}	10/3/2008	SSL	51.32^{***}	12/12/2008
BRT	64.15^{***}	10/3/2008	SAM	54.81^{***}	12/12/2008
EFK	59.69^{***}	8/15/2008	SSH	53.81^{***}	12/12/2008
CPR	75.95^{***}	10/3/2008	MBN	69.07^{***}	8/15/2008
LYD	39.81^{***}	12/26/2008	DBF	63.75^{***}	8/15/2008
IMS	54.03^{***}	12/26/2008	DKN	70.95^{***}	8/15/2008
MYA	66.60^{***}	1/9/2009	IRL	55.52^{***}	1/2/2009
CLM	46.04^{***}	12/26/2008	IRH	57.62^{***}	1/2/2009
ORT	68.39^{***}	12/26/2008	KWT	57.55^{***}	8/15/2008
CBD	61.08^{***}	1/2/2009	SHR	57.81^{***}	8/15/2008
KLE	61.63^{***}	8/15/2008	BNL	62.73^{***}	8/22/2008
SUZ	55.64^{***}	8/15/2008	FCD	61.17^{***}	8/22/2008
OMN	67.88^{***}	8/15/2008	ESD	62.17^{***}	2/13/2009
GPL	63.04^{***}	10/3/2008	MNS	62.08^{***}	10/3/2008
TPS	57.00^{***}	10/3/2008	TJN	59.76^{***}	12/26/2008
CDQ	47.79^{***}	11/21/2008			

Note: This table shows the supremum Wald test statistics and break date of Russian Urals' (URL) coefficients at predicting other crudes' prices. The null hypothesis is no structural break in the coefficients of Russian Urals when it is used as regressor to predict the other crude's prices. The break date is in "mm/dd/yyyy" format.
*** significant at 1%

the coefficients does not necessarily indicate a structural break of the Granger causality relationship, because the latter depends on the joint significance of coefficients rather than the coefficients themselves, the presence of a structural break could, to some extent, explain why the price setting role of Russian Urals disappears if the sample period is extended to include the 2008 global financial crisis.

It is possible to apply the Granger causality tests to sub-sample period before and after the structural break date. However, according to Figure 3.1, the Wald test statistics do not reduce to a low level after the indicated structural break date, particularly for Angola Cabinda (CBD), Cameroon Kole (KLE), China Daqing (CDQ), Saudi Arabia Saudi Light (SSL), Saudi Arabia Arab Medium (SAM), Saudi Arabia Saudi Heavy (SSH), Mediterranean Seri K Iran Light (IRL), Mediterranean Seri K Iran Heavy (IRH), Algeria Saharan Blend (SHR), Europe Forcados (FCD), and Europe Libyan Es Sider

(ESD). The continuous high Wald test statistics implies that the coefficients of Russian Urals did not return to a stable state. In fact, a second maximum Wald test statistic may indicate a second structural break, especially when it has a very close value with the first maximum one. Because the coefficients are not stable, the inference from the equation is not robust. Therefore the Granger causality test was not applied to the sub samples separated by the detected structural date.

Figure 3.1: Dynamic Wald test statistics of Russian Urals' coefficients

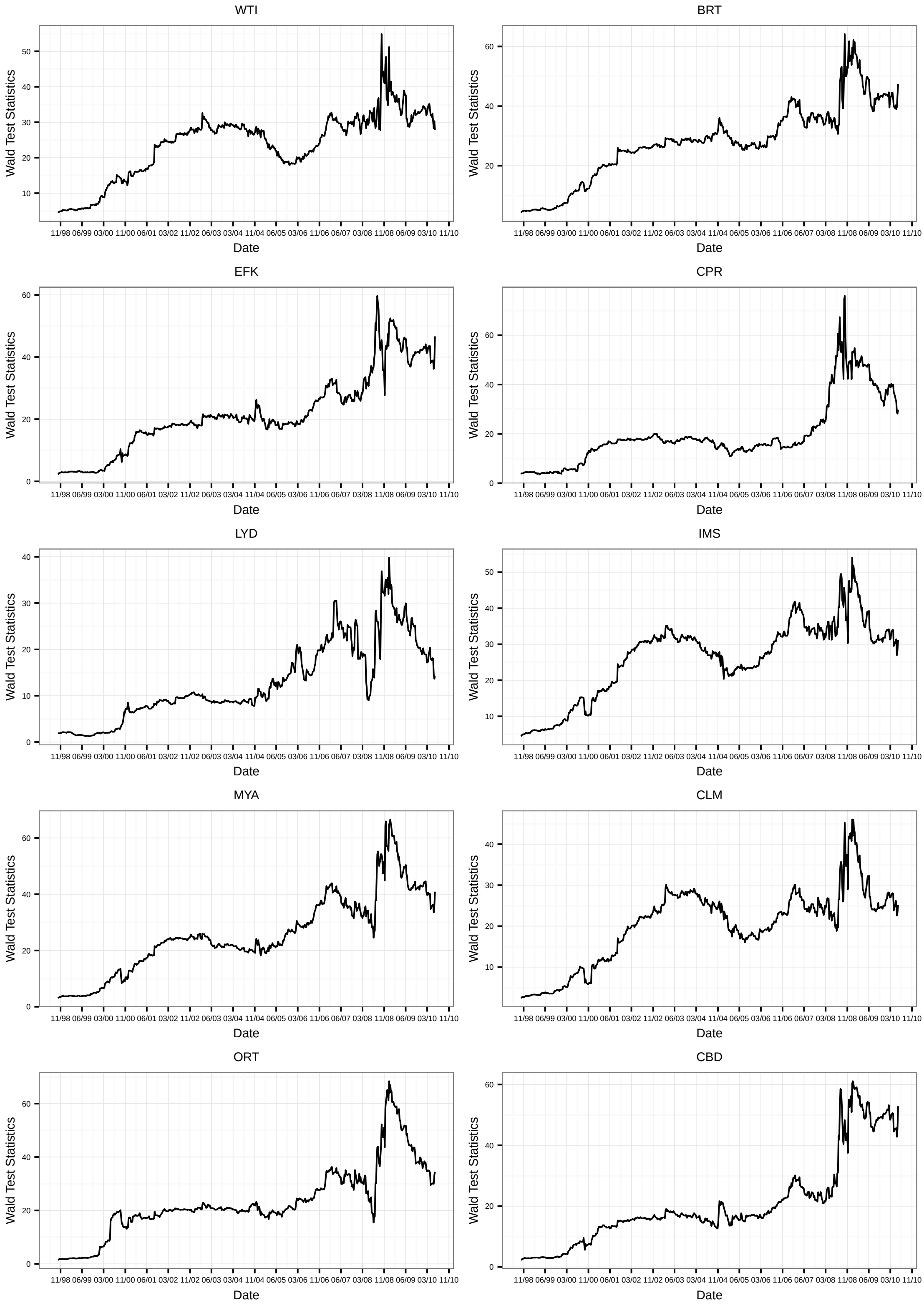


FIGURE 3.1 (cont.): Dynamic Wald test statistics of Russian Urals' coefficients (Cont.)

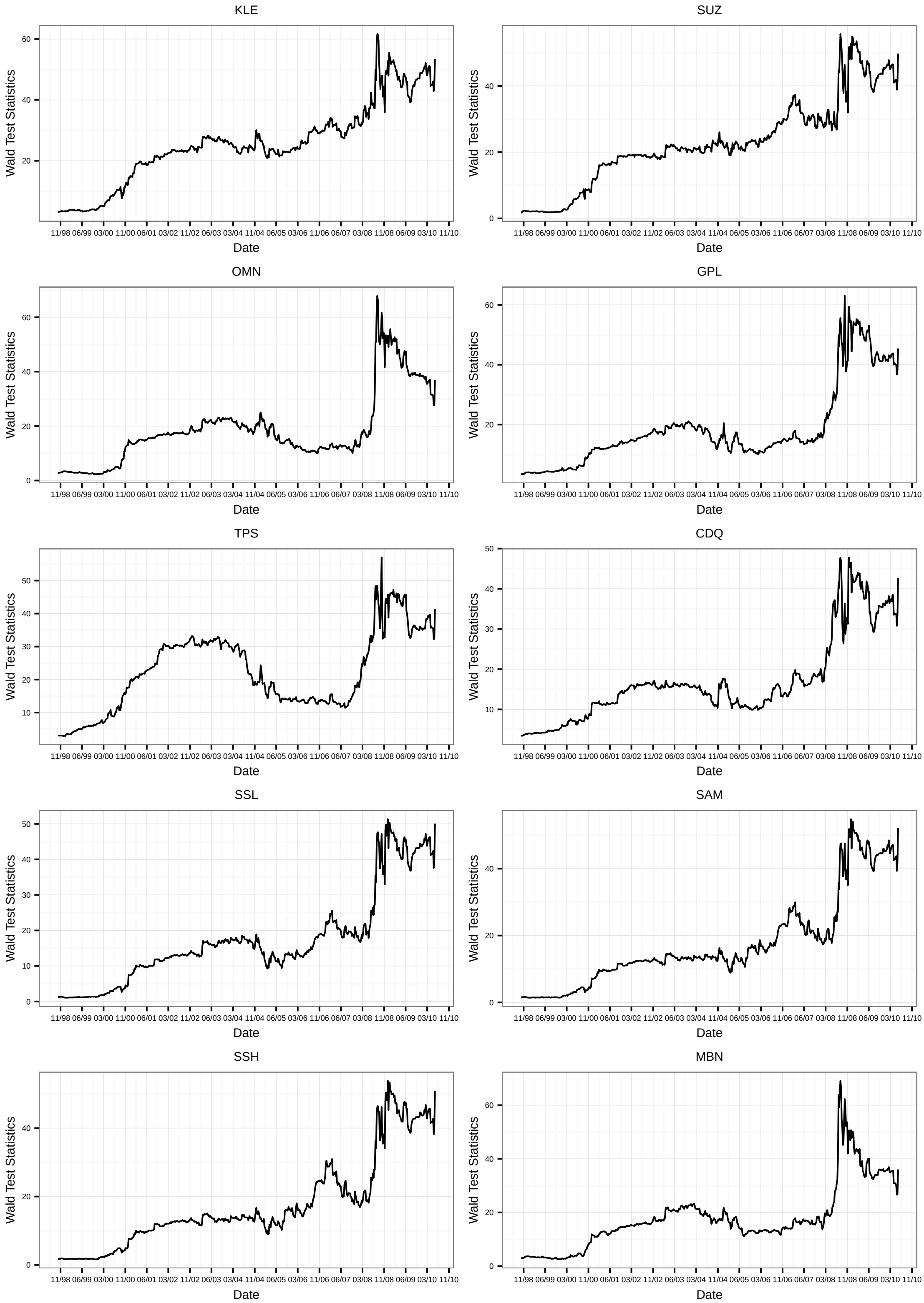


FIGURE 3.1 (cont.): Dynamic Wald test statistics of Russian Urals' coefficients (Cont.)

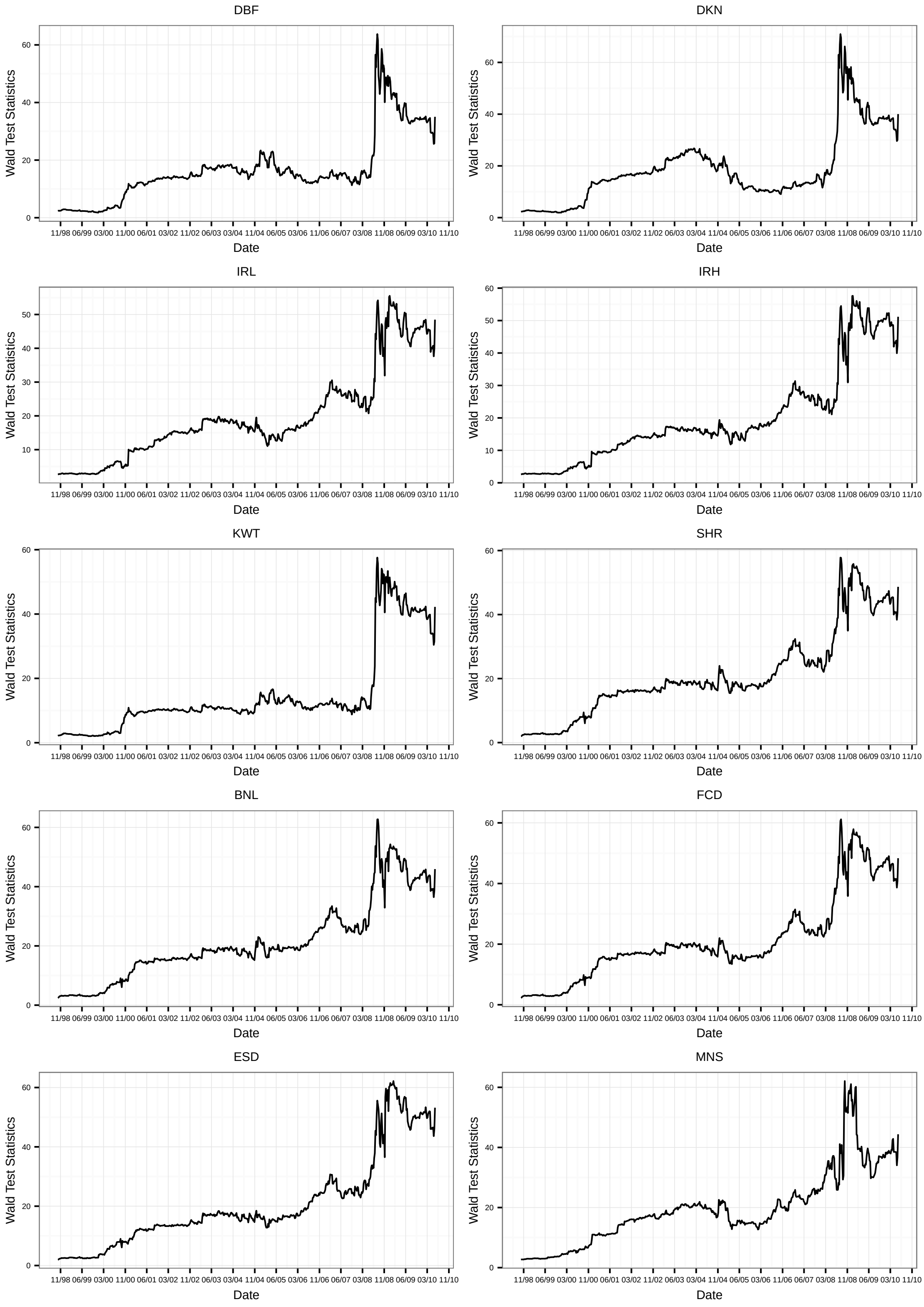
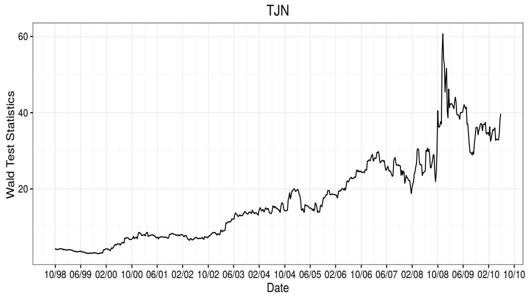


FIGURE 3.1 (cont.): Dynamic Wald test statistics of Russian Urals' coefficients (Cont.)



Notes: These figures plots the observation-level Wald test statistics for the coefficients of Russian Urals (x_{16} in the equation). The maximum value of Wald test statistics corresponds to the structural break point indicated by the test. The horizontal scale is in the format of "mm/yy", and the interval is eight months.

3.7 Conclusion

This paper investigated the impact of structural breaks on the crude oil prices and price dependency relationships by incorporating structural breaks in traditional time series models. The unit root tests with structural breaks identify two structural breaks in both the abrupt change (AO) model and the gradually shift (IO) model. Through the analysis of the corresponding market situation, breaks detected by the former model (i.e. the AO model) relate to breaking-out events such as geo-political issues, while the breaks in the latter model are more closely related to market fundamentals. Moreover, the time series properties of crudes do not change if structural breaks are considered: the crude price series are always I(1).

Cointegration tests with structural breaks confirm the existence of long-run relationships among crudes with the presence of structural breaks. Moreover, the detected break dates coincide with identifiable events. WTI's dislocation problem in 2011 lead to a break in its long-run relationship with crudes of same quality or from the same region. This break is remarkable because it shifts the level, trend and regime of the long-run relationships.

In contrast, the Asian financial crisis only induced a shift in the level in the long-run relationships among crudes in Asia. The Libyan crisis in 2011 is also reflected in the test, although it does not show a great influence.

Granger causality tests with structural breaks are based on the break points detected by supreme Wald tests. Empirical results show that the 2008 global financial crisis destroyed the stability of coefficients in the equation of the Granger causality tests, making the findings of Wlazlowski et al. (2011), that Russian Urals could serve as potential benchmark invalid over a longer time period.

This analysis illustrates the importance of structural breaks in time series modeling. Generally speaking, if a break occurs in the population regression function during the sample, then the OLS regression estimates over the full sample will estimate a relationship that holds "on average", in the sense that the estimate combines the two different periods. Depending on the location and the size of the break, the "average" regression function can be quite different from the true regression function at the end of the sample, and this leads to a poor estimation and poor forecasts. Therefore, in practice, it is critical to consider structural breaks and their influence on the conclusion.

Chapter 4

Spillover effects of return and volatility

4.1 Introduction

Return links and volatility spillovers across capital markets are now of greater interest to the financial community due to the increasing trend of globalization. Spillover, if broadly defined, is changes in one financial market in response to changes in factors in other markets, regardless of whether these are during a crisis or tranquil period. They reflect co-movement within the market. Spillover effects are transmissions due to links between markets, and they have important implications for market participants and policy makers. For example, if return and volatility are found to spread from one market to another, portfolio managers and policy makers in the latter market should adjust their actions to prevent contagion risks during crisis periods in the former market. This issue has been investigated extensively in various asset markets, especially during and after the recent 2008 financial crisis. Such examples include, but not limited to, K. J. Forbes and Rigobon (2002) and Syriopoulos (2007) for stock markets, Barassi, Caporale, and Hall (2005) and Wang, Yang, and Li (2007) for monetary markets, and Skintzi and Refenes (2006) and Johansson (2008) for bond markets. Generally these studies find evidence of significant return and volatility spillovers across markets, and argue that the degree of spillover is highly dependent on economic and financial integration, as well as on the coordination of monetary policy.

However, little work has been done on spot crude oil markets. Moreover, the majority of the current studies on crude oil markets have focused on crudes which have been viewed as markets are limited because they have focused on crudes which have been viewed as benchmarks, because these crudes are thought to reflect the bigger picture of crude oil markets as a whole. Unfortunately these studies have ignored the reality that the range of traded crudes has expanded rapidly over recent years; the 2010 edition of the international crude oil handbook describes over 200 types of crude oil, a 25% in crease from the 160 types of crudes recorded in the 2006 edition. Hamilton (2014) points out that the main growth in oil supply since 2005 has come from lower-quality hydrocarbons, not the high-quality benchmarks. Academia has also noticed this problem and has found evidence that the traditional benchmarks cannot now reflect the true picture of crude oil markets, for example, see Wlazlowski et al. (2011),Jin, Lin, and Tamvakis (2012) and Ghoshray and Trifonova (2014).

To understand how return and volatility are transmitted between markets is very important in crude oil markets. In physical oil markets, agents often have exposure to a number of different grades of crude oil, which may be priced based on one or more of the traditional benchmarks; in paper oil markets, agents frequently build portfolios which include some or all of the benchmarks. More generally, an understanding of volatility and the channel in which it is transmitted is important for determining the cost of capital, for assessing investment and leverage decisions, and for computing the optimal hedge ratio and portfolio weights. Substantial changes in volatility in crude oil markets may have significant negative effects on risk-adverse investors (Jin et al., 2012).

The importance of the spillover, combined with the lack of previous attention to the issue of spot oil markets motivate this study, which seeks to answer the following research questions:

1. What are the spillover effects in the spot crude oil markets as more low-quality crudes are joining the markets? Specifically, is the spot crude oil market more or less integrated with the increasing importance of low-quality crudes?
2. Do benchmark crudes have stronger spillover effects than non-benchmark crudes?
3. Are there any difference between return and volatility spillover patterns?
4. Does the spillover effect behave different in tranquil and crisis periods?
5. What is the trans-group spillover effect? For example, do the return or volatility of crudes in OPEC countries spill over to non OPEC countries, or vice versa? What if the crudes are grouped by qualities, or by geographic regions?

By examining 32 crude varieties with both benchmark and non-benchmark crudes, this research aims to provide a complete and dynamic picture of the spillover effects in spot crude oil markets.

To this end, I use a recently developed methodology, introduced by Diebold and Yilmaz (2009b) to construct spillover measures. This methodology circumvents the difficulty of GARCH-class model at dealing with high dimension variables[1], and has the benefits of

[1]There is no clear definition of high dimension time series. In the context of multivariate GARCH model, data with a few dozen dimensions could be viewed as high dimension, which beyond the analysis capacity of multivariate GARCH model..

aggregating spillover effects across markets, distilling information into several measures and allowing for dynamic analysis. It has been demonstrated to be successful in describing the cycle and patterns of total spillover effects in various financial markets. B. Zhang and Wang (2014) apply it to the crude oil market, but their work only included WTI, Brent and China Daqing. My analysis aims to give a comprehensive analysis about crude oil market by including more crude varieties.

This study contributes to the literature in the following ways. First, this research provides a comprehensive analysis about the return and volatility spillover in the spot crude oil market, with a dataset including crudes of various qualities, geographic sources and institutional arrangements. Hence this research will provide new evidence about the integrated nature of the crude oil market. Second, the methodology employed allows analysis from both static and dynamic perspectives, therefore the time-varying characteristics of spillover can be described. Moreover, the spillover effect from different levels are discussed, including the systematic, individual, pairwise and group levels. As far as the author is aware, this is the only study to have such a comprehensive analysis.

In summary, this chapter gives a comprehensive and dynamic analysis of return and volatility spillover effects in the spot crude oil market. With a sample of 32 crude varieties, this analysis provides evidence to support the benchmark role of WTI and Brent in terms of transmitting return and volatility shocks. The dynamic analysis further shows that their transmitting patterns are different and time-varying. Specifically, Brent is found to be more influential with respect to return, while WTI is more influential with respect to volatility, especially since 2007.

The remainder of this chapter is structured as follows: Section 2 provides a review of the relevant studies of spillover effects in crude oil markets and the development of the methodology to do this. Section 3 describes the empirical methodology used to measure the return and volatility spillover effects in spot crude oil markets. Section 4 presents the data and static analysis over the whole sample period. In Section 5 a dynamic analysis is applied and the empirical results are discussed and explained. Section 6 presents a series of robustness tests, including changing the parameters of the model and applying various return and volatility measures. Section 7 concludes.

4.2 Literature Review

There are relatively few studies on the relationship between the oil price volatilities across spot oil markets. The existing literature mainly focuses on transmission, among spots, forward and futures of the same underlying asset, or between major markets in different locations. Lin and Tamvakis (2001) studied the volatility spillover effects between New York Mercantile Exchange (NYMEX) and the International Pertroleum Exchange (IPE) crude oil contracts in both non-overlapping and simultaneous trading hours. They found significant spillover effects when both markets were open, and that the closing price of the previous day on the NYMEX seemed to affect opening price of the IPE. Their later paper Lin and Tamvakis (2004) applied an autoregressive conditional duration (ACD) model to examine the information spillover between Brent and WTI futures, and found that the NYMEX had a dominant effect on Brent futures. Feng-bin et al. (2008) analyzed information spillover between the WTI, Brent, Dubai, Tapis and Minas crudes. They use tests developed by Hong Hong (2001) and found that WTI and Brent were dominant, and that WTI futures had a slight edge over those of Brent. The tests developed by Hong (2001) were also applied by Fan et al. (2008) to study spillover in value-at-risk between WTI and Brent, and two-way risk spillover effects were found.

Chang, McAleer, and Tansuchat (2009) studied the conditional correlations of spot, forward and futures returns of three major benchmarks of the international crude oil markets (i.e. Brent, WTT and Dubai). They found evidence of ARCH and GARCH effects for returns and showed the presence of significant interdependences in the conditional volatilities across returns for each market. In subsequent research (Chang, McAleer, & Tansuchat, 2010) they studied the volatility spillover effect across spot, forward and futures prices in four international oil markets: Brent (North Sea), WTI (USA), Dubai/Oman (Middle East) and Tapis (Asia-Pacific), for the period of the 30$^{\text{th}}$ April 1997 to 10$^{\text{th}}$ November 2008. With the application of a variety of bivariate GARCH-type models, they found evidence of volatility spillovers from Brent futures returns to Brent spot and forward returns, from Brent spot returns to WTI spot returns, and from WTI futures returns to Brent spot returns. However, they do not find spillover from WTI futures to WTI spot. Moreover, the estimation results show that most of the Dubai and Tapis returns had volatility spillover effects from the WTI spot and vice versa. Generally speaking, their empirical work confirms the "marker" crude position of Brent and WTI which set crude oil prices and influence other crude oil markets.

However, the empirical result of Chang et al. (2010) are somewhat different to the work of Kaufmann and Ullman (2009) within the context of price discovery. Kaufmann and Ullman (2009) investigated where changes in the price of crude oil originate and how they spread by examining causal relationships among prices for crude oils from North America (WTI), Europe (Brent), and Africa and the Middle East (Dubai) on both spot and futures markets. Their empirical results indicate that innovations first appear in spot price for Dubai-Fateh and spread to other spot and futures prices. Essentially they argue that the primary spot market is the Dubai and the importance of Dubai-Fateh price stems from both demand (from developing Asian nations, including China and

India) as well as supply (due to a shift towards more production by OPEC nations).

Another study by Jin et al. (2012) investigated the volatility transmission of WTI, Dubai and Brent futures markets, mainly focusing on volatility impulse response functions for two historical shocks, namely the 2008 financial crisis and the BP Deepwater Horizon oil spill. They found that Brent and Dubai crude were highly responsive to market shocks, whereas WTI crude showed the least responsiveness of the three benchmarks used, which raises questions about its predominance as a benchmark crude oil. Lu et al. (2014) investigated time-varying information spillover effects on the daily WTI and Brent futures prices and Dubai and Tapis crude spot prices with a Granger-causality framework. In particular, they studied the impact of significant events on the causal effects. Such events included the Iraq War in March 2003, OPEC's announcement of a record oil production cut in December 2008, and the Libyan civil war in early 2011. They found the causal effects of Dubai and Tapis crudes on Brent and WTI become stronger when such events occurred in major oil-producing countries, although in normal time Dubai and Tapis crudes play subordinate roles. They concluded that the time-varying causal relationships between global markets indicated that the roles played by crude benchmarks may change over time, so oil pricing mechanisms should be adjusted gradually.

B. Zhang and Wang (2014) examined the return and volatility spillovers between China and the world oil market. But they only used WTI and Brent to represent the world oil market. Their focus was the dynamic role of China Daqing. It was found that return and volatility spillovers between China and world oil markets are bi-directional and asymmetric.

From above studies it can be seen that there has been limited research into the return and volatility spillover effects on spot crude oil markets. The existing literature focuses on only a few crudes and has not reached a consensus about the role of benchmark crudes. It also leaves the following questions unanswered: What would the spillover effects be if more crudes were included? Will the benchmark crudes have stronger spillover effects than other crudes? Is there any difference between return and volatility spillover? Are the spillover effects different between crisis and tranquil periods? This research aims to answer these questions by studying 32 crude varieties and providing a complete and dynamic picture of the spillover effect in spot crude oil markets.

Additionally, because spillover effects are transmissions due to links between markets, this research will also provide evidence relating to the famous “One great pool” hypothesis, which is stated succinctly by Adelman (1984), that “The world oil market, like the world ocean, is one great pool”. However policy makers have often implicitly held the opposite assumption - that the world market is fragmented - as evidenced by the efforts of many importing-country government to seek special arrangement for “secure supply” from exporters. Likewise, oil exporters have sought “secure outlets” for their crudes. If the world crude oil market is integrated, such arrangement makes no sense. In addition, a policy of diversifying suppliers by importers, is senseless in a globally unified market.

Weiner (1991) first challenged the ‘one great pool’ hypothesis by conducting an empirical examination using two approaches; correlation analysis, which evaluates the relationship between the changes in the landed prices for crude oil, and an arbitrage model to evaluate the same data. The results from both analyses indicated a high degree of market regionalisation, implying that the world oil market was far from being unified in the period studied (1980-1987). Following his approach, a number of studies have attempted to re-examine the hypothesis with different datasets and more advanced time-series econometric techniques. Such examples include, but not limited to Sauer (1994), R. D. Ripple and Wilamoski (1995), Gülen (1999), R. Ripple (2001), Bentzen (2007), Li and Leung (2011), Ji and Fan (2014) and Giulietti et al. (2014). Most of this literature supports the integration hypothesis. My analysis will provide evidence from the perspective of d ynamic spillover effects.

Regarding methodologies, the most commonly used method in the analysis of spillover effects is multivariate GARCH-class models, which suffers from dimensionality. For a N-dimensional times series, the volatility matrix consists of N conditional variance and $N(N-1)/2$ conditional covariances. In our case, $N = 32$, therefore the volatility matrix contains 528 elements, making it impossible to analyze under GARCH-class models. I then refer to the methodology developed by Diebold and Yilmaz (2009b). They constructed spillover measures by forecast error variance decomposition, and illustrated this method's wide and flexible applicability to various markets in a series of papers (see Diebold & Yilmaz, 2009a, 2012, 2013 and 2014). The major advantages of this methodology is that it is not restricted by the number of dimensions and that it allows the clear decomposition of total shocks to a given market into domestic market generated and spillover components across markets. Combined with the rolling window technique, it enables researchers to study spillovers in both crisis and non-crisis periods.

Some researchers have followed this methodology. McMillan and Speight (2010) applied it to analyze return and volatility spillovers in different exchange rates, arguing that this method can give hints as regards market interdependence, financial integration and the potential for contagion effects. They found that euro-dollar exchange rate dominates other euro exchange rates in terms of return and volatility spillovers. Bubák et al. (2011) used this approach to study the dynamics of volatility spillovers between quotes of some non-euro currencies and EUR/USD quotes. They found specific volatility transmission patterns for each currency, and interpreted differences in pre- and post-crisis patterns as increased short-term interrelationships indicating “a generally faster reaction of the market to volatility dynamics”. Fujiwara and Takahashi (2012) also used this method to assess the interlinkages between Asian financial markets and their links to other developed markets. They found some regularity in international spillover dynamics and stressed the importance of US and China as main drivers of market fluctuations.

In sumary, this paper will study the return and volatility spillover effects on spot crude oil markets. It will use a large dataset of 32 crudes, apply a methodology that circumvents the problems of dimensionality suffered by the GARCH-class model, and thus provide an dynamic overall picture of the spillover effect on the spot crude oil market.

4.3 Methodology

The methodology of Diebold and Yilmaz (2012) was designed to measure spillover effects through the explanatory power which specific moves in financial markets may have with regard to the uncertainty associated with unexpected similar moves in other markets. The key word is uncertainty, because the method focus on how much of the forecasting error variance can be explained. The model used to complete forecasting is basically a vector autoregressive (VAR) model. Consider the N-variables VAR(p) model:

$$Y_t = \Phi_1 \mathbf{Y}_{t-1} + ... + \Phi_p \mathbf{Y}_{t-p} + \varepsilon_t \tag{4.1}$$

where $\mathbf{Y}_t$ represents time series on financial market real returns or volatility, ε represents an N-dimension white noise and $\Phi_1, \Phi 2, ...\Phi_t$ being coefficient matrices. This VAR can be expressed in MA representation

$$Y_t = \varepsilon_t + \mathbf{A}_1\varepsilon_{t-1} + \mathbf{A}_2\varepsilon_{t-2} + ... \tag{4.2}$$

Denote Σ_ε as the co-variance matrix of ε, we get:

$$\Sigma_Y = \Sigma_\varepsilon + \mathbf{A}_1\Sigma_\varepsilon\mathbf{A}_1^{'} + \mathbf{A}_2\Sigma_\varepsilon\mathbf{A}_2^{'} + \dots \tag{4.3}$$

In order to define spillover measures, we are interested in the H-step-ahead forecast at time t, $P(\mathbf{Y}_{t+H} \mid \mathbf{Y}_t, \mathbf{Y}_{t-1}, \dots)$, i.e. at time t, based on the current and past values of Y, a forecast of Y in H periods is given. The corresponding forecast error is

$$\begin{aligned}
&\mathbf{e}_{t+H,t} = \mathbf{Y}_{t+H} - P(\mathbf{Y}_{t+H} \mid \mathbf{Y}_t, \mathbf{Y}_{t-1}, \dots) \\
&= \mathbf{Y}_{t+H} - P(\varepsilon_{t+H} + \mathbf{A}_t\varepsilon_{t+H-1} + \mathbf{A}_2\varepsilon_{t+H-2} + \dots \mid \mathbf{Y}_t, \mathbf{Y}_{t-1}, \dots) \\
&= \mathbf{Y}_{t+H} - (\mathbf{A}_H\varepsilon_t + \mathbf{A}_{H+1}\varepsilon_{t-1} + \mathbf{A}_{H+2}\varepsilon_{t-2} + \dots) \\
&= \varepsilon_{t+H} + \mathbf{A}_t\varepsilon_{t+H-1} + \mathbf{A}_2\varepsilon_{t+H-2} + \dots + \mathbf{A}_{H-1}\varepsilon_{t+1}
\end{aligned}$$

The forecast error's covariance matrix hence is

$$\Sigma_{e,H} = \Sigma_\varepsilon + \mathbf{A}_1\Sigma_\varepsilon\mathbf{A}_1^{'} + \dots + \mathbf{A}_{H-1}\Sigma_\varepsilon\mathbf{A}_{H-1}^{'} = \sum_{h=0}^{H-1} \mathbf{A}_h\Sigma_\varepsilon\mathbf{A}_h^{'} \tag{4.4}$$

The forecast error variance is the diagonal elements of $\Sigma_{e,H}$. To decompose it, Diebold and Yilmaz (2009b) use the lower-triangular Cholesky factor $\mathbf{L}$ of Σ_ε, i.e. the lower triangular matrix $\mathbf{L}$ with $\mathbf{L}\mathbf{L}^{'} = \Sigma_\varepsilon$. The idea is that, every h, $\mathbf{A}_h\Sigma_\varepsilon\mathbf{A}_h^{'}$ can be written as $(\mathbf{A}_h\mathbf{L})(\mathbf{A}_h\mathbf{L})'$, from which we find the i-th diagonal element $(\mathbf{A}_h\Sigma_\varepsilon\mathbf{A}_h')_{ii}$ to equal $\sum_{j=1}^{N}(\mathbf{A}_h\mathbf{L})_{ij}^2$. Consequently the spillover from variable j to variable i is defined as

$$sot_{ij} = 100 \times \frac{\sum_{h=0}^{H-1}(\mathbf{A}_h\mathbf{L})_{ij}^2}{\sum_{h=0}^{H-1}(\mathbf{A}_h\Sigma_\varepsilon\mathbf{A}_h')_{tt}} \tag{4.5}$$

The values of sot_{ij} with i, j from 1 to N form a matrix SOT, which is called a spillover table. It can tell how much forecast error variance could be explained by spillover from other markets.

Excluding own variance shares, i.e. spillovers from any variable to itself, Diebold and Yilmaz (2009b) condense the information of a spillover table into a single number called the total spillover index, which is defined as

$$SOI = 100 \times \frac{\sum_{i=1}^{N}\sum_{j\neq i}\sum_{h=0}^{H-1}(\mathbf{A}_h\mathbf{L})_{ij}^2}{\sum_{i=1}^{N}\sum_{h=0}^{H-1}(\mathbf{A}_h\Sigma_\varepsilon\mathbf{A}_{h=0}')_{ii}} = 100 \times (1 - \frac{tr(\sum_{h=0}^{H-1}(\mathbf{A}_h\mathbf{L})^{\boxed{2}})}{tr(\sum_{h=0}^{H-1}\mathbf{A}_h\Sigma_\varepsilon\mathbf{A}_h')}) \tag{4.6}$$

with the operator $()^{\boxed{2}}$ which squares a matrix elementwise.

This forecast error variance decomposition relies on the Cholesky-factor identification of VARs, therefore the resulting decompositions are dependent on the variable ordering. The variables entering the model at an early stage have a higher probability of (possibly wrongly) being chosen as the origin of spillovers, i.e. they tend to have larger spillover effects. Diebold and Yilmaz (2012) introduce a generalized VAR framework developed by Koop, Pesaran, and Potter (1996) and H. H. Pesaran and Shin (1998) to circumvent this limitation. Unlike Cholesky factorization which orthogonalizes shocks, the generalized VAR approach allows correlated shocks but accounts for them appropriately using the historically observed distribution of errors. Although Diebold and Yilmaz (2012) claim this approach is order-invariant, Klößner and Wagner (2012) and Klößner and Wagner (2014) point out that the generalized approach tends to overestimate the spillover index, both theoretically and empirically. A better approach is to explore all VAR orderings, or at least calculate over considerably large number of randomly created ordering permutations. In later sections I will give evidence of different results under various orderings, and base my analysis on the average values of the spillover table over permutations.

4.4 Static analysis

The spillover of return and volatility of 32 crude oil varieties was studied.[2] The daily FOB spot prices (measured in US dollar per barrel) was collected from Thomas Reuters Datastream. The sample began in January 1997 and ended in November 2011, due to the data availability. Weekly return series were calculated as the change in log price. [3]

Volatility is latent and hence must be estimated. This was done by following the measure developed by Diebold and Yilmaz (2009b) which was adopted following Garman and Klass (1980). This assumes that volatility is fixed within periods (in this case, weeks), but variable across periods. Weekly crude oil return volatility is estimated using weekly high, low, opening and closing prices.

[2]The varieties are: West Texas Intermediate (WTI) OK Cushing, Europe (UK) Brent Blend, Europe (Ekofisk, Norway) Blend, Canadian Par, Canada Lloyd Blend, Mexico Isthmus, Mexico Maya, Colombia Caño Limon, Ecuador Oriente, Angola Cabinda, Cameroon Kole, Egypt Suez Blend,Oman Blend, Australia Gippsland,Malaysia Tapis Blend, Mediterranean (Russia, Urals), China Daqing, Saudi Arabia Light, Saudi Arabia Medium, Saudi Arabia Heavy, Abu Dhabi Murban, Asia Dubai Fateh, Qatar Dukhan, Mediterranean Sidi Kerir Iran Light, Mediterranean Sidi Kerir Iran Heavy, Kuwait Blend, Algeria Saharan Blend, Nigeria Bonny Light, Europe (Forcados, Nigeria), Libya Es Sider, Indonesia Minas and Venezuela Tia Juana. Data on Canadian Lloyd Blend were discontinued in June 2007 so I augmented the series with Canada's Heavy Hardisty which has the same API as Lloyd Blend. Table A.1 provides the details of each crude oil series.

[3]I select Wednesday price to avoid weekend effect. The robustness of this choice is checked in Section 6.

$$\sigma^2 = 0.511(H_t - L_t)^2 - 0.019[(C_t - O_t)(H_t + L_t - 2O_t) - 2(H_t - O_t)(L_t - O_t)] - 0.383(C_t - O_t)^2 \tag{4.7}$$

Where H is the Monday-Friday high, L is the Monday-Friday low, O is the Monday open and C is the Friday close (all in natural logarithms).[4] This range-based[5] measure of volatility has the benefit of using all readily available information which may contribute to estimator efficiency, such as opening price, high price and low price. Intuitively high/low price would contain more information regarding volatility than open/close price, and Parkinson (1976) has verified it. Alizadeh, Brandt, and Diebold (2002) have further shown that "range-based volatility proxies are not only highly efficient, but also approximately Gaussian and robust to microstructure noise." The robustness of empirical result based on GARCH estimator of the conditional variance will be examined in Part 6. Table A.5 shows the descriptive statistics on Wednesday return and volatility. Figure B.1 and Figure B.2 plot the time series of Wednesday return and volatility, providing a much more detailed insight into the pattern over time. Both return and volatility are highly volatile in early 2009, corresponding to the timing of global financial crisis.

To determine the optimal lag length of VAR, four information criteria were applied with a maximal lag length of eight[6]. For Wednesday return series, HQ and SC gave the optimal lag number $p = 1$, whereas AIC criterion indicates $p = 8$ and FPE indicates an optimal lag length of $p = 4$. For volatility series, again HQ and SC give the optimal lag

[4]Refer to Garman and Klass (1980) for detailed derivation.

[5]The range is defined as the difference between highest and lowest log prices over a fixed sampling interval (week in this case).

[6]This maximal lag length is enough as we have 32 variables. Degree of freedom losses very fast as the lag increases. No constant or trend is included because return and volatility series have no tendency and fluctuate around zero.

number $p = 1$ while the other two criteria indicates $p = 8$. Because each VAR equation has 32 variables, one more lag results in 32 more parameters to estimate, decreasing model's degree of freedom. Therefore less lag is preferred. VAR(1) is chosen for both return and volatility series.

To make Cholesky decomposition, Forecast horizon is a parameter which needs to be decided before estimation. Intuitively shocks to j may impact the forecast error variance of i with a lag, so the spillover may be small for small forecast horizons but large for larger horizons. In this paper a horizon of $H = 16$ was used, i.e. 4 months, but a range of nearby values will be examined to provide a "robustness check" in Section 6.

Table 4.1 and Table 4.2 present the spillover table for weekly return and volatility respectively. The upper-left block of the table is the variance decomposition matrix. The ij entry in this matrix (i.e. the element with row number i and column number$j$) is the estimated contribution to the forecast error variance of crude i coming from innovations to crude j. Specifically, it measures the percent of 16-week-ahead forecast error variance of crude i due to shocks from crude j. It is then labelled as "pairwise directional spillover index". The rightmost column is the sum of the row, excluding the diagonal number. The i^{th} element of this off-diagonal row sums represents the share of the H-step forecast error variance of variable i coming from shocks arising in all other variables. It is named spillover from all the other crudes to crude i for short, and is labeled as "From" in the table.

Similarly the bottom row labeled "To" is the column sums excluding the figure on the diagonal, whose j^{th} element represents the spillover transmitted to all the other variables by variable j. The "Net" row is equal to spillovers transmitted to other crudes less spillover received from other crudes in aggregate, reflecting the net effect of spillover.

TABLE 4.1: Average spillover table SOT_{avg} for weekly return

	WTI	BRT	EFK	CPR	LYD	IMS	MYA	CLM	ORT	CBD	KLE	SUZ	OMN	GPL	TPS	URL	CDQ	SSL	SAM	SSH	MBN	DBF	DKN	IRL	IRH	KWT	SHR	BNL	FCD	ESD	MNS	TJN	From
WTI	14.85	4.99	2.73	2.36	2.19	5.78	3.49	4.21	3.59	2.48	2.31	2.81	2.69	1.79	0.96	3.35	2.09	2.32	2.39	2.33	2.08	2.00	2.20	2.19	2.33	2.68	2.49	2.28	3.69	2.91	2.12	3.31	85.15
BRT	4.26	14.30	3.69	1.74	1.62	3.00	2.79	2.28	1.98	3.41	3.36	3.74	3.05	1.82	0.95	6.14	1.67	2.38	2.39	2.27	2.44	2.27	2.38	2.49	2.66	2.38	3.68	3.19	4.24	3.75	1.54	2.16	85.70
EFK	3.36	10.76	5.87	1.49	1.60	2.65	2.41	2.09	1.83	3.86	3.85	4.16	3.09	1.78	0.86	6.85	1.57	2.34	2.39	2.37	2.45	2.28	2.43	2.39	2.54	2.32	4.27	3.65	5.08	4.18	1.32	1.87	94.13
CPR	3.98	4.79	1.91	31.58	4.28	2.65	2.15	1.93	1.54	1.92	1.76	2.27	2.85	1.44	0.87	3.69	1.60	1.60	1.69	1.61	1.73	1.75	2.18	1.63	1.82	2.28	2.00	1.72	2.37	2.37	2.34	1.68	68.42
LYD	3.90	4.09	1.66	6.29	40.10	2.40	3.42	1.75	1.80	1.41	1.57	1.68	1.75	1.10	0.57	3.73	0.98	1.39	1.65	1.50	1.23	1.31	1.41	1.28	1.45	2.33	1.42	1.50	1.56	1.51	0.89	1.36	59.90
IMS	5.44	6.75	3.16	1.86	2.02	7.48	3.66	3.76	3.29	2.89	2.82	3.25	2.81	2.03	1.03	5.28	2.07	2.37	2.53	2.50	2.34	2.20	2.37	2.33	2.50	2.99	3.05	2.79	4.09	3.38	1.77	3.20	92.52
MYA	4.29	6.80	2.49	1.64	2.23	4.36	16.83	3.09	2.70	2.58	2.59	2.84	2.59	2.03	1.19	4.49	1.89	2.13	2.30	2.28	2.15	1.97	2.16	2.18	2.35	2.38	2.61	2.44	3.55	2.81	1.58	2.48	83.17
CLM	5.91	5.56	2.73	1.71	2.05	4.86	3.84	12.20	4.49	2.42	2.35	2.82	2.40	1.94	0.91	5.57	2.07	2.23	2.28	2.24	2.08	2.00	2.08	2.16	2.27	2.47	2.58	2.37	3.71	2.88	2.04	2.80	87.80
ORT	5.52	4.94	2.54	1.49	1.63	4.83	3.47	5.24	16.13	2.32	2.12	3.07	2.44	1.87	0.95	4.37	2.07	2.10	2.17	2.09	2.01	2.04	2.10	2.12	2.28	2.47	2.51	2.45	3.37	2.54	1.90	2.86	83.87
CBD	3.34	10.46	3.96	1.60	1.69	2.72	2.65	2.10	1.87	5.13	3.77	4.10	3.02	1.83	0.99	6.27	1.71	2.36	2.45	2.43	2.51	2.37	2.58	2.49	2.67	2.61	4.01	3.49	5.14	4.40	1.32	1.96	94.87
KLE	3.08	10.55	4.30	1.55	1.54	2.64	2.59	1.98	1.78	4.02	8.35	4.00	3.45	1.76	0.97	5.63	1.59	2.21	2.28	2.23	2.43	2.31	2.66	2.33	2.49	2.41	3.99	3.43	4.60	3.75	1.19	1.91	91.65
SUZ	3.23	9.73	3.93	1.60	1.56	2.67	2.53	2.11	1.81	3.50	3.40	7.06	3.16	1.77	0.90	7.33	1.62	2.41	2.49	2.49	2.70	2.36	2.51	2.40	2.56	2.45	3.86	3.48	4.75	4.38	1.37	1.85	92.94
OMN	3.68	8.58	2.71	1.72	1.71	2.47	2.45	2.33	1.96	2.55	2.59	2.91	6.65	2.38	1.14	4.07	2.13	2.82	2.88	2.93	4.04	4.13	5.11	2.97	3.10	4.57	2.84	2.36	4.01	2.85	1.60	1.76	93.35
GPL	4.30	8.72	2.43	1.43	1.87	2.64	3.00	2.63	1.91	2.42	2.20	3.01	3.19	13.54	1.53	3.58	3.71	2.33	2.42	2.38	2.28	2.38	2.72	2.35	2.46	2.93	2.48	2.36	3.89	2.75	2.24	1.93	86.46
TPS	2.57	4.04	1.25	1.26	0.56	1.59	1.33	1.17	1.75	1.61	1.03	2.73	1.84	2.64	50.33	1.10	1.73	1.47	1.45	1.34	1.13	1.24	1.52	1.86	1.66	1.19	1.11	1.01	2.73	1.21	0.97	1.58	49.67
URL	2.82	8.20	3.18	2.02	2.10	2.31	2.28	1.68	1.69	2.68	2.67	3.27	2.66	1.35	0.90	27.81	1.20	1.73	1.74	1.63	2.08	1.87	1.98	1.86	2.06	2.13	3.08	2.61	2.99	2.82	1.00	1.63	72.19
CDQ	3.30	7.69	2.37	1.46	1.74	2.48	2.80	2.85	1.92	2.41	2.05	2.48	3.08	4.16	1.53	3.34	14.42	2.26	2.26	2.16	2.15	2.25	2.55	2.28	2.33	2.69	2.25	2.25	3.38	2.59	6.70	1.83	85.58
SSL	3.61	8.82	3.02	1.45	1.59	2.55	2.39	2.23	1.91	2.79	2.75	3.12	3.58	2.30	1.15	3.42	2.12	5.47	5.15	4.80	2.97	2.81	3.10	3.12	3.22	3.53	2.96	2.59	4.22	3.53	1.84	1.89	94.53
SAM	3.66	8.61	2.99	1.41	1.63	2.57	2.37	2.22	1.95	2.79	2.74	3.11	3.53	2.29	1.13	3.38	2.10	4.90	5.57	5.45	2.91	2.77	3.01	3.12	3.24	3.51	2.91	2.58	4.23	3.65	1.81	1.90	94.43
SSH	3.58	8.28	2.95	1.39	1.63	2.55	2.42	2.18	1.97	2.75	2.74	3.09	3.50	2.29	1.12	3.27	2.08	4.80	5.79	6.16	2.88	2.76	2.99	3.11	3.25	3.51	2.86	2.55	4.15	3.72	1.81	1.88	93.84
MBN	3.72	8.74	2.68	1.48	1.73	2.38	2.46	2.17	1.81	2.56	2.51	2.89	4.76	2.22	1.04	4.47	1.97	2.81	2.96	3.10	6.16	5.11	4.30	2.89	3.07	4.62	2.88	2.34	4.03	2.96	1.50	1.71	93.84
DBF	3.68	8.74	2.73	1.56	1.80	2.41	2.48	2.25	1.86	2.56	2.51	2.86	4.83	2.22	1.06	4.65	1.99	2.76	2.89	3.00	5.00	5.88	4.30	2.88	3.12	4.63	2.89	2.35	3.87	2.98	1.54	1.71	94.12
DKN	3.76	8.68	2.73	1.71	1.70	2.48	2.40	2.30	1.99	2.56	2.55	2.84	5.66	2.35	1.11	3.93	2.08	2.81	2.90	2.98	4.09	4.02	6.25	2.94	3.08	4.59	2.85	2.36	4.05	2.94	1.55	1.76	93.75
IRL	3.58	8.92	3.29	1.58	1.74	2.59	2.36	2.35	1.97	2.88	2.82	3.76	3.59	2.24	1.14	3.86	1.98	3.10	3.26	3.27	2.88	2.88	3.11	5.77	5.30	3.12	3.13	2.56	4.03	3.40	1.65	1.92	94.23
IRH	3.51	9.20	3.26	1.61	1.78	2.58	2.36	2.42	1.96	2.85	2.78	3.77	3.64	2.22	1.09	3.85	1.98	3.02	3.18	3.15	2.90	2.95	3.14	5.12	6.13	3.18	3.09	2.53	3.83	3.41	1.64	1.86	93.87
KWT	3.55	8.86	2.67	1.61	1.84	2.48	2.38	2.17	1.95	2.55	2.57	2.93	4.90	2.21	1.08	4.19	2.07	2.92	3.06	3.12	4.20	4.31	4.31	2.97	3.25	6.60	2.88	2.33	3.86	2.87	1.55	1.77	93.40
SHR	3.48	11.04	4.18	1.51	1.48	2.67	2.43	2.10	1.83	3.74	3.60	3.93	3.01	1.81	0.89	6.21	1.60	2.33	2.37	2.32	2.50	2.34	2.51	2.40	2.56	2.49	5.94	3.56	5.27	4.60	1.29	1.98	94.06
BNL	3.31	10.26	4.19	1.43	1.40	2.56	2.40	2.09	1.86	3.77	3.86	4.06	2.88	1.77	0.89	6.33	1.59	2.21	2.23	2.15	2.51	2.19	2.41	2.41	2.52	2.35	4.03	7.25	5.90	4.05	1.33	1.81	92.75
FCD	3.38	10.89	4.32	1.46	1.58	2.60	2.35	2.08	1.84	4.00	3.60	4.15	2.96	1.77	0.88	6.79	1.53	2.27	2.30	2.25	2.55	2.33	2.47	2.39	2.54	2.40	4.32	4.05	6.55	4.39	1.20	1.83	93.45
ESD	3.35	10.79	3.93	1.50	1.58	2.69	2.46	2.13	1.92	3.66	3.47	4.29	2.96	1.84	0.90	6.29	1.64	2.37	2.43	2.40	2.63	2.36	2.49	2.44	2.61	2.53	4.20	3.48	4.95	6.38	1.39	1.93	93.62
MNS	2.98	7.55	1.85	1.31	1.37	2.25	2.17	2.58	1.70	1.82	1.79	1.98	2.49	3.20	1.09	3.57	10.26	2.01	1.88	1.72	1.71	1.86	2.00	1.89	1.95	1.79	2.01	1.99	2.19	2.05	23.37	1.62	76.63
TJN	4.79	6.01	2.68	1.49	1.46	4.76	3.04	3.29	2.99	2.63	2.50	2.75	2.26	2.06	1.37	3.73	1.97	2.13	2.31	2.31	1.95	1.85	2.05	2.10	2.19	2.37	2.98	2.46	4.10	3.04	1.71	16.69	83.31
To	116.90	252.04	92.53	53.73	54.66	90.17	81.31	75.75	65.40	86.40	83.25	98.68	98.60	64.48	32.18	142.73	66.68	76.90	80.45	78.78	79.50	77.29	83.13	77.08	81.43	87.89	92.23	81.10	121.84	98.65	53.69	61.76	**SOI**
Net	31.75	166.34	-1.60	-14.68	-5.24	-2.35	-1.86	-12.06	-18.47	-8.46	-8.41	5.74	5.25	-21.98	-17.49	70.54	-18.90	-17.63	-13.98	-15.06	-14.34	-16.83	-10.62	-17.16	-12.44	-5.51	-1.83	-11.65	28.39	5.04	-22.93	-21.55	**87.10%**

Note: This table provides the spillover table with average entries for Wednesday returns. The sample covers January 1997 to November 2011. The predictive horizon is 16 weeks. The $ij-th$ entry of the upper 32×32 crude submatrix gives the $ij-th$ pairwise directional spillover, i.e. the percent of 16-week-ahead forecast error variance of crude i due to shocks from crude j. The rightmost "From" column gives total directional spillovers (from), i.e. row sums (from all others to i). The bottom "To" row gives total directional spillovers (to), i.e. column sums (to all others from j). The bottommost (Net) row gives the difference in total directional spillover (to-from). The bottom-right element (in bold) is the total spillover index, which is the mean of the "FROM" column, or the mean of the "TO" row. The crudes names are in abbreviation. Refer to Table A.1 for full names of crudes.

Therefore it is named "net directional spillover index". The bottom right number is the "Total Spillover Index" figure, which summarizes the degree to which shocks are attributable to spillovers for the entire sample expressed as a percentage. It is the sum of all the off-diagonal variance (i.e. the sum of "From" column) divided by the total row sum.

Before making a detailed analysis, we have to make sure that the spillover table is reliable. As mentioned above, the variance decomposition based on Cholesky-factor identification of VAR can depend on the variable ordering, which means the spillover table could change if the ordering of variables in the VAR varies. To see to what extent the ordering of variables could affect the spillover table, the minimal, maximal and average of spillover index over all permutations of the variables (denoted by SOI_{min}, SOI_{max} and SOI_{avg} respectively) as well as the variance decomposition matrix with minimal, maximal and average entries in the spillover tables (denoted by SOT_{min}, SOT_{max} and SOT_{avg}) were calculated[7]. For weekly returns, $SOI_{min} = 86.01\%$[8], $SOI_{max} = 87.99\%$ [9]and $SOI_{avg} = 87.11\%$. Similarly, for volatilities, the minimal spillover index $SOI_{min}$is 79.27%[10], the maximal spillover index SOI_{max} is 81.92% [11] and the average spillover

[7]The number of all possible orderings is 32!, which is roughly 10^{35} in our case. Although Klößner and Wagner (2012) provide a fast algorithms to calculate these qualities (19 variables in their model), the capacity of normal personal computer (computer with an Intel Core i5-2520 CPU @ 2.5 GHz) is not enough to calculate these numbers over all permutations. Therefore 10,000 randomly created permutations are used instead to estimate these qualities. When the calculations were repeated for different 10,000 randomly created permutations, the resulting spillover tables/Indexes did not change much. Thus the estimated spillover table/index is reliable to be used to draw conclusions. The minimal, maximal and average SOI corresponds to the minimal, maximal and average spillover index calculated from the 10,000 randomly created permutations.

[8]The corresponding ordering of the variables is (BRT, LYD, TJN, TPS, MBN, SHR, DBF, CPR, ESD, KLE, MNS, SSL, SSH, WTI, URL, IMS, MYA, GPL, ORT, SUZ, IRH, CDQ, BNL, FCD, CBD, DKN, EFK, IRL, SAM, CLM, OMN, KWT)

[9]The corresponding ordering of the variables is (OMN, CBD, IMS, DKN ,SHR, KWT, GPL, SSL, ESD, BNL ,ORT, EFK, CDQ, CLM, CPR, MYA, BRT, DBF, KLE, SAM, SUZ, MNS, TJN, LYD, URL, IRL, WTI, SSH, FCD, IRH, TPS, MBN)

[10]The corresponding ordering of the variables is (LYD, ORT, URL, SSL, MYA, SAM, KWT, CDQ, BRT, TJN, SSH, KLE, WTI, BNL, IRH, ESD, MNS, SHR, EFK, OMN, TPS, CPR, IMS, SUZ, GPL, DKN, DBF, MBN, CBD, FCD, CLM, IRL).

[11]The corresponding ordering of the variables is (OMN, IRL, BRT, SUZ, MBN, KWT, CBD, KLE, SSL, GPL, FCD, IMS, CLM, CDQ, URL, SAM, DBF, IRH, ESD, EFK, SSH, BNL, MNS, ORT, TPS, SHR, CPR, LYD, MYA, TJN, WTI, DKN).

index $SOI_{avg} = 80.57\%$. Therefore the maximal, minimal and average spillover index are quite similar in values. This result confirms the assertion by Diebold and Yilmaz (2009b) that the total spillover index is robust to reordering of the variables[12].

However, the spillover tables are severely affected by the ordering of variables. Compare Table A.6 and Table A.7, for each pair of crudes, the minimal spillover of weekly returns is mostly zero, while the maximal spillovers between crudes are mostly over 40%. Take WTI as an example to demonstrate such sharp contrast. The influence of weekly returns on it varies from 82.88% in maximal spillover table to 7.43% in minimal spillover table. Its spillover to Brent, is 63.98% under the maximal variable ordering and 0.02% under the minimal variable ordering. For volatility, such contrast is still present, with most numbers in the maximal spillover table (Table A.8) between 30% to 70% while those in the minimal spillover table (Table A.9) are around zero. In order to draw a solid conclusion, the analysis in this research is based on average spillover tables. Both of Table 4.1 and Table 4.2 are average spillover tables.

As mentioned above, there are three types of index in the spillover tables: pairwise directional spillover index, net directional spillover index and total spillover index. For weekly returns (Table 4.1), excluding the diagonal elements which measure the percentage of forecast error variance due to own shocks, the largest pairwise directional spillover indexes appear in the column of BRT, which means that among all the crudes, Brent spills over most to other crudes. This is not surprising because Brent serves as a major benchmark price for purchases of oil worldwide, and the basis of the oil pricing system is formula pricing, which prices a crude by adding a price differential to a benchmark crude price. Therefore the shocks on a benchmark crude will affect most other crudes. Another benchmark crude WTI, however, does not show obvious spillover effect. This

[12]This assertion is concluded from empirical evidence. The theoretical work needs future research.

result could serve as evidence in support of the view that WTI is no longer a reliable benchmark due to the lack of stability in its relationship with other crudes (e.g Kao & Wan, 2012 and Giulietti et al., 2014).

The role of any benchmark can be observed most clearly in net directional spillover index located in the bottom row of "Net". The crudes with largest net directional spillover index (in descending order) are Brent (BRT), Russian Urals (URL), WTI, Europe Forcados (FCD). Russian Urals oil is a reference oil used as a basis for pricing for the Russian export oil mixture. Wlazlowski et al. (2011) found Russian Urals crude exhibits significant global price setting behavior. My result supports this view. Europe Forcados has been found to appear as benchmark in downside price movements (Candelon et al., 2013). Another benchmark crude, Dubai Fateh (DBF), has a negative net directional spillover index thus does not show spillover effect. Under the Granger causality framework of Wlazlowski et al. (2011), Dubai Fateh does not display price setting properties either. According to Montepeque (2005), this crude performs badly mainly due to low output. Oman Blend (OMN), which joins Dubai to serve as combined benchmark, only shows small spillover effects. The total spillover index for weekly return is 87.1%, indicating that almost 87.1% of forecast error variance comes from spillovers. This large number is due to the formula pricing mechanism on the spot crude market, which links different crudes so closely that 87.1% of the total forecast error variance could be explained by shocks across different crude oil markets, with the remaining 13.9% is explained by idiosyncratic shocks.

Applying a similar analysis to volatility (Table 4.2), the pairwise directional spillover index shows that WTI, Mexico Isthmus (IMS), Brent (BRT) and Russian Urals (URL) have the argest spillover effect. Because volatility reflects the extent to which the market evaluates and assimilates the arrival of new information, this result implies that

TABLE 4.2: Average spillover table SOT_{avg} for volatility

	WTI	BRT	EFK	CPR	LYD	IMS	MYA	CLM	ORT	CBD	KLE	SUZ	OMN	GPL	TPS	URL	CDQ	SSL	SAM	SSH	MBN	DBF	DKN	IRL	IRH	KWT	SHR	BNL	FCD	ESD	MNS	TJN	From
WTI	37.97	3.66	1.92	4.60	1.76	8.37	2.18	4.13	1.80	1.77	1.51	1.86	1.08	1.01	0.74	1.97	0.52	1.59	1.31	1.15	1.04	1.02	1.06	1.48	1.45	1.89	1.63	1.62	1.98	1.91	0.48	3.53	62.03
BRT	13.25	22.14	1.91	3.02	2.04	4.56	1.87	1.61	1.04	2.10	2.13	2.02	1.75	1.33	0.95	10.23	0.96	1.75	1.83	1.72	1.49	1.67	1.78	2.23	2.18	1.81	2.05	1.41	2.21	2.27	0.90	1.79	77.86
EFK	9.32	4.67	7.25	1.90	0.76	4.49	1.89	2.39	1.25	5.00	3.79	4.12	1.94	1.62	0.68	6.45	1.18	2.22	2.29	2.06	1.96	2.02	2.03	2.43	2.49	2.03	4.75	2.70	6.18	4.88	1.10	2.15	92.75
CPR	13.65	2.64	1.77	37.08	2.52	6.15	1.65	2.33	1.22	1.77	1.40	1.58	1.37	1.36	0.60	1.83	0.66	1.35	1.39	1.19	1.05	1.07	1.28	1.28	1.24	1.20	1.51	1.39	1.77	1.83	0.61	2.28	62.92
LYD	4.01	1.58	0.67	4.45	66.21	2.48	1.80	1.42	0.83	0.60	0.46	0.90	0.55	0.99	0.78	1.24	0.33	0.76	0.84	0.85	0.54	0.43	0.59	0.83	0.78	0.41	0.52	1.61	0.65	0.66	0.33	0.88	33.79
IMS	12.22	5.15	2.85	3.15	1.65	12.53	3.23	4.20	2.19	2.95	2.40	2.91	1.90	2.35	1.04	3.88	1.41	2.14	2.21	2.00	1.44	1.63	1.76	2.39	2.55	1.61	2.66	2.63	2.99	3.15	1.18	3.68	87.47
MYA	10.13	3.42	1.91	2.61	1.79	6.36	24.18	2.80	1.62	2.14	1.96	2.05	2.10	1.78	1.70	1.91	2.10	1.88	1.99	1.98	1.72	1.87	1.98	2.26	2.50	1.79	1.85	1.65	2.13	2.12	1.49	2.21	75.82
CLM	6.49	6.45	2.79	2.25	2.39	6.42	2.51	20.84	2.98	2.61	1.98	2.81	1.50	1.96	0.93	5.68	1.19	1.72	1.74	1.56	1.32	1.46	1.45	1.94	1.91	1.39	2.44	1.80	3.02	2.72	0.96	2.79	79.16
ORT	9.53	4.25	1.76	1.57	1.08	4.94	1.95	3.84	34.99	1.83	1.46	1.84	1.22	1.55	0.60	3.00	0.85	1.48	1.60	1.56	1.06	1.23	1.22	1.74	1.83	1.19	1.78	1.81	1.96	2.52	0.76	2.01	65.01
CBD	10.05	4.85	4.67	2.07	0.96	4.60	2.05	2.26	1.26	6.67	3.94	3.59	2.11	1.74	0.73	4.78	2.09	2.34	2.47	2.23	2.08	2.20	2.20	2.62	2.70	2.21	4.30	2.66	5.21	4.46	1.81	2.12	93.33
KLE	11.60	5.04	3.79	2.08	0.88	4.56	1.80	1.83	1.07	4.41	13.63	2.99	1.86	1.55	0.59	4.67	1.88	2.06	2.23	2.08	1.67	1.91	1.84	2.31	2.42	1.94	3.73	2.22	3.91	3.70	1.72	2.01	86.37
SUZ	8.86	4.11	4.59	1.83	0.80	4.72	2.06	2.71	1.34	4.19	3.28	10.54	1.99	1.53	0.81	5.88	0.94	2.25	2.37	2.19	2.06	2.09	2.08	2.33	2.40	2.05	4.09	2.72	5.10	5.14	0.91	2.04	89.46
OMN	18.04	3.15	1.88	2.67	1.15	3.96	1.70	2.01	1.04	2.08	1.80	1.80	6.38	2.20	0.80	1.67	0.95	2.72	2.75	2.54	4.83	5.13	5.73	3.40	3.46	5.35	1.99	1.65	2.19	2.21	1.00	1.76	93.62
GPL	16.54	3.35	1.56	2.73	1.75	4.13	1.81	1.96	1.25	1.80	1.55	1.71	2.43	17.07	1.06	1.70	3.37	2.33	2.36	2.12	1.98	2.18	2.66	2.21	2.23	2.60	1.64	3.14	1.92	2.15	2.82	1.88	82.93
TPS	3.67	0.48	0.43	0.64	0.31	1.23	0.49	0.55	0.89	0.40	0.34	0.61	0.60	1.49	79.32	0.23	0.43	0.38	0.39	0.38	0.48	0.41	0.68	0.94	0.84	0.41	0.41	0.65	0.59	0.43	0.40	0.50	20.68
URL	8.25	14.36	1.75	2.62	1.53	3.79	1.73	1.51	0.85	1.93	1.71	2.36	1.41	0.88	0.80	31.26	0.68	1.50	1.63	1.54	1.12	1.29	1.33	1.73	1.74	1.41	1.71	1.23	2.19	1.96	0.58	1.61	68.74
CDQ	5.45	2.70	1.28	1.02	1.62	2.46	1.36	1.17	0.83	2.12	2.21	1.30	1.39	4.42	0.61	1.52	24.44	2.49	2.94	3.31	1.13	1.34	1.34	1.63	1.63	1.19	1.26	2.00	1.66	1.46	19.59	1.14	75.56
SSL	10.01	3.35	2.04	1.46	1.24	3.44	1.78	2.23	1.29	2.12	1.90	2.00	2.76	2.19	0.94	1.90	1.59	9.93	8.05	6.79	3.01	3.02	2.77	4.28	4.30	3.23	2.25	2.08	2.30	2.34	1.53	1.87	90.07
SAM	12.50	3.20	1.97	1.77	1.24	3.71	1.80	2.05	1.33	2.07	1.91	2.00	2.67	2.10	0.99	1.88	1.51	7.16	8.15	7.68	2.85	2.90	2.68	4.07	4.21	3.29	2.11	2.16	2.20	2.27	1.61	1.93	91.85
SSH	12.77	2.96	1.89	1.84	1.26	3.66	1.74	1.97	1.33	2.00	1.88	1.94	2.61	1.99	1.00	1.80	1.48	6.68	8.43	9.11	2.77	2.85	2.63	3.93	4.15	3.33	2.01	2.18	2.11	2.16	1.66	1.88	90.89
MBN	16.92	3.37	1.84	2.41	1.30	3.64	1.70	1.99	1.04	2.00	1.73	1.77	4.96	2.00	0.91	1.78	0.89	2.86	2.85	2.68	7.26	6.33	4.89	3.43	3.61	5.47	1.94	1.56	2.15	2.10	0.90	1.74	92.74
DBF	16.66	3.42	1.87	2.43	1.34	3.70	1.71	2.01	1.10	2.08	1.77	1.79	5.03	2.02	0.90	1.86	0.92	2.82	2.86	2.68	6.01	7.04	4.87	3.45	3.57	5.46	1.99	1.60	2.19	2.15	0.95	1.74	92.96
DKN	19.76	2.99	1.83	2.97	1.08	4.13	1.62	1.99	0.99	2.00	1.75	1.75	5.65	2.26	0.75	1.55	0.85	2.60	2.64	2.45	4.67	4.85	6.57	3.22	3.28	5.18	1.95	1.66	2.12	2.17	0.94	1.77	93.43
IRL	12.95	3.60	2.17	2.15	1.36	3.97	1.96	2.14	1.32	2.40	2.14	2.03	3.33	2.12	1.03	1.95	1.55	3.88	3.89	3.56	3.31	3.45	3.20	7.82	6.79	3.59	2.34	1.82	2.45	2.48	1.38	1.92	92.18
IRH	12.72	3.29	2.06	2.14	1.35	3.84	1.97	2.00	1.32	2.37	2.11	1.96	3.29	2.10	1.17	1.89	1.66	3.89	4.01	3.74	3.27	3.39	3.15	6.91	8.54	3.72	2.25	1.82	2.35	2.35	1.49	1.86	91.46
KWT	19.99	2.88	1.68	2.87	1.23	4.11	1.59	1.90	0.96	1.86	1.64	1.65	4.94	1.92	0.77	1.58	0.83	2.61	2.78	2.66	4.99	5.19	4.76	3.13	3.34	8.29	1.76	1.53	1.92	1.91	0.97	1.76	91.71
SHR	10.23	4.40	4.73	2.19	0.91	4.33	2.01	2.23	1.26	4.56	3.70	3.67	2.09	1.86	0.80	4.21	1.47	2.37	2.40	2.17	2.05	2.15	2.19	2.63	2.69	2.10	8.02	2.63	5.45	4.88	1.31	2.32	91.98
BNL	5.72	3.18	3.28	1.50	1.41	4.08	1.72	1.82	1.52	3.15	2.68	3.00	1.56	4.31	0.90	3.73	1.98	2.46	2.85	3.02	1.38	1.57	1.79	2.03	2.24	1.67	3.11	20.12	5.03	3.62	1.65	1.92	79.88
FCD	8.18	5.07	5.32	1.70	0.83	4.41	2.03	2.34	1.28	5.09	3.67	4.03	2.12	1.76	0.75	5.48	1.31	2.37	2.42	2.18	2.18	2.24	2.21	2.57	2.66	2.15	4.77	3.05	7.58	5.04	1.15	2.06	92.42
ESD	10.40	4.86	4.52	2.07	0.83	4.76	1.98	2.34	1.37	4.45	3.48	4.26	2.06	1.90	0.72	4.26	1.20	2.32	2.38	2.18	2.06	2.14	2.12	2.60	2.64	2.16	4.63	2.79	5.28	8.02	1.07	2.15	91.98
MNS	9.35	2.38	1.27	1.39	1.53	2.72	1.11	1.05	0.77	1.77	2.19	1.12	1.46	3.75	0.63	1.40	18.43	2.45	3.02	3.65	1.22	1.37	1.49	1.62	1.62	1.32	1.18	1.73	1.57	1.23	23.03	1.18	76.97
TJN	9.32	2.97	2.17	2.26	1.10	6.13	2.07	2.83	1.57	2.24	1.83	2.16	1.62	1.82	0.92	3.86	1.12	1.69	1.68	1.53	1.18	1.36	1.43	1.84	1.86	1.26	2.84	1.87	2.35	2.26	0.98	29.88	70.12
To	348.50	121.80	74.16	70.40	41.02	133.84	56.86	67.60	39.87	77.86	66.28	69.59	71.31	61.84	26.59	95.77	56.32	77.12	82.61	77.47	67.94	71.76	71.20	79.47	81.32	74.42	73.46	61.37	85.12	80.54	54.24	60.50	**SOI**
Net	286.47	43.94	-18.58	7.49	7.23	46.37	-18.96	-11.56	-25.14	-15.48	-20.09	-19.87	-22.30	-21.09	5.92	27.03	-19.24	-12.95	-9.24	-13.43	-24.80	-21.20	-22.24	-12.71	-10.14	-17.29	-18.52	-18.51	-7.30	-11.44	-22.73	-9.62	**80.57**

Note: This table provides the spillover table with average entries for volatility. The sample is January 1997 through November 2011. The predictive horizon is 16 weeks. The $ij-th$ entry of the upper 32×32 crude submatrix gives the $ij-th$ pairwise directional spillover, i.e. the percent of 16-week-ahead forecast error variance of crude i due to shocks from crude j. The rightmost "From" column gives total directional spillovers (from), i.e. row sums (from all others to i). The bottom "To" row gives total directional spillovers (to), i.e. column sums (to all others from j). The bottommost (Net) row gives the difference in total directional spillover (to-from). The bottom-right element (in bold) is total spillover index, which is the mean of "FROM" column, or the mean of "TO" row. The crudes names are in abbreviation. Refer to Table A.1 for full names of crudes.

the benchmark crudes of WTI and Brent, and the potential benchmark Russian Urals, present a dominant role among crudes in the ability to process information. The exception is Mexico Isthmus (IMS), which is not a benchmark crude. Its transmitting role may be due to the close oil trade linkage of Mexico and U.S, with the United States primarily importing crude oil from Mexico and exporting refined petroleum products to Mexico (EIA, 2013). According to EIA, the United States received approximately 68% of Mexico's oil exports (EIA, 2015).

The net spillover index of WTI is three times as large as that of Mexico Isthmus (IMS) and Brent (BRT). This result generally supports the argument of Elder et al. (2014) that WTI maintains a dominant role in price discovery relative to Brent, with an estimated information share in excess of 80%, over a sample from 2007 to 2012. The information share is defined by Hasbrouck (1995) as the proportion of the variance in the common price process that is attributable to a particular price series. The market with higher information share is more information efficient. My analysis indicates that WTI's dominant role maintains to a large scope of crudes, in terms of transmitting shocks. Shocks to volatility in WTI have a substantial indirect impact on volatility in other markets.

The total spillover index for volatility is 80.57%. This high number may due to the fact that crude oil market is vulnerable to a number of shocks, not only these specific crude shocks but also shocks from other markets (e.g. FX or stock markets). And the high degree of integration enhances the spread of shocks. Thus crude oil market has the largest spillover indexes in the literature (87.1% for return and 80.57% for volatility) even when compared to the global stock market (40% according to Diebold and Yilmaz (2012)for developed stock markets, and 68.1% according to Prasad, Grant, and Kim (2014) when emerging stock markets are taken into account).

The total spillover index of volatility (80.57%) is smaller than the number of return (87.1%). This is consistent with the claim of Diebold and Yilmaz (2015a) regarding the difference of total return and volatility spillovers. Return spillover generally reflects the integration of market: the more likely it is that positive or negative return shocks will spread to other markets, the more markets are integrated. However, volatility spillover does not necessarily reflect increased interdependence over time. In period of tranquility, volatility spillover across markets does not have to be high, even when markets are highly integrated. Since financial crisis are characterized by shocks to volatility, volatility spillovers tends to become a major phenomenon during a crisis period. Nevertheless, crisis represents only a small fraction of time periods. Global markets went through more tranquil times compared with crisis in the sample period. Therefore, in the full sample static analysis, the volatility spillover index is smaller than the return spillovers. However, in crisis periods, The volatility spillover index could increase more significantly than the return spillover index. This is discussed next in the dynamic analysis.

4.5 Dynamic analysis

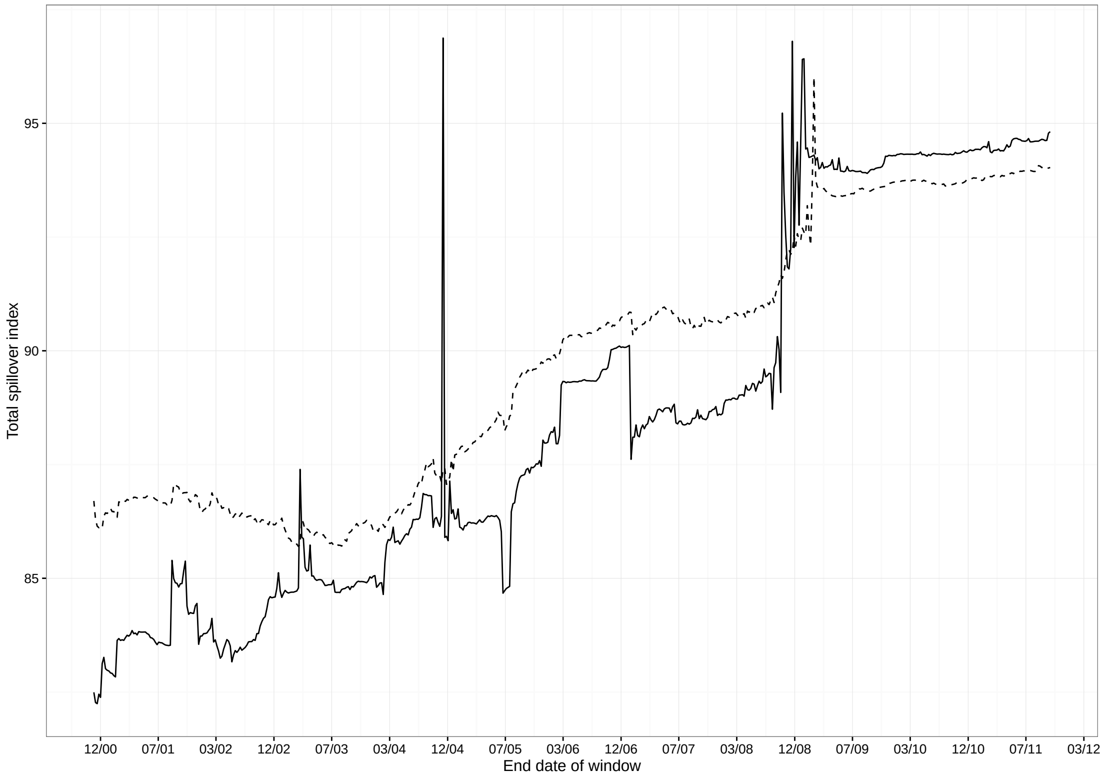
4.5.1 Total spillover index

The spillover table shows a static and average picture of the spot crude oil market over the whole sample period. However, the crude oil market evolves, and a single fixed-parameter model cannot apply over the entire sample. A simple way to gain a better picture is to estimate the VAR model on a rolling-window sample to track the variation of the total spillover index over time. The rolling estimation window of 200 weeks, approximately 4 years was chosen[13]. Due to the high correlation of variables,

[13]In this way 576 return spillover tables and 577 volatility spillover tables over the whole sample period are gained.

the design matrix on a small sample is not invertible and therefore cannot develop the model. In practice, 200 weeks is the smallest sample size required to run the regression. The robustness of the choice of the window width will be checked in Section 6.

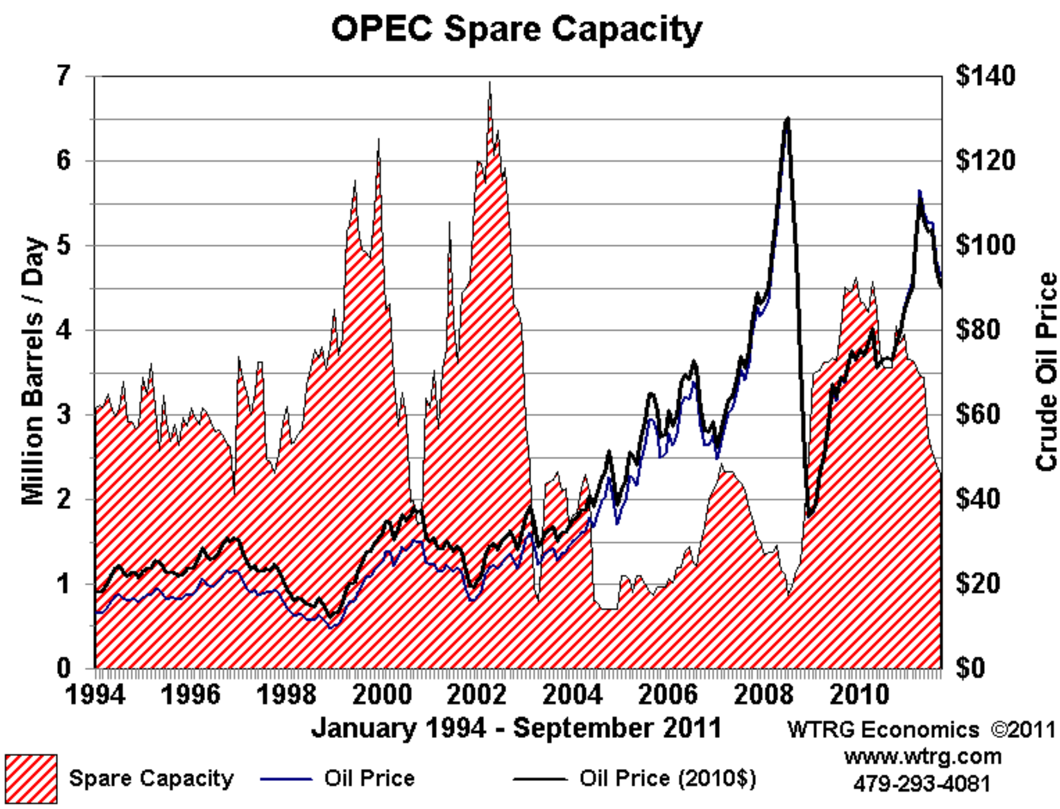
FIGURE 4.1: Spillover plots of weekly return and volatility



Note: This figure shows the time series of the spillover index for both weekly return and volatility. The dashed line represents the dynamic of spillover index of return, while the solid line represents the spillover index of volatility. The format of the horizontal scale is "mm/yy", and the interval is eight months.

If we display the time series of total spillover index in plots, we get the spillover plots. The resulting spillover time series is shown in Figure 4.1 and begins on the 27^{th} of Octtober 2000 and, after accounting for the first 200 observations, ends on the 11^{th} of November 2011. The dynamic spillover index of return is relatively smooth except for the period of global financial crisis in 2008, when it shows a very sudden spike: a jump of over 95%, before dropping again at the beginning of 2009; however, it does not drop to the level of before the spike. In general the return spillover index series displays an increasing trend, implying that more and more forecast error variance for the whole shocks across crudes. In other words, less and less of the forecast error variance is due to idiosyncratic shocks. This is consistent with an increase in crude market integration. This increasing trend is most obvious from 2003 to the middle of 2007; a period associated with the soaring price of crude oil. During this period the US economy was recovering from the collapse of dot-com bubble, and demand for oil was increasing. Asian demand for crude oil was also growing at a rapid pace. However OPEC spare production capacity was shrinking. From Figure 4.2 we can see the excess production capacity was below two million barrels a day during most of this time period. Meanwhile, the world consumption of petroleum products was more than 80 million barrels a day. The crude oil market experienced an integration under the tight market condition. Besides this increasing trend and the spike during global financial crisis, the return spillover index series is relatively flat.

FIGURE 4.2: OPEC spare production capacity



Note: Source: WTRG economics.

The spillover plot for volatility is more volatile than the return spillover plot, with several spikes representing extreme spillovers. The first obvious spike happened in September of 2001, reflecting the effect of 9/11 terrorist attacks on the crude oil market. After the attack, crude oil prices plummeted. WTI spot prices were down 35 percent by November. Given the political climate OPEC delayed quota reductions until early 2002, when the influence of the 9/11 terrorist attack had faded in the volatility spillover plot.

The second spike is in the early 2003, when the military action commenced in Iraq. The 2003 invasion of Iraq lasted from the 19$^{\text{th}}$ of March to the 1$^{\text{st}}$ of May 2003. Express (2003) reported that Iraq had launched missile attacks on Kuwait, but there was no effect on any production facilities. Reflected in the plot, the volatility spillover index jumped and then dropped to almost the same level after the event.

The third spike from October to November in 2004 is mainly due to the China Daqing (CDQ) and Indonesia Minas (MNS) crudes. It is not obvious in the dynamic total spillover index in Figure 4.1 , but is visible in the dynamic individual or pairwise directional spillover index in Sections 4.5.2 and 4.5.3. The observation of the large volatility contribution of China Daqing (CDQ), is consistent with the result of B. Zhang and Wang (2014), who found that since the end of 2004, the Chinese oil market has become the net transmitter of volatility[14]. In their plot, the net volatility spillover of China Daqing made a jump at the end of 2004. They attribute this to China's huge demand for imported oil from the world market caused by rapid economic growth. Moreover, the Daqing Oilfield decided to slash its production by two million tons in 2004, because of a shortage of renewable resources and a shrinkage in exploitable oil reserves, putting

[14] In fact, Figure 8 of B. Zhang and Wang (2014) shows that the net volatility spillover index of China Daqing had a jump at the end of 2004, but declined and diminished to negative after three quarters.

an end to 27 years of stable output[15]. Indonesia was in similar situation in 2004; declining oil production and increased consumption resulted in Indonesia becoming a net oil importer in late 2004 and suspending its OPEC membership shortly thereafter (PWC, 2014).

From early 2007 to summer 2008, volatility spillover index was stable and low, which implies that more volatility forecast error variance was due to idiosyncratic shocks rather than spillovers across crudes. This is quite different with stock markets, where the spillover index reaches a high during this period because of a subprime crisis (Prasad et al., 2014 and Diebold & Yilmaz, 2009b). During this period, the path of oil prices was not steadily increasing but steepened sharply, sending the nominal price to an all-time high (See Figure B.3.). What caused this remarkable behavior in oil prices is still a controversial topic. Two mainstream explanations are financial speculation (e.g Masters, 2008 andEinloth, 2009) and macroeconomic fundamentals, such as increased demand from emerging Asia and low interest rate (e.g Hamilton, 2009). But this topic is beyond the scope of this analysis. The low and stable spillover index of the spot crude oil market during this period, may have arisen for two reasons. First, in 2007 the western world began to slide into recession, therefore the international transaction of crude oil reduced due to reductions in economic activity (WTRG, 2011). Second, the period from January 2007 to August 2008 is associated with the soaring of crude oil price and speculation in future markets. The oil storage trade was very popular at this time. Traders could buy and store spot crude oil and sell on futures market because they expected the future price would increase. When delivery dates approached, they closed out existing contracts and sold new ones for future delivery of the same oil. Actually no real oil was delivered through. They just rolled the futures contract (Norris, 2008).

[15]See the report of Xinhua News Agency. "Daqing oilfield to slash output in 2004". 2004. Available at http://www.china.org.cn/english/BAT/86495.htm

Therefore the shock to crudes would only depend on local market conditions for each of the crudes. After summer 2008 the price dropped and such strategies no longer worked. The spot crude oil markets was hit hardly by the crisis over all financial markets, and the spillover index jumped.

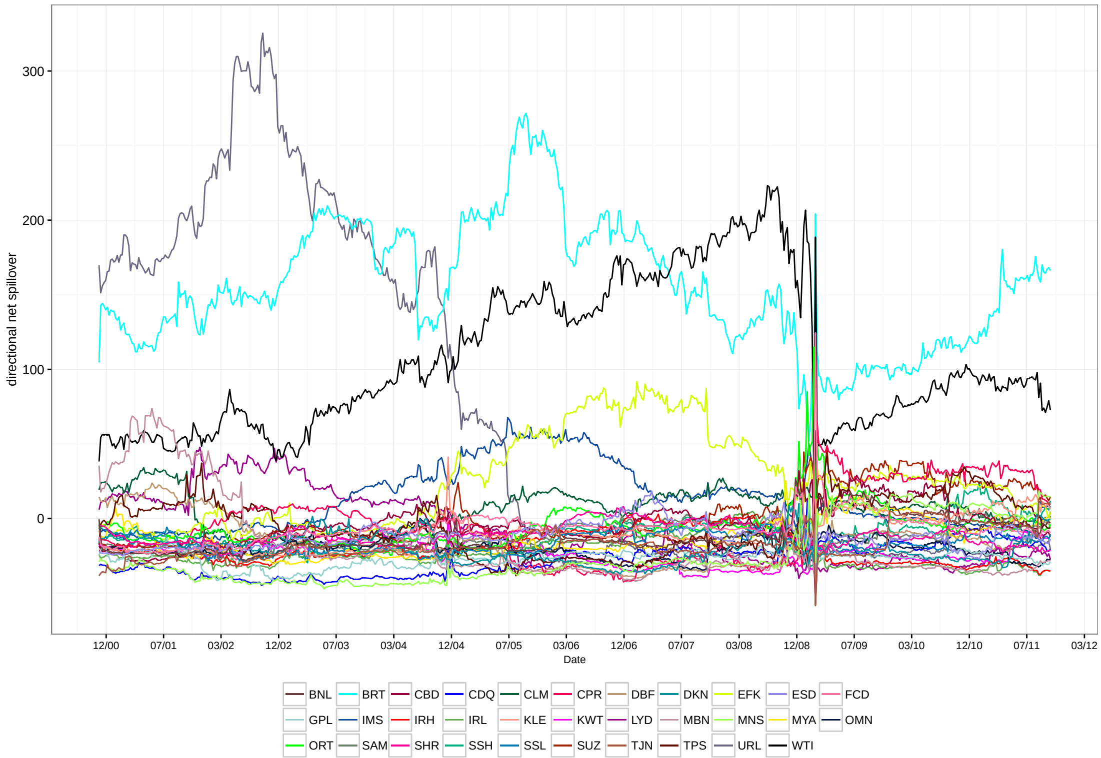
The chaos of spillover plot from August 2008 to February 2009 is associated with the jump in crude oil prices from peak to nadir. Following an OPEC cut of 4.2 million b/d in January 2009 and the rising demand from Asia, oil prices rose steadily. Interestingly the spillover index does not drop but rather keeps above 90% from early 2009 until 2011, the end of sample. Because over 90% of forecast error variance is due to spillovers across crudes, for both return and volatility, spot crude oil markets integration is enhanced by the systematic risk from macroeconomic shocks in 2008. This finding is consistent with Ji and Fan (2014), although their analysis is based on graph theory. Their measure of correlation coefficients among crude markets has kept rising at a relatively stable high-level, approximately 0.9. Meanwhile, this measure has a lower variance, implying the relationships are stable. They further split the sample in August 2008, but only found the influence of African markets was enhanced after 2008 financial crisis. OPEC still plays an important role in the market system; this is evidenced by the fact that no changes occur in the link between North and South Amarica; although geographic attributes are still a significant factor-crude oil markets always tends to link to nearby regional markets. Ji and Fan (2014) therefore attribute the enhanced crude oil market integration to the financial crisis.

4.5.2 Individual directional spillover

The benefit of Diebold and Yilmaz (2012) framework is that it can not only provide an overview of dynamic spillover for the whole system, but also allow the investigation of spillover from individual and pairwise perspective. This section focuses on the role of individual crude. If we display the time series of "Net" index of each crude in the spillover table, we get the individual directional spillover plots. As mentioned previously, the "Net" index is equal to spillovers transmitted to other crudes minus spillovers received from other crudes, so it measures the net effect of spillover. If the "Net" index is positive, it means that this crude tends to transmit shocks to other crudes, so we call it a "transmitter". In contrast, if "Net" index is negative, this crude is a "receiver". In crude oil market, we are more concerned with "transmitters" because they quickly reflect market movements and transmit shocks to other crudes, while "receivers" tend to follow "transmitters". Therefore if benchmarks in crude oil markets are indeed benchmarks, they should be "transmitters", i.e. have large positive "Net" spillover index. The "Net" row of spillover table in Section 4.4 provides an average overview of the individual spillover index over the sample period. This section will further discuss the dynamics of the individual spillover index. Figure 4.3 and Figure 4.4 display the dynamic behavior of these transmitters for return and volatility, respectively.

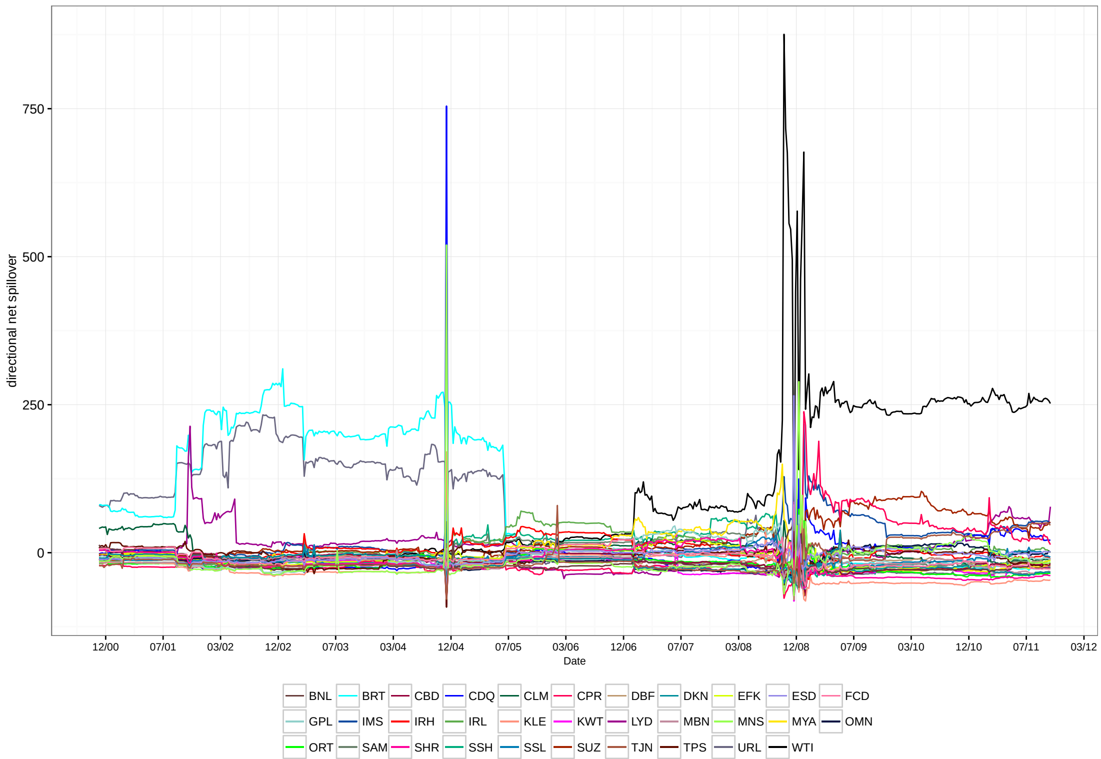
Figure 4.3 shows the dynamics of net individual directional spillover index for return. WTI, Brent (BRT), Russian Urals (URL) are the dominant transmitters. This is consistent with the static analysis which captures the average behavior over the sample period. Figure 4.3 also shows the exact period when these transmitters have an impact. For Urals, it only behaved as a transmitter before September 2005, after this it is a "receiver". Wlazlowski et al. (2011) has found the price setting behavior of Russian Urals by Granger causality tests based on a sample period from January 1997 to March 2006. My analysis shows that this conclusion cannot be extended beyond 2006. The traditional benchmarks, WTI and Brent, are still dominant in crude oil market, although there are doubts as to their benchmark status. For example, Kao and Wan (2012) found

FIGURE 4.3: Dynamic individual spillover index of return



Note: This plot provides the dynamic net spillover index of return for each crude. The format of the time for the x axis is "mm/yy". The names of crudes are abbreviated. Refer to A.1 for full names.

FIGURE 4.4: Dynamic individual spillover index of volatility



Note: This plot provides the dynamic net spillover index of volatility for each crude. The format of the time for the x axis is "mm/yy". The names of crudes are abbreviated. Refer to A.1 for full names.

WTI's efficiency in processing information has been surpassed by that of Brent after the second half of 2004 when using sample period from October 1991 to February 2009. In my analysis, WTI's transmitter role of return shock is surpassed by that of Brent most of the time, except during the global financial crisis period from 2007 to 2008. Therefore despite the controversy about their benchmark status, there are currently no crudes that could serve as a better benchmarks in the global crude oil market, at least among the 32 crude series we investigate.

Figure 4.4 shows the dynamics of the net individual directional spillover index for volatility. Russian Urals (URL) was a net volatility spillover transmitter until middle of 2005. Therefore it was indeed an important crude in global market before 2005. However, its influence disappeared since late 2005. Two remarkable spikes happened in November 2004 and late 2008, as shown in Figure 4.1. But in this part it is clear that the spikes are due to China Daqing (CDQ) and Indonesia Minas (MNS) in 2004, and WTI in late 2008. WTI transmitted volatility shocks since global financial crisis in 2007, and its transmission effect was most remarkable when crude oil price collapsed in 2008. The reason is possibly that the origin of 2008 crisis was the United States.

The dynamic volatility spillover transmitters are mostly consistent with static analysis, such as WTI, Brent (BRT) and Russian Urals (URL), having persistent significant net positive spillover effects in some periods. However, Mexico Isthmus (IMS) which has a large static net spillover index as discussed in Section 4.4, but does not show a significant effect in the dynamic analysis. Its volatility spillover effect may be positive and small, but it is persistent over the long sample period, making it insignificant in individual dynamic plot but giving it a large static individual spillover index.

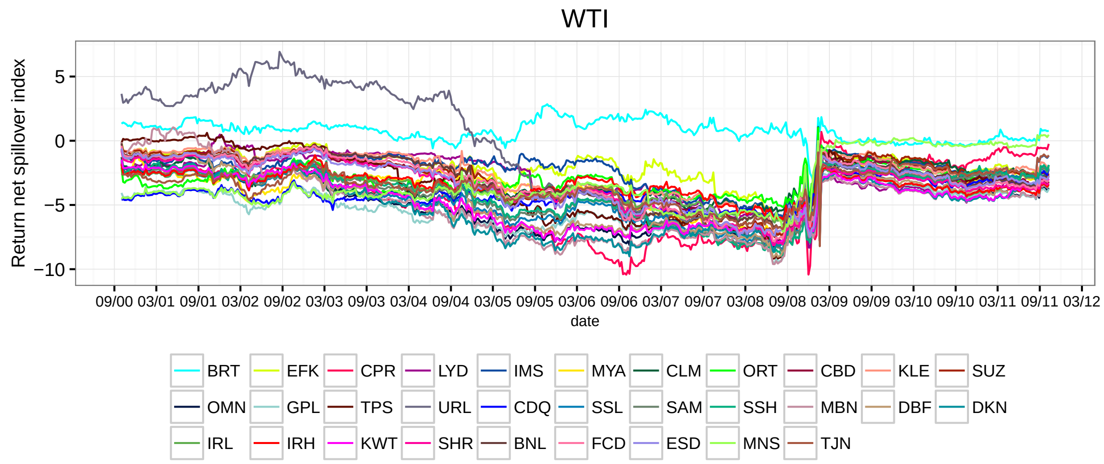
4.5.3 Pairwise directional spillover

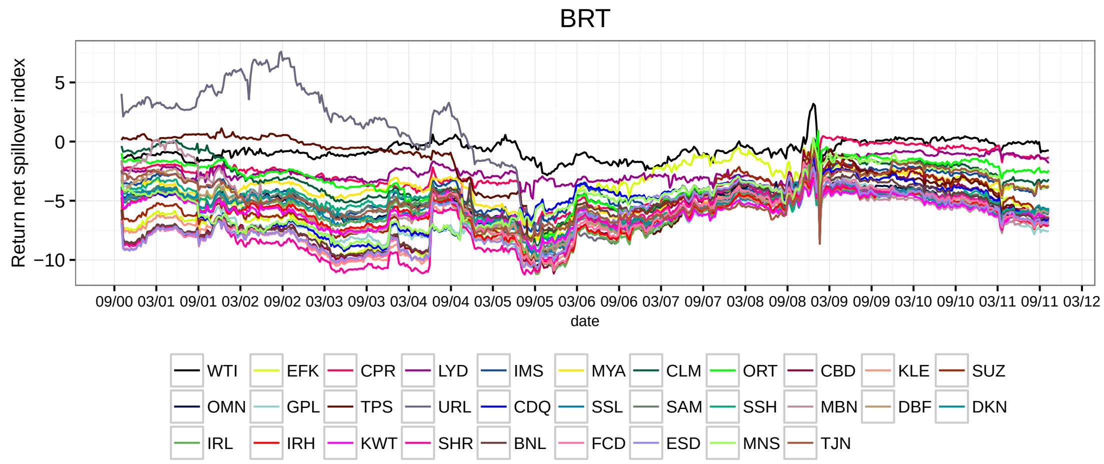
In this section a further step is taken to investigate the dynamic pairwise directional spillover because market participants may need to know exactly the spillover effect of one crude to another crude in addition to the overall picture. The net spillover index for each pair of crudes is therefor calculated next. For crude pair ij, the net spillover from i to j is equal to spillover from i to j minus spillover from j to i. To display the time series of net spillover in aplot, we use the pairwise directional spillover plot. For each crude, there are therefore 31 pairs to analyze. If the dynamic of each pair was plotted in one graph, there will be 992 graphs, which would be too many to display here. To save space and observe the relative importance any crude, the pairs for each crude are plotted in one picture to reduce the number of pictures to 32. Even so there are 64 plots in total, 32 for return spillover and 32 for volatility spillover. To maintain the consistency of analysis, I select shock transmitters discussed in previous analysis, i.e. WTI, Brent (BRT), Russian Urals (URL), China Daqing (CDQ) and Indonesia Minas (MNS) to give a general analysis. The other graphs are given in Appendix B.

In pairwise analysis, the problem investigated is: for a specific crude i, how does another crude j impact it? Does j transmit shocks to i, or vice versa? The net spillover measures the impact of j to the crude i studied. If this index is positive, it means crude j is a net transmitter to i: it transmits net shocks to i in net level. If this index is negative, the opposite is true i.e. crude i transmits shocks to j. This analysis could provide useful information. For example, if a Chinese buyer mainly importing crude from Saudi Arabia, e.g. "Saudi Arabia Saudi Light" (SSL), wanted to know which crudes transmit shocks to SSL, then he could monitor these crudes closely and make hedges when necessary.

Figure 4.5 display the pairwise net return spillover of several crudes. The first panel

FIGURE 4.5: Pairwise net return spillover: some examples





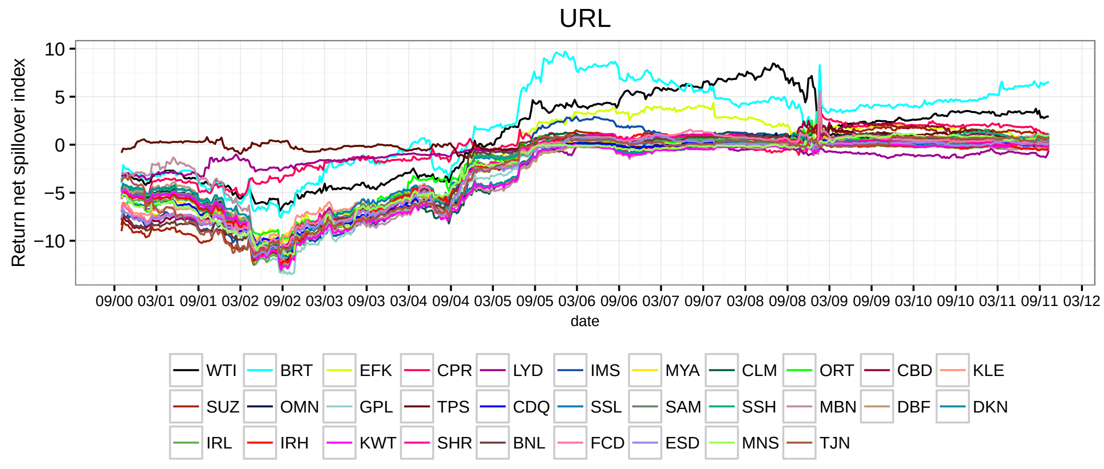
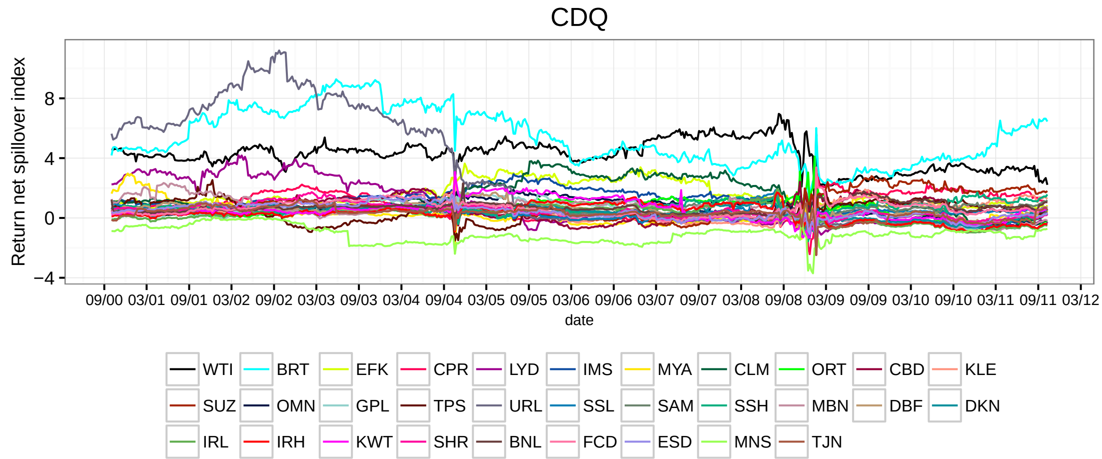
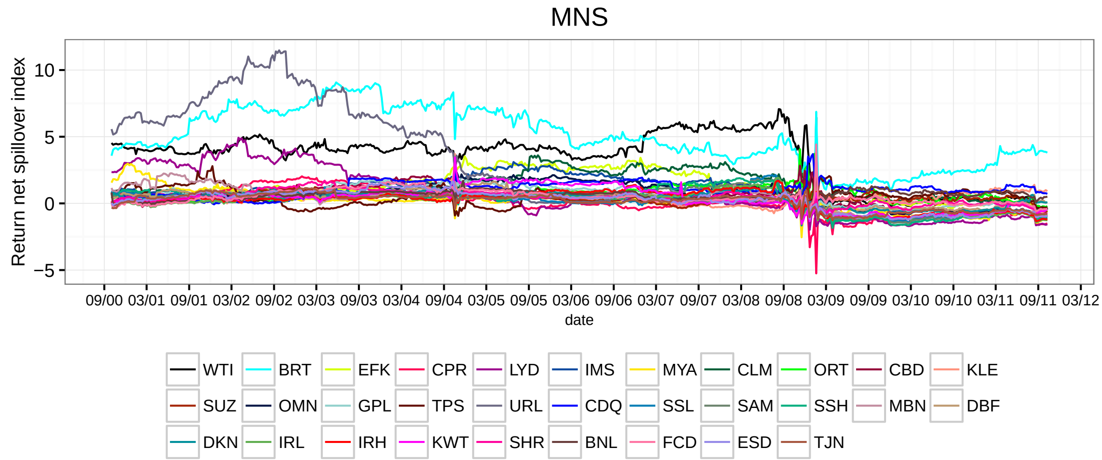


FIGURE 4.5 (cont.): Pairwise net return spillover: some examples (Cont.)





Note: These graphs show the pairwise net return spillovers of WTI, Brent (BRT), Russian Urals (URL), China Daqing (CDQ) and Indonesia Minas (MNS) with the rest crudes in the sample. The format of the date is "mm/yy" format. If a line stays above zero (i.e. positive net spillover index), it means the crude represented by the color of the line transmits shocks to the crude investigated. If a line stays below zero (i.e. negative net spillover index), it means the crude represented by the color of the line receives shocks from the crude being investigated.

shows the pairwise relationship of WTI with all the other crudes in the sample, represented by different colors as shown in the legend. It shows that the bulk of lines lie below zero except Russian Urals (URL) and Brent (BRT). Therefore only Russian Urals and Brent have positive net spillover indexes and transmit shocks to WTI. The other crudes only receive shocks from WTI. Again the disappearing influence of Urals after 2005 is visible, which is consistent with Figure 4.3. In addition, Brent's influence to WTI was most significant from early 2005 untill the financial crisis. This time period is similar to the finding of Kao and Wan (2012) that WTI was surpassed by Brent from the second half of 2004. During the crude oil collapse, all crudes had negative influence over WTI, implying WTI was transmitting shocks to all the other crudes in this process. After the collapse, Brent's influence became small, reflected by the line of Brent being close to zero.

For Brent, only Russian Urals (URL) had positive influence over it before 2005. All the other crudes were receiving shocks from Brent over the study period except WTI during the crude oil price collapse process, confirming its benchmark role in the global crude oil market.

For Russian Urals (URL), before 2005 all the lines lie below zero, implying that Urals transmitted shocks to the other crudes, not the opposite. But after 2005 Urals was receiving shocks, mainly from Brent and WTI, but also from other crudes such as Ekofisk (EFK) and Mexico Isthmus (IMS) during part of this time. The crude it could impact most after oil price collapse is Canada Lloyd Blend (LYD).

China Daqing (CDQ) is basically a return shock receiver, because most crudes have a positive net return spillover to it. The most influential crudes are Brent and WTI, and Russian Urals (URL) before 2005. The crude that it influences the most is Indonesia Minas (MNS), as the line of MNS lies at the bottom of plot shows.

Indonesia Minas (MNS) is also a receiver and its plot has a similar pattern to that of China Daqing (CDQ).

The plots of all the other crudes are attached in Figure B.4 in Appendix. The general conclusion from individual directional spillover analysis is confirmed by the pairwise analysis. Russian Urals (URL) used to be an important transmitter to all of the other crudes, but it lost this role after 2005. In most time period, Brent and WTI transmitted shocks to the other crudes, and the former surpassed the latter as transmitters. However, when crude oil price collapsed from its record high in 2008, it was WTI that transmit shocks to the other crudes, perhaps because the financial crisis is originated in the US, making it the center of the storm.

To calculate pairwise volatility net spillover, a similar methodology to the above was followed. Figure 4.6 displays example crudes. As we have seen in individual directional spillover analysis, Russian Urals (URL) used to transmit volatility shocks to the other crudes before middle of 2005. This is reflected in the other crudes' pairwise volatility spillover plots as the line of Urals stays over zero , and is also confirmed in Ural's own plot by the lines for all other crudes lying below zero during this period.A similar conclusion applies to Brent, which was a volatility shock transmitter before 2005 but became a receiver after 2008.

WTI behaved as volatility spillover transmitters during and after the collapse of crude oil price in 2008, as discussed in the individual directional spillover analysis.

As discussed in Section 4.5.1 and Section 4.5.2, the spike in 2004 in dynamic volatility spillover plots (Figure 4.1 and Figure 4.4) was caused by China Daqing (CDS) and Indonesia Minas (MNS). This fact is more visible in the pairwise volatility spillover plot, as the spike in the plot of these two crudes points downwards, implying that other crudes had negative volatility spillover to them, i.e. China Daqing (CDS) and Indonesia Minas (MNS) had positive volatility spillover to other crudes at this time point.

From the combined individual and pairwise volatility spillover analysis, it can be concluded that traditional global benchmarks like Brent and WTI transmit shocks to other crudes at return level, with the former's role surpasses the latter. However, in terms

FIGURE 4.6: Pairwise net volatility spillover: some examples

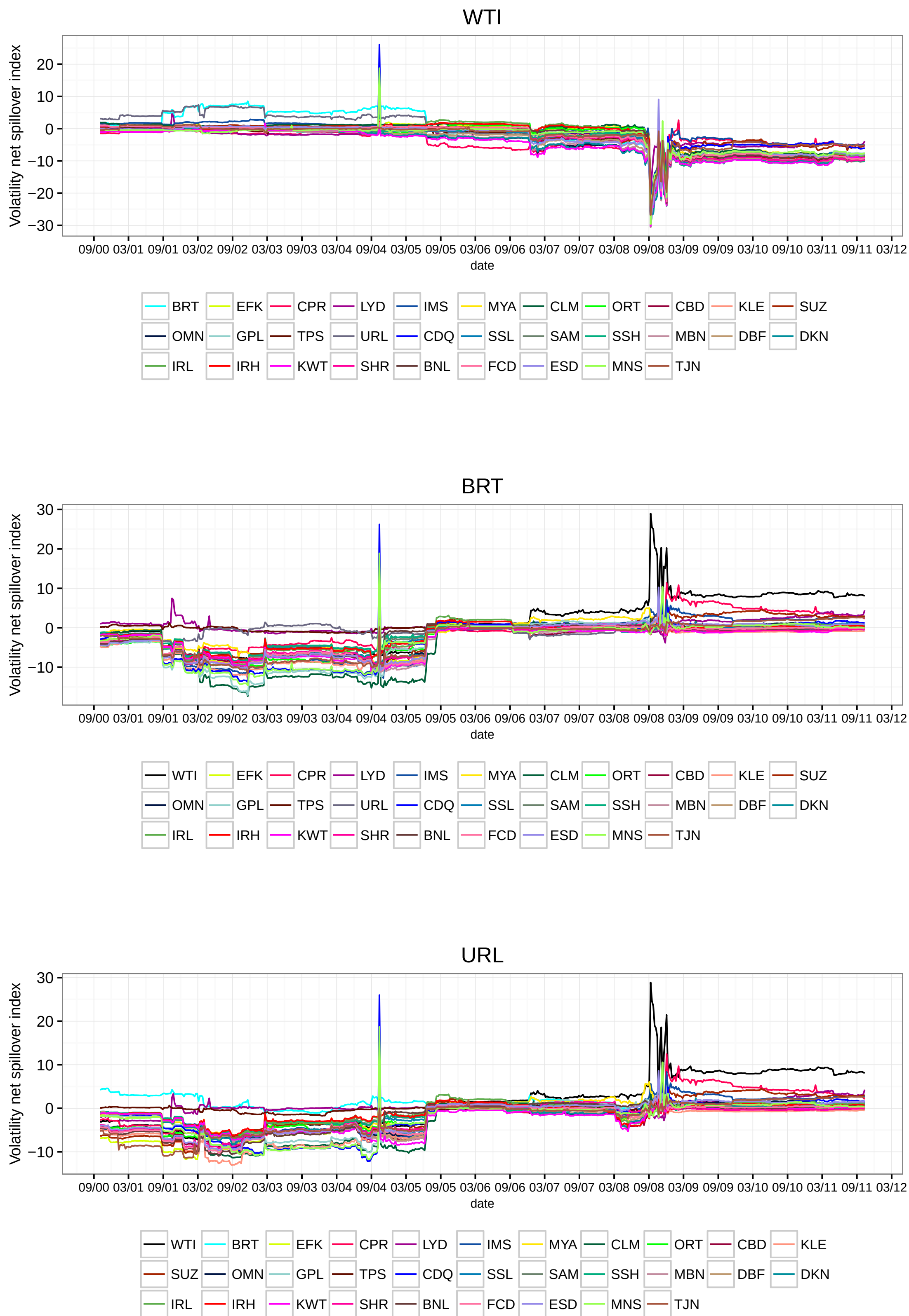
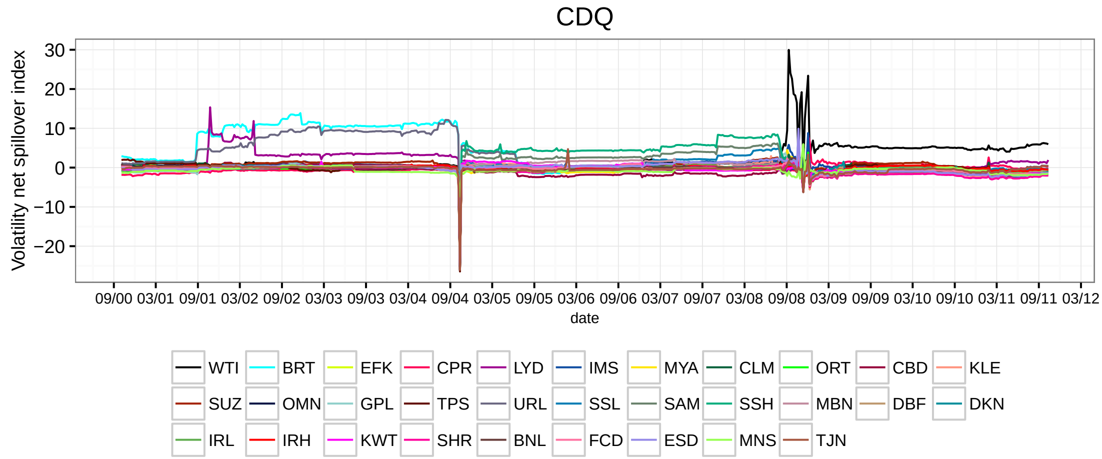
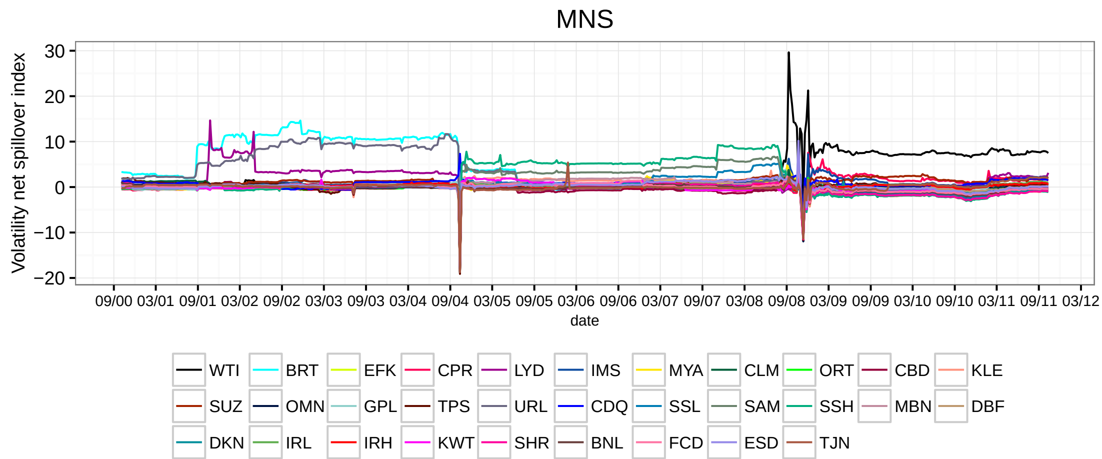


FIGURE 4.6 (cont.): Pairwise net volatility spillover: some examples (Cont.)





Note: These graphs show the pairwise net volatility spillover of WTI, Brent (BRT), Russian Urals (URL), China Daqing (CDQ) and Indonesia Minas (MNS) with the rest crudes in the sample. The format of the date is "mm/yy". If a line stays above zero (i.e. has a positive net spillover index), it means the crude represented by the color of the line transmits shocks to the crude investigated. If a line stays below zero (i.e. negative net spillover index), it means the crude represented by the color of the line receives shocks from the crude being investigated.

of volatility, WTI and Brent are not always transmitters. Brent was only transmitting volatility shocks before middle of 2005. After 2007, WTI dominated other crudes as a volatility transmitters, and after this its transmitting role seems to be persistent. Russian Urals (URL), although behaving as important transmitter both in return and volatility, its role disappeared after 2005. Therefore, market participants should treat benchmarks differently. Those who care more about price or return should pay more attention to Brent, while those with a greater concern about volatility or risk should track WTI closely.

4.5.4 Trans-group directional spillover

In this section I aggregate the spillover index of crudes at group level, to see how the shocks transmit within and across different groups. Diebold and Yilmaz (2015b) illustrate that the spillover table is still informative after aggregating. They aggregate stocks of financial institutions at national level, and find the aggregated spillover table and plot could help to show how shocks to stocks in one country spread to stocks in other country. Following a similar method, I classify the crudes by region, by quality and by OPEC/non-OPEC memberships according to Table A.1.

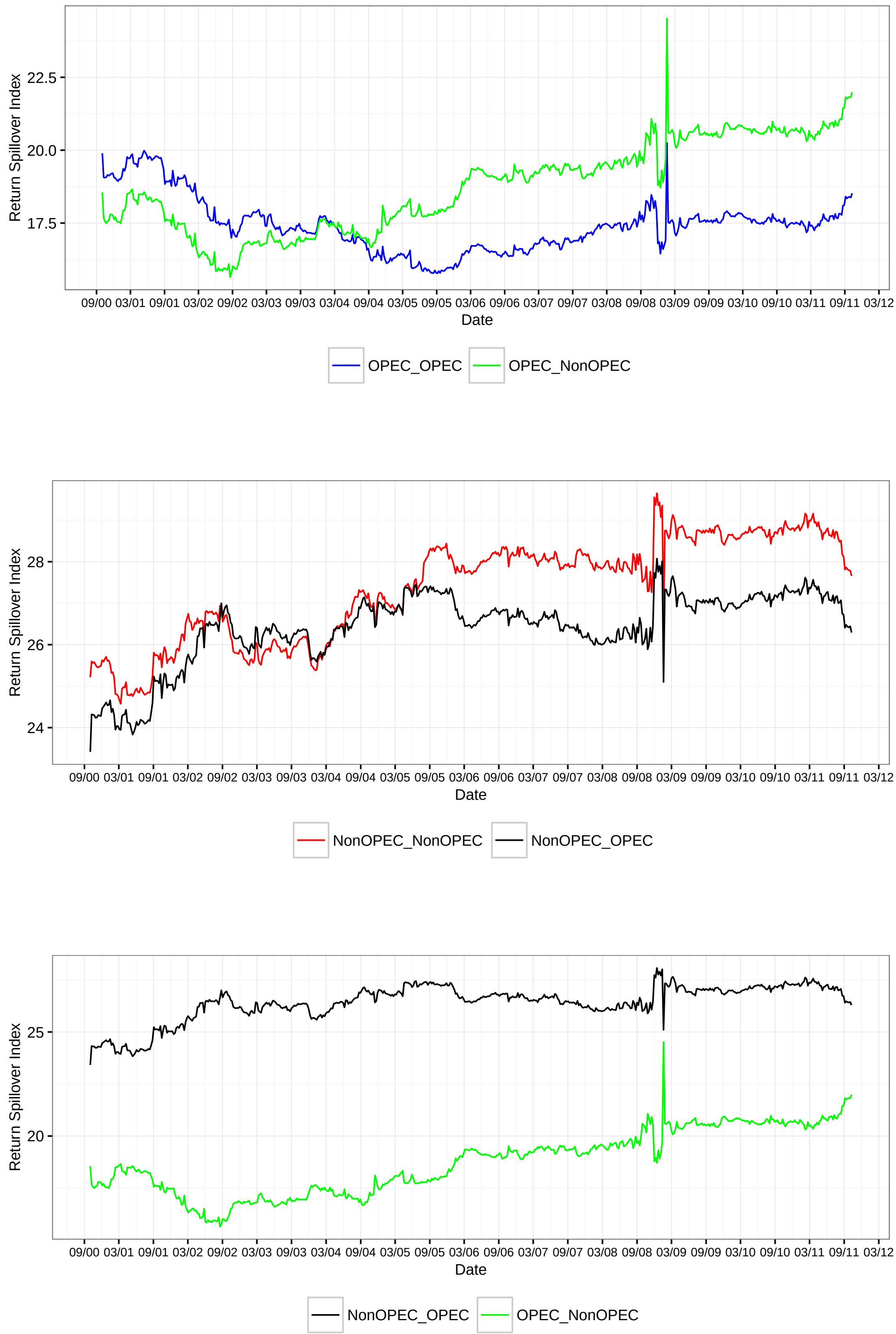
4.5.4.1 Grouped by OPEC membership

OPEC, as a price cartel, used to have strong market power. However, recently some researchers have challenged their status. For example, Huppmann and Holz (2012) pointed out that after 2008, OPEC has become less able to exercise market power, possibly because of the market restructuring engendered by 2008 global recession. But there are also empirical evidence which shows the difference between OPEC crudes and non-OPEC crudes: Wlazlowski et al. (2011) found prices of crudes from OPEC countries follow each other more closely than prices of non-OPEC countries, which is in line with OPEC's pricing policy; Giulietti et al. (2014) found that if two crudes are both produced by OPEC countries, they are slower to adjust to equilibrium after an exogenous shock, compared with two crudes produced by non-OPEC countries. Thus they conclude that OPEC is able to protect them from global price competition when exogenous shock moves the price away from equilibrium. In this analysis, the question: 'does the OPEC group transmit shocks (return or volatility) to non-OPEC group, or vice versa?' is investigated. In order to obtain the spillover index at group level, the pairwise spillover index is aggregated as follows: if both crudes in the pair are produced by OPEC countries, this pair is marked as "$OPEC\_OPEC$"; if the spillover is from an OPEC crude to non-OPEC crude, the pair is marked as "$OPEC\_non-OPEC$". In a similar fashion there are also "$non-OPEC\_OPEC$" and "$non-OPEC\_non-OPEC$" pairs. All the pairwise spillover that belong to the same group are then added together to get the group spillover index. The diagonal elements of the spillover table are not included, i.e. the spillover of its own. This operation is applied to the spillover table at every time point to get the time series of group spillover index. Figure 4.7 and Figure 4.8 display the group directional spillover of return and volatility, respectively.

In Figure 4.7, the upper panel presents the plot of return spillover originating from crudes in OPEC group, while the middle panel displays the return spillover originating from Non-OPEC group. The lower panel brings together the return spillover from OPEC to non-OPEC and from non-OPEC to OPEC that appeared as green and black lines in the first two panels.

First, from the lower panel, it can be observed that it is the non-OPEC group that transmits shocks to OPEC group, not the other way around. This is reasonable because WTI and Brent, the two largest return spillover transmitters, as discussed in individual and pairwise analysis, belong to the non-OPEC group. Second, the spillover index from the OPEC to the non-OPEC group increases with time, as reflected by the ascending green line in the plot. Therefore our analysis does not support the claim that OPEC's market power is diminishing. Finally, notice that difference between the two lines had an expansion in late 2008 and then had a sharp decrease at the beginning of 2009. Referring

FIGURE 4.7: Return spillover: grouped by OPEC membership



Note: This picture presents the return spillover aggregated according to OPEC/non-OPEC membership. The “’” in the legend could be read as “to”, i.e. the plot shows the net spillover from the former group to the latter group. The format of the date on the x axis is “mm/yy”.

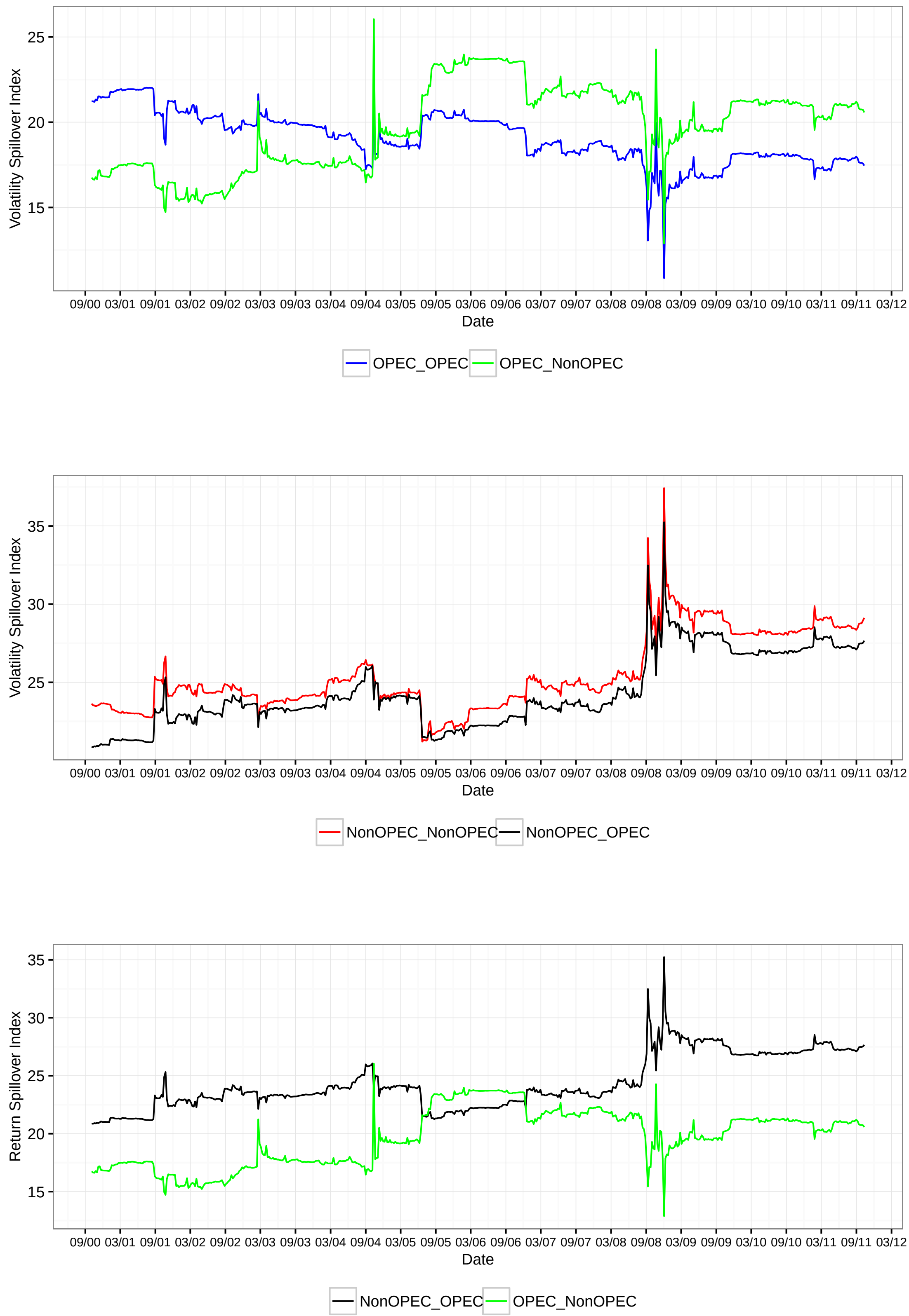
to the crude oil price plot in Figure B.3, the crude oil price jumped to a peak in the middle of 2008, and bumped down again at the beginning of 2009. Therefore during the price collapse, it was non-OPEC crudes that transmitted shocks to OPEC crudes, but at the rebound, the difference between two groups was very small, implying a close interdependence during this process, i.e. the shocks transmitted to and from the other group were almost the same, resulting a close to zero net effect.

The within-group return spillover is represented by the blue line in the first panel and the red line in the second panel. The return spillover within the OPEC group is always below 20%, less than that within the Non-OPEC group, which is above 25%. On the other hand, there is no clear trend of spillover within the OPEC group, but in the non-OPEC group, the return spillover is generally increasing, implying an integrating market. The relationship of crudes in the OPEC group, is relatively stable.

Comparing the two lines in each panel, the OPEC group transmitted more shocks to the non-OPEC group than that within the OPEC group after 2005. But for the non-OPEC group, the return spillover happened more within its own group rather than being transmitted to the OPEC group.

Figure 4.8 presents the volatility spillover within and across OPEC/non-OPEC groups. regarding From the lower trans-group panel it can be observed that: before the middle of 2005, it was the non-OPEC group that transmit volatility to the OPEC group, possibly because of Brent and Russian Urals (URL), both non-OPEC crudes, transmitted volatility shocks to all the other crudes before 2005, as we have discussed in the individual and pairwise analyses. When its influence diminished in 2005, the OPEC group became a net volatility transmitter to the non-OPEC group. But their roles soon reversed. Since 2007 the OPEC group was a pure volatility receiver from non-OPEC crudes. Similar to

FIGURE 4.8: Volatility spillover: grouped by OPEC membership



Note: This picture presents the volatility spillover aggregated according to OPEC/non-OPEC membership. The “” in the legend could be read as “to”, i.e. the plot shows the net spillover from the former group to the latter group. The date at the x axis is in “mm/yy” format.

return spillovers across the group, the difference between two groups was almost zero at the beginning of 2009, reflecting a close interdependence between them.

Comparing the within-group spillover, the non-OPEC group has a slightly higher index than the OPEC group: its within volatility spillover is above 20% while the latter one fluctuates around 20%. Similar to the return spillover, there is no clear trend of volatility spillover within the OPEC group, but in the non-OPEC group, the volatility spillover is generally increasing, implying an integrating market. The relationship of crudes in the OPEC group, is relatively stable.

Comparing the two lines in each panel, the OPEC group transmitted more volatility to the non-OPEC group than that within its own group since 2005. The non-OPEC group, however, has more volatility spillover within its own group than to the OPEC group, although the net effect is not particularly obvious. This is reflected in that the two lines in the middle panel are very close to each other most of the time.

4.5.4.2 Grouped by qualities

One reality in the spot crude oil market is that there is more and more low-quality crudes, due to the fact of increasing demand and depletion of old oil fields. However, the benchmarks like WTI and Brent are both light and sweet, high quality crudes. Some researchers therefore question the relevance of these benchmarks (e.g.Bahree & Gold, 2006; and Ghoshray & Trifonova, 2014). Because the share of low quality crudes in worlds production is increasing, the influence of these crudes should increase as well. In this section this will be analysed.

Crudes are classified into five groups according to their physical features. These groups are light sweet (9), light sour (2), medium sweet (6), medium sour (13) and heavy sour (2)[16]. Table A.1 presents the physical properties of each crude.

Because there are five groups, it is difficult to compare the net effect by observing the difference between lines as in the OPEC/non-OPEC group. Therefore the **net** group spillover indexes will be calculated plotted. After aggregating the pairwise spillover index into groups as with the OPEC/non-OPEC group, I obtrain the net trans-group spillover index by subtracting the spillover in opposite direction. For example, the “Light Sweet _ Medium Sour ” group spillover index minus the “Medium Sour _ Light Sweet” group spillover index is the net trans-group spillover index, which captures the net directional effects between groups. However, in this way it is not possible to observe the net spillover index within group, because it is always zero after netting.

Figure 4.9 shows the dynamics of net return spillover between different groups. From the first panel, we can observe that light sweet group is a net transmitter of return spillover to all the other groups, because all the lines representing the net spillover index from light sweet to other groups are above zero. Among these groups the light sweet group has most influential power over the medium sour group, as shown by the black line in the plot. This observation is also confirmed by the other four panels, in which the blue line representing the net return spillover from one specific group to light sweet group, is always below zero, implying that this group is receiving shocks from the light sweet group. This is not surprising, because the WTI and Brent benchmarks are both high quality light sweet crudes.

The medium sour group, which has a share of 40% in our sample, was a net transmitter to the medium sweet group before September 2004, as can be observed from the second

[16]The numbers in brackets are the amount of crudes in the group.

FIGURE 4.9: Return net spillover: grouped by quality

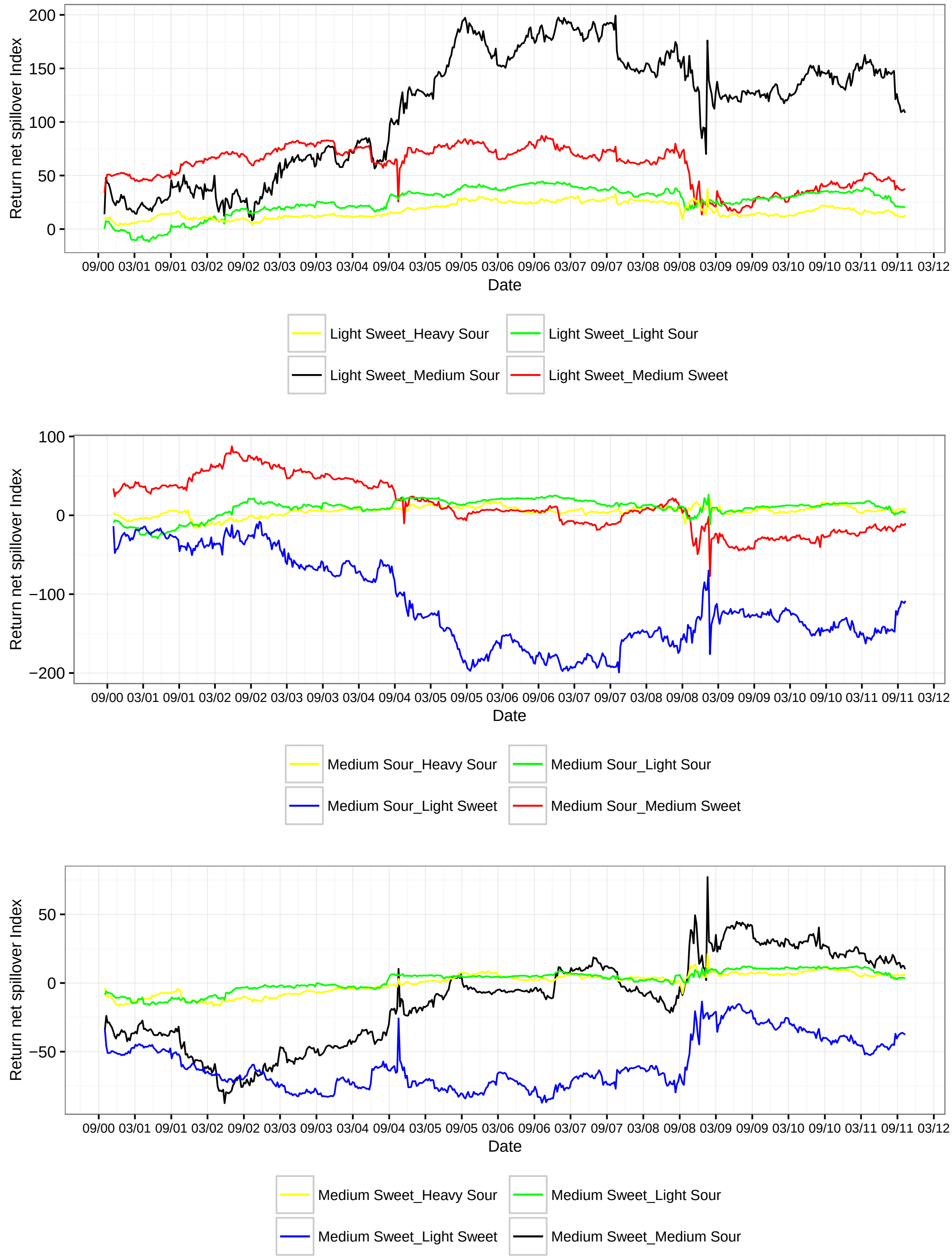
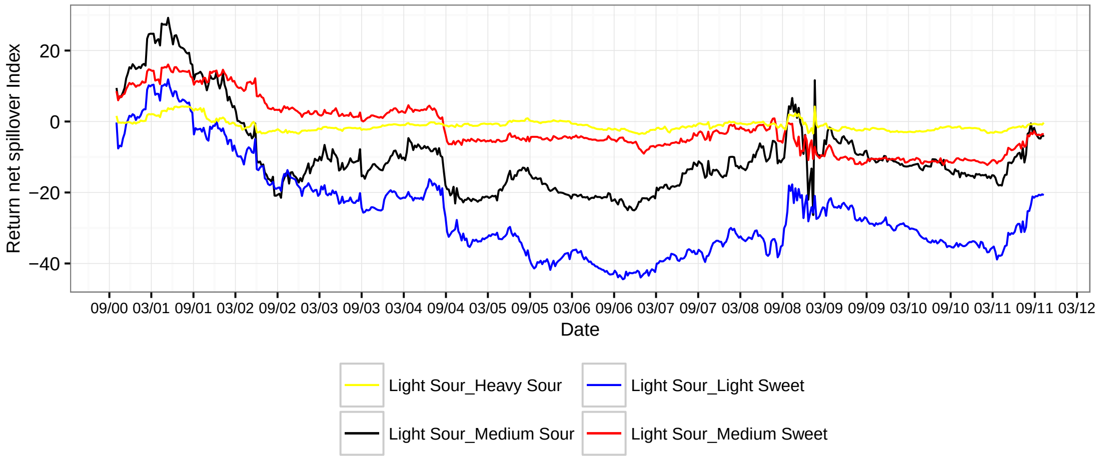
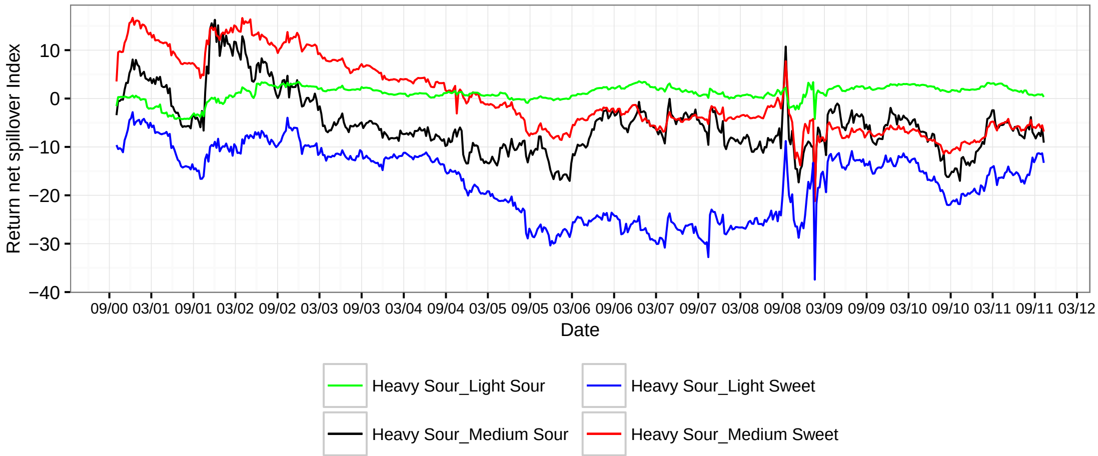


FIGURE 4.9 (cont.): Return net spillover: grouped by quality (Cont.)





Notes: These graphs show the return net spillover across different quality groups. The "_" in the legend could be read as "to", i.e. the plot shows the net spillover from the former group to the latter group. The format of the date on the x axis is "mm/yy".

panel in Figure 4.9. However, their roles reversed after September of 2008, when the medium sour group became a net receiver of shocks from the medium sweet group. This can be confirmed in the third panel. Therefore although the medium sour crudes occupy a large share of the market, they do not have large and stable influence on other kinds of crudes in terms of return spillover.

In most of the study period, the light sour and heavy sour groups are net receivers. Although they had some spillover effect at the beginning of the sample period, this effect was small compared with the effects shown in the first three panels (note the scale of y axis in the different panels).

FIGURE 4.10: Volatility net spillover: grouped by quality

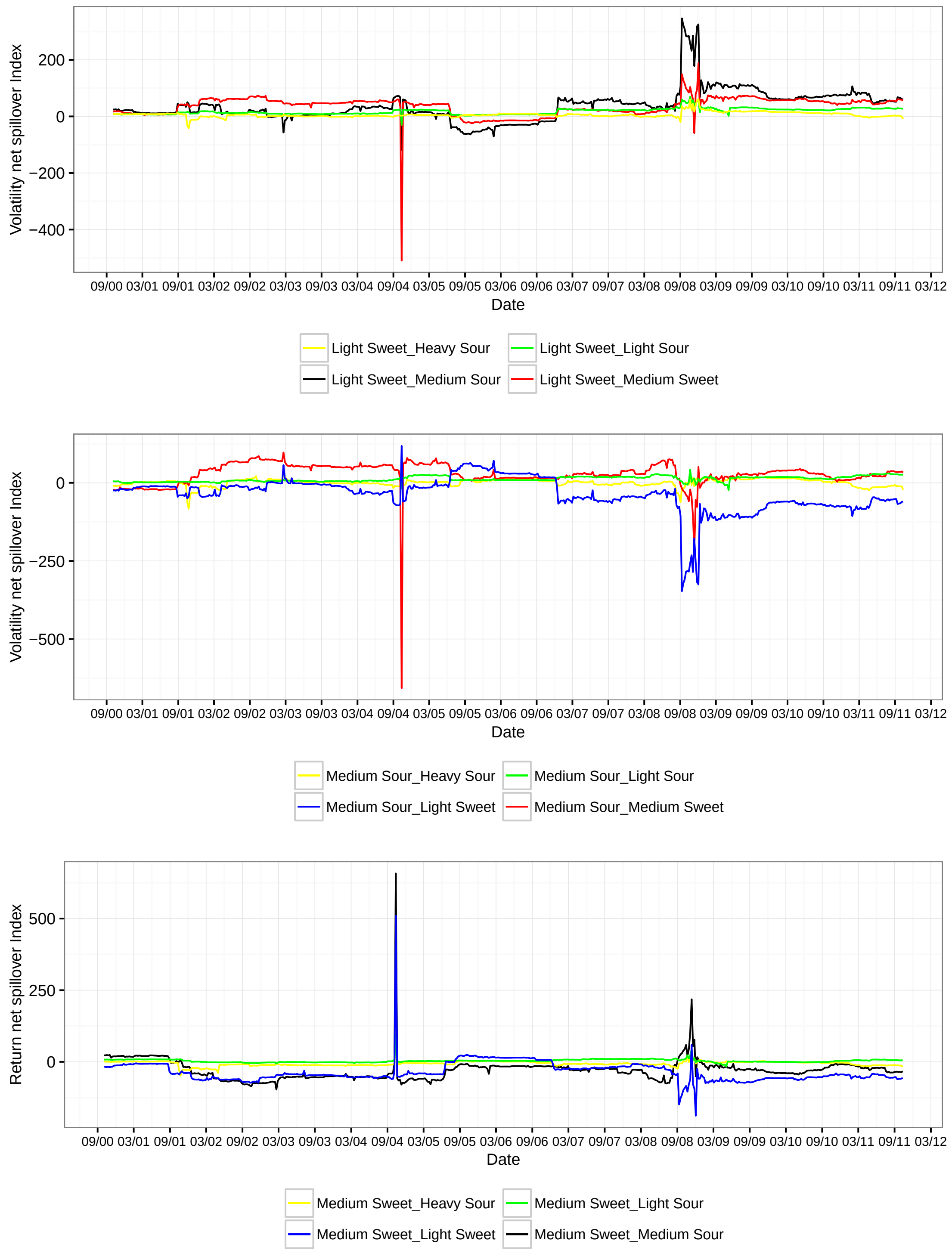
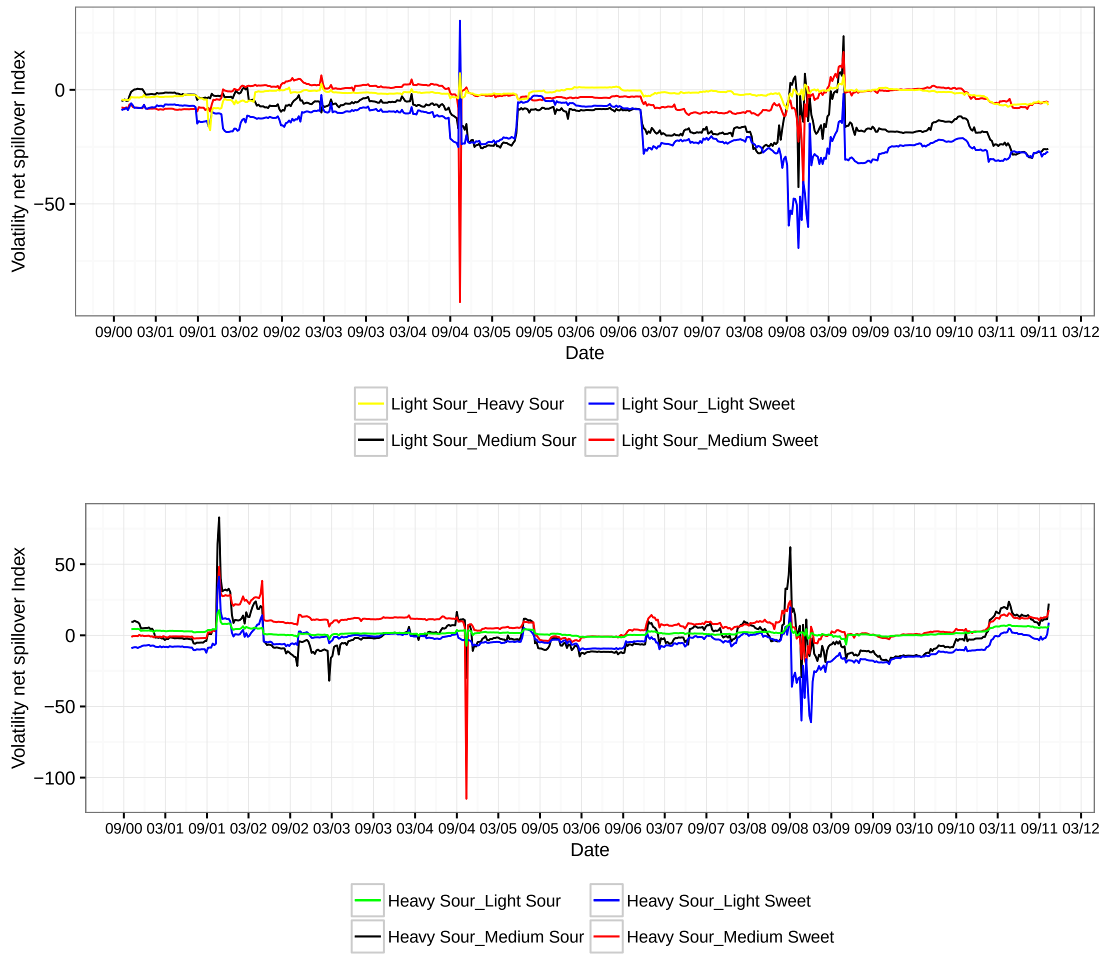


FIGURE 4.10 (cont.): Volatility net spillover: grouped by quality (Cont.)



Notes: These graphs show the volatility net spillover across different quality groups. The “_” in the legend could be read as “to”, i.e. the plot shows the net spillover from the former group to the latter group. The format of the date on the x axis is “mm/yy” format.

Figure 4.10 displays the dynamic of volatility net spillover between the different groups. The volatility spillover plot is characterized by spikes, as was noticed previously. In this section we focused on the constant and stable effect. From the first panel of Figure 4.10, the light sweet group was transmitting volatility shocks to the medium sweet group before the middle of 2005, but then receiving then from the medium sour crudes until early 2007. After that the light sweet group was generally transmitting volatility shocks to all the other groups, especially during the financial crisis when crude oil price collapsed. WTI, as the largest volatility transmitter since 2007 as discussed in Section 4.5.2, is a light and sweet crude, and therefore contributed significantly to the transmitting behavior of light sweet group since 2007.

The second panel of Figure 4.10 shows that before the middle of 2005 the medium sour group transmits volatility shocks to the medium sweet group. This fact may due to Russian Urals, which is a medium sour crude and acted as volatility shock transmitter before 2005. Since 2007 the medium sour group was receiving volatility shocks from the light sweet group. During financial crisis in late 2008, it was also receiving volatility shocks from the medium sweet group.

The third panel shows that the medium sweet group is a net volatility receiver during most of the study period, mainly from the medium sour and light sweet group. It can be observed that the medium sweet group caused the spikes in October 2004. This is because China Daqing (CDS) and Indonesia Minas (MNS) belong to this group.

The light sour and the heavy sour groups are generally net volatility receivers, mainly from the medium sour and the light sweet groups, as shown in the fourth and fifth panels.

4.5.4.3 Grouped by regions

In this section the crudes are classified according to their origins, as labeled in Table A.1. Diebold and Yilmaz (2015a) have observed that stock markets located in the same region have a high pairwise spillo ver. Although within-group spillover is not visible because of netting, it can be inferred that crudes from nearby geographic regions will have a high spillover index. Ji, Zhang, and Fan (2014) identify three trading blocs in the current global oil trade network, these are, the 'South America-West Africa-North America' trading bloc, the 'Middle East- Asian-Pacific region' trading bloc, and 'the former Soviet Union-North Africa-Europe' trading bloc. Therefore we expect crudes from these regions to have a high spillover index because of their close trading relationship s. In our sample there are five regional groups (each with a number of crudes): America (8), Europe (3), Middle East and North Africa, MENA for short (13), Asia and Australia (4), and Sub-Saharan Africa (4)[17].

Figure 4.11 displays the dynamics of the trans-region net return spillovers. The first panel shows that America was transmitting shocks to MENA, but receiving shocks from Europe. It was also a net transmitter to Asia and Australia. The net transmitting effect to Sub-Saharan Africa was not obvious. The American region is relatively independent from other continents geographically, and is comparatively far from the Middle East, so its significant influence over MENA cannot be a result of geography.

The second panel shows that Europe is a net transmitter to all the other regions, with a temporary exception during the financial crisis when it was receiving shocks from America. The group it could influence most is MENA. This may be a result of close distance and trading relationships. The influence over MENA, however, is generally decreasing.

Middle East and North Africa (MENA), although the basis of OPEC membership, was surprisingly, in general, a receiver of shocks from other regions. The only region it had positive influence on, is Asia and Australia and only before the financial crisis. This is consistent with the relationships within the 'Middle East- Asian-Pacific region' trading bloc proposed by Ji et al. (2014). However, after the crisis this influence disappeared.

The Asia and Australia region was generally a receiver of shocks, but after the 2008 financial crisis it was a net transmitter to MENA. The reason could be the demand

[17]Numbers in brackets are the amount of crudes in this group.

FIGURE 4.11: Return net spillover: grouped by regions

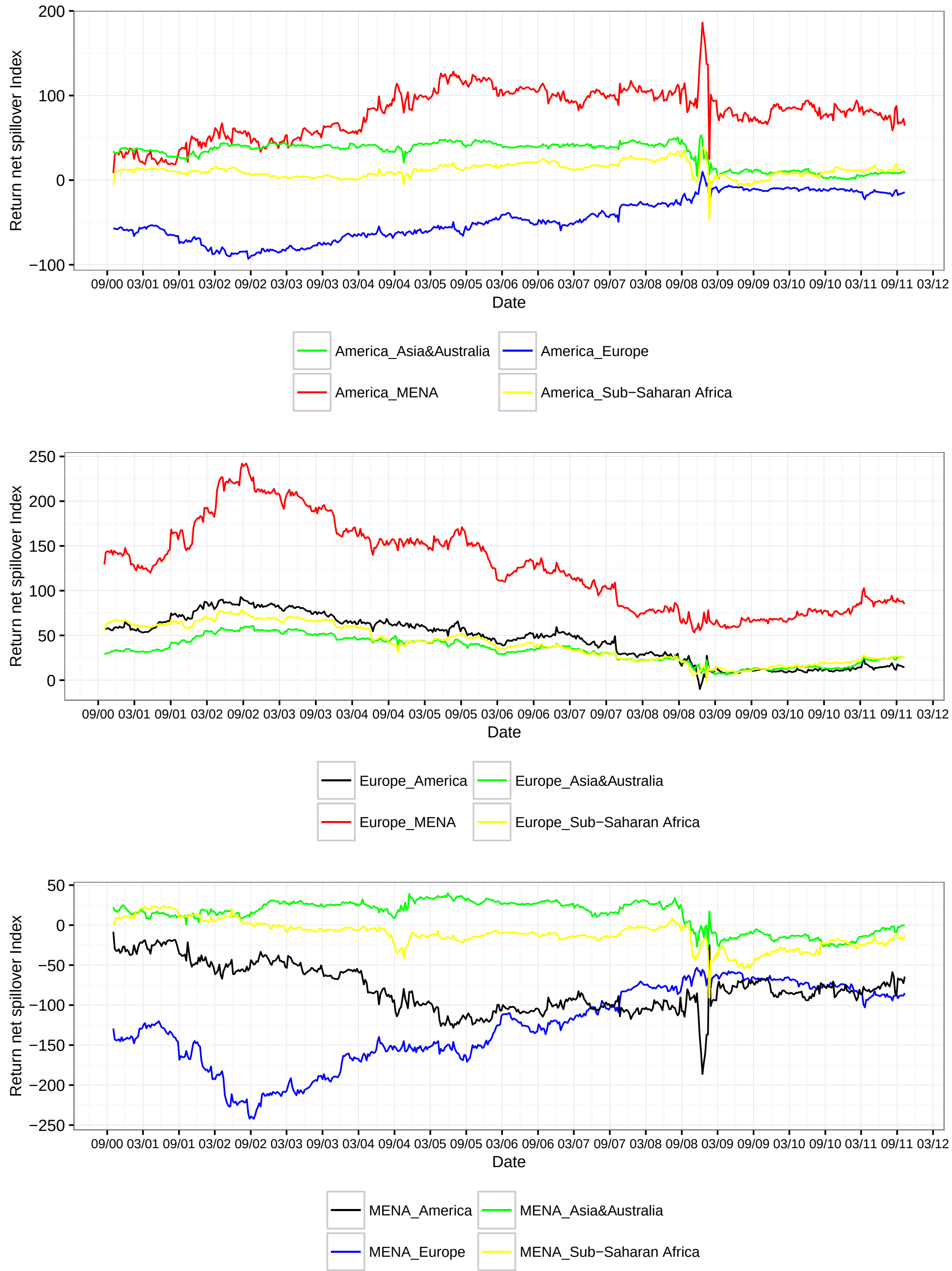
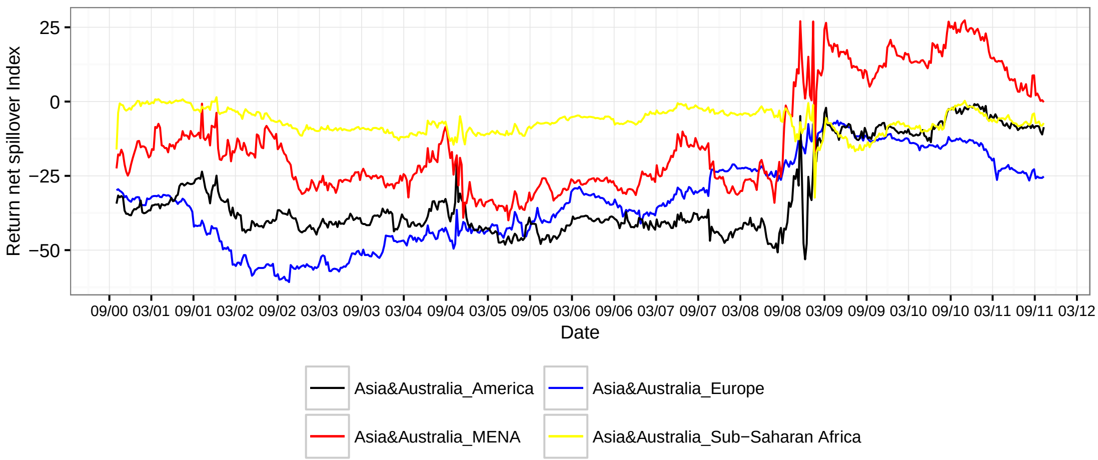
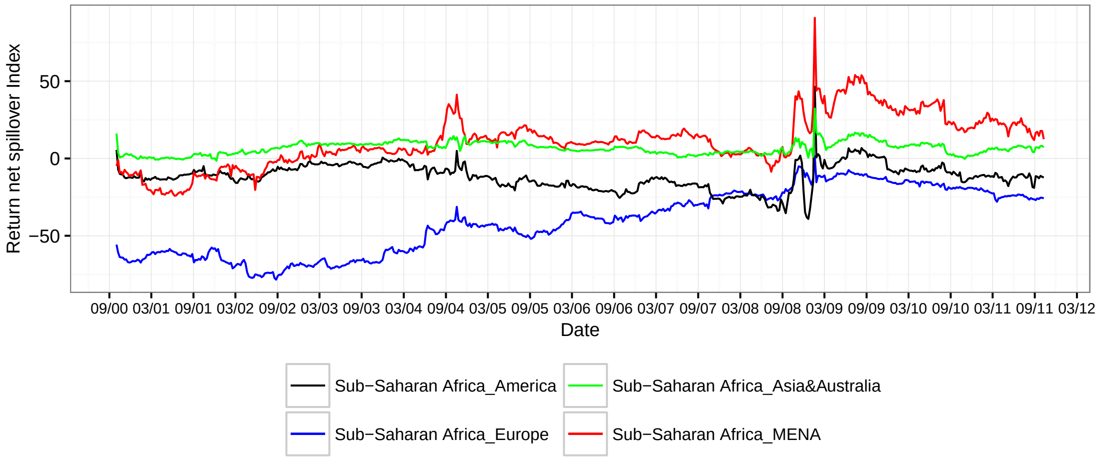


FIGURE 4.11 (cont.): Return net spillover: grouped by regions (Cont.)





Notes: These graphs show the return net spillover across different region groups. The "_" in the legend could be read as "to", i.e. the plot shows the net spillover from the former group to the latter group. The format of the date on the x axis is "mm/yy".

shock from the fast development of China in this period. However, at the end of 2011 this net transmission effect was diminishing towards zero.

Sub-Saharan Africa region is a net receiver of shocks from Europe and America, but is a small transmitter to Asia and Australia and MENA. Its influence over MENA became significant during and after the financial crisis.

Figure 4.12 displays the dynamics of trans-region net volatility spillovers. America received volatility from Europe before the middle of 2005. During and after the 2008 financial crisis it was a net transmitter to all the other regions, especially MENA.

FIGURE 4.12: Volatility net spillover: grouped by regions

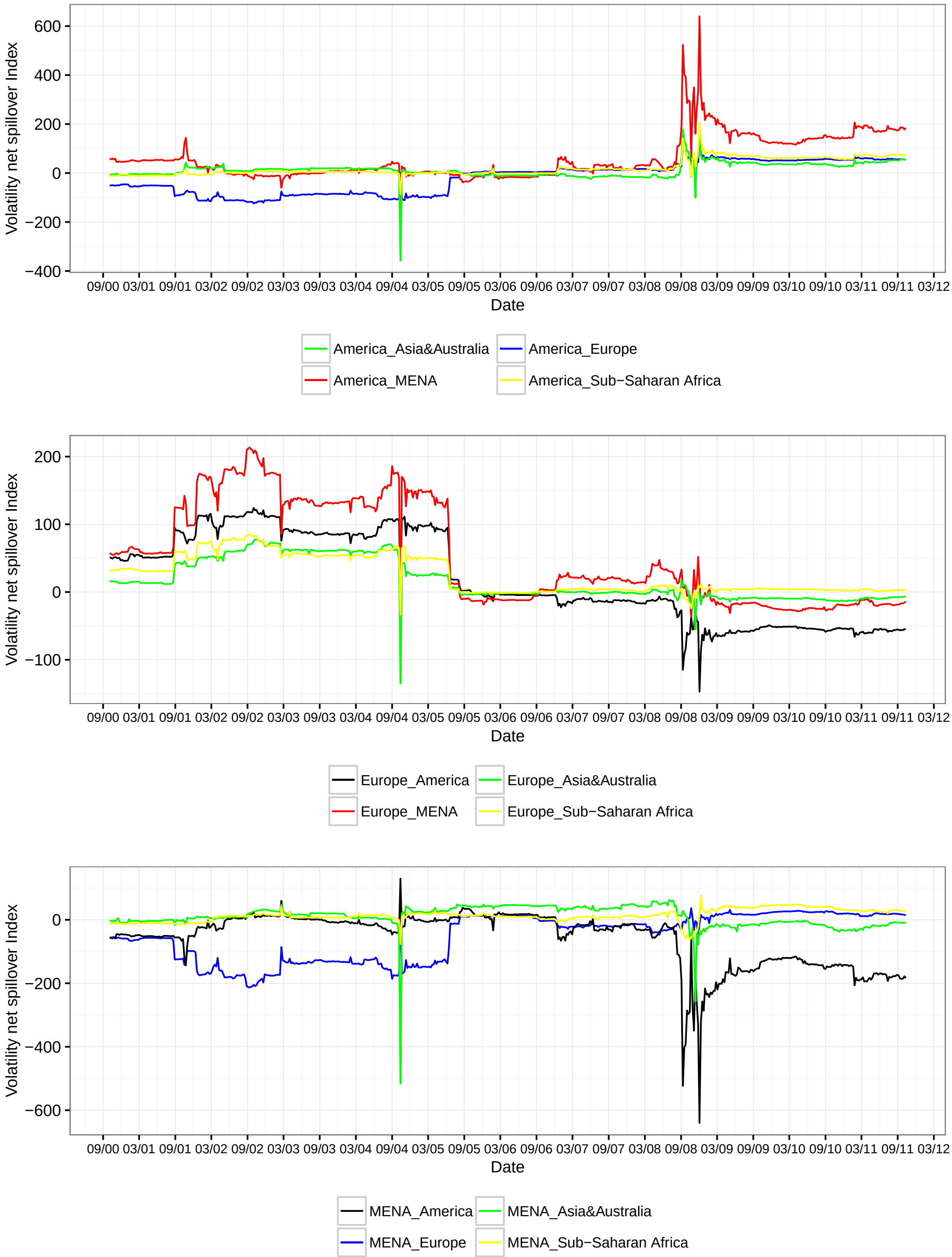
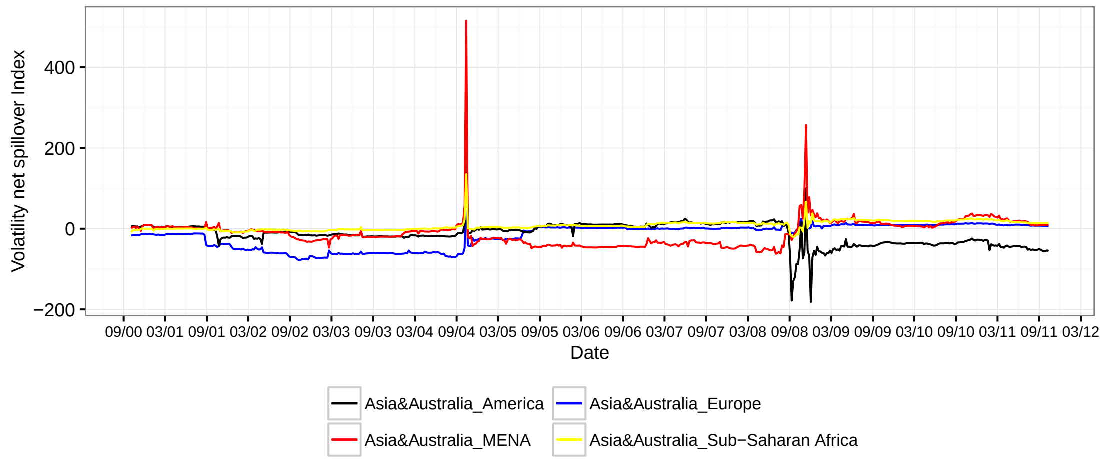
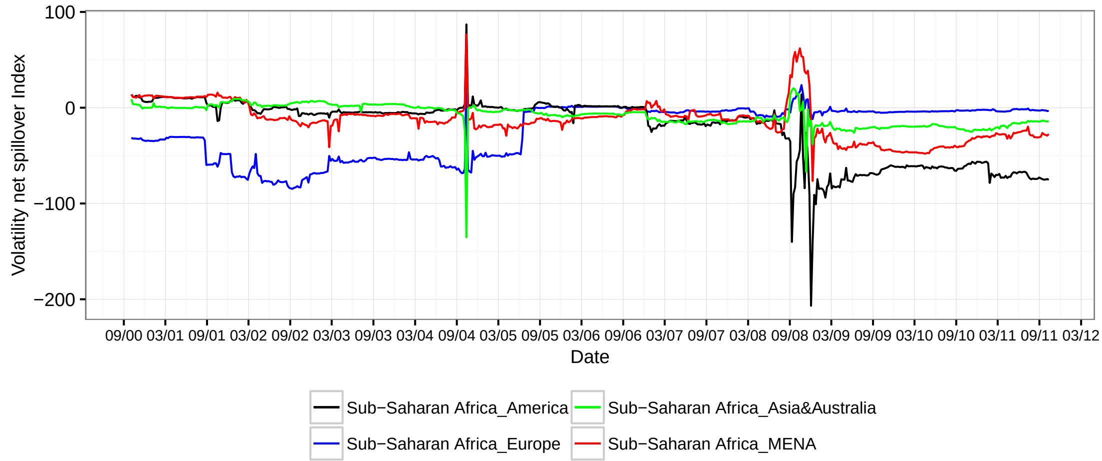


FIGURE 4.12 (cont.): Volatility net spillover: grouped by regions (Cont.)





Notes: These graphs show the volatility net spillover across different region groups. The "_" in the legend could be read as "to", i.e. the plot shows the net spillover from the former group to the latter group. The format of the date on the x axis is "mm/yy" format.

Europe was transmitting volatility to the other regions before the middle of 2005, but afterwards it was receiving volatility from other regions, especially America.

MENA was a small volatility transmitter to the Asia and America region from 2005 until the financial crisis. During the crisis it was receiving volatility shocks from America.

Asia and Australia was generally a volatility receiver, from Europe from 2001 to 2005, and from MENA from 2005 to 2008. Since the financial crisis it has received volatility from America.

Sub-Saharan Africa only temporarily transmitted spillover to MENA during the financial crisis. In general it was a volatility receiver, and recently the volatility was mainly from America and MENA.

4.5.5 Summary of dynamic analysis

Dynamic analysis gives much more information than static analysis. Particularly, it can show the role of a crude in a time line. The majority of previous studies suffer from the problem of sensitivity of spillover effect with regards to different sample periods, which makes their conclusions valid only during a specific time period (Zheng & Zuo, 2013). In this analysis, the conclusion of Wlazlowski et al. (2011) about Urals as a potential benchmark is quite robust, for both return and volatility. But this conclusion was only valid before September 2005. After that the influence of Russian Urals disappeared. This dynamic analysis can capture the time - varying roles of crudes, and allow it to be visualized detailed way. In addition, the netting and aggregating of the spillover index allow us to gauge the spillover effects at different levels.

The findings are summarized as follows. First, the individual directional spillover study shows that WTI and Brent are dominant return spillover transmitters over the whole sample period, which is consistent with their benchmark role in the crude oil market. Russian Urals used to have a large net return spillover effect to other crudes, but this effect disappeared after 2005.

However, in terms of volatility, benchmarks such as WTI and Brent do not always spread volatility to the others. Instead, their transmitting roles are time varying. Before 2005, it was Brent that transmitted volatility shocks, as well as Russian Urals (URL). However, since 2007, WTI has become the dominant transmitter, and its spillover effect was most significant during the financial crisis.

The different behavior of WTI and Brent regarding return and volatility in this analysis, to some extent, reconciles the debate over WTI's role between Kao and Wan (2012) and Elder et al. (2014). Kao and Wan (2012) proposed that compared to Brent, the ability of WTI to reflect market conditions decreases sharply from the second half of 2004 to February 2009. The rising inventories in Cushing significantly deteriorate WTI's ability to serve as world benchmark. This is consistent with my analysis of pairwise return spillover, as displayed in Figure 4.5, in which Brent's influence to WTI was most significant from early 2005 till late 2008. In contrast, Elder et al. (2014), with similar method but high frequency data, found WTI maintains a dominant role in price discovery relative to Brent, in a sample period from January 2007 to April 2012. This is consistent with my analysis of pairwise volatility spillovers, as displayed in Figure 4.6, in which WTI became a dominant transmitter of volatility shocks from early 2007 until the end of the sample. Therefore, the high-frequency analysis of Elder et al. (2014) is more relevant to volatility which mainly reflects the ability to incorporate new information, while the analysis of Kao and Wan (2012) is more relevant to returns. As commented in Lehmann (2002), the information measure in the model of Hasbrouck (1995), i.e. the method used by Kao and Wan (2012) and Elder et al. (2014), is based on the residuals of a vector error correction model in the reduced form, which does not always make the interpretation of information share measure clear. My analysis may shed some light on this issue. Although Kao and Wan (2012) and Elder et al. (2014) apply the same method, the information share measure with different frequency data may reveal different information, resulting in different results.

Second, pairwise directional spillover plots provide a more detailed picture of spillover effects between each pair of crudes. The results are generally consistent with those of the individual directional spillovers, but the pairwise spillover analysis reveals more information, such as which crude has what kind of influence over the other crudes.

Finally the crudes are classified into groups in different ways. The spillover indexes are aggregated to study the trans-group spillover effect. The non-OPEC group is a return transmitter to the OPEC group. This is possibly because the two benchmarks, WTI and Brent, belong to the non-OPEC group. However, the OPEC group's influence over the non-OPEC group is shown to be increasing over time. For volatility, two groups roles have changed several times during the sample period. Generally the OPEC group is a volatility receiver from the non-OPEC group, particularly before 2005 and after 2007.

The net spillover index can be used to measure the trans-group effect of quality and region. The light sweet group is a return transmitter to all of the other groups, and has had the largest impact on the medium sour group since 2004. Although the low quality of medium sour crudes occupies a large share of the market, it fails to have large and stable influence over other crudes. The light sour and heavy sour groups are generally receivers. In terms of volatility, there is no constant receiver or transmitter, but the light sweet group has been a net volatility transmitter to other groups since 2007.

For the regional groups, the Europe group is the net return transmitter to all the other groups. The America group is the second most significant transmitter, following Europe. MENA, although the base of OPEC membership, is generally receiving return shocks from the other regions. It only has a small return spillover effect to the Asia and Africa region before 2009. The Asia and Africa region and Sub-Saharan Africa regions are generally receivers, but had some transmission effect to MENA groups during and after the 2008 financial crisis. In terms of volatility, the roles of each group is time varying. Before 2005, the Europe group is largest net transmitter to other regions. From 2005 to early 2008 MENA slightly transmitted volatility, mainly to Asia and Australia. Since the financial crisis in late 2008, the America group has become a net transmitter to other regions.

4.6 Robustness test

4.6.1 Alternative forecast horizon and window width

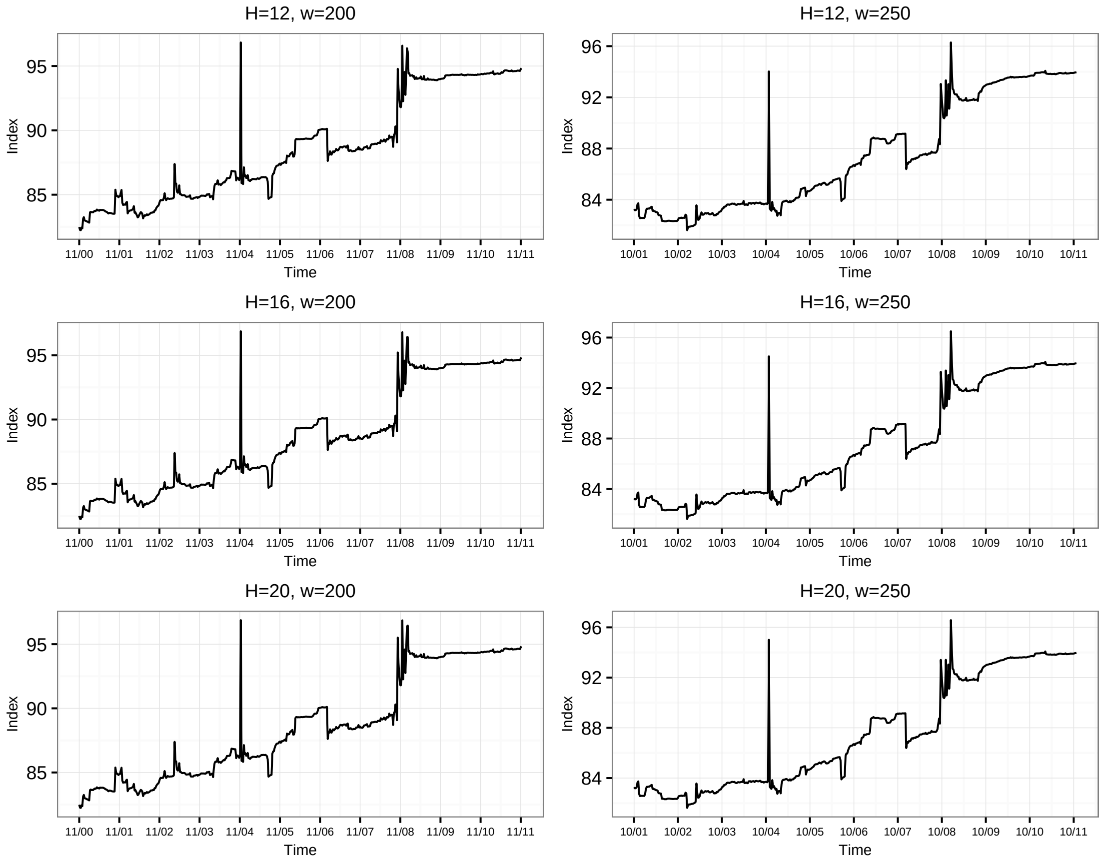
A forecast horizon of 16 weeks and rolling sample width of 200 weeks was chosen in the above analysis. To check if the patterns discovered previously are still valid under different conditions, the dynamic spillover indexes of volatility for alternative forecast horizons (12 weeks and 20 weeks[18] in addition to the original 16 weeks) and window width (250 weeks[19]) are plotted.

Figure 4.13 shows that the patterns of total spillover index series are almost the same under alternative forecast horizons but the same window width. However, the patterns changes slightly under the increased window width with same forecast horizon. First, the spike caused by the 9/11 terrorist attack disappears under the 250 week window, mainly because the first window contains the timing of 9/11 attack, thus the rolling cannot show its effect. Second, the size of spike decreases compared with that of smaller width. The spike caused by the 2003 Iraq invasion is not obvious under the 250-week condition. However, the spike caused by China Daqing and Indonesia Minas in 2004, remains remarkable. In general, a larger rolling window width keeps the pattern of the smaller rolling width, especially the bursts corresponding to events. Therefore the dynamic behavior of total spillover index over the rolling-sample windows is robust to the choice of forecast horizons and sample window width.

[18] That is 3 months and 5 months respectively.

[19] As stated in Section 4.5.1, sample size smaller than 200 cannot develop the model. Therefore for robustness test, only sample size larger than 200 could be selected as alternative choice.

FIGURE 4.13: Robustness of spillover plots



Notes: This figure presents spillover plots with different forecast horizons H and window width w for volatility. The interval of the axis x is 10 months.

4.6.2 Alternative return: based on Friday price

Wednesday price was employed to generate weekly returns in the previous analysis in order to avoid weekend effects. In this section Friday to Friday price is checked to determine if this generates different results.

First the spillover indexes and spillover tables are checked for robust to variable orderings. The Friday to Friday spillover index $SOI_{min} = 84.08\%$[20],$SOI_{max} = 86.2\%$[21], and $SOI_{avg} = 85.32\%$. These numbers are close to those generated by Wednesday to Wednesday prices.

[20]The corresponding ordering of variables is (URL, TJN, WTI, ESD, DBF, ORT, SSH, MYA, KWT, TPS, CBD, LYD, TJN, CDQ, MBN, CLM, IRL, IRH, DKN, SHR, GPL, EFK, FCD, OMN, SUZ, SSL, CPR, BNL, KLE, IMS, SAM, BRT)

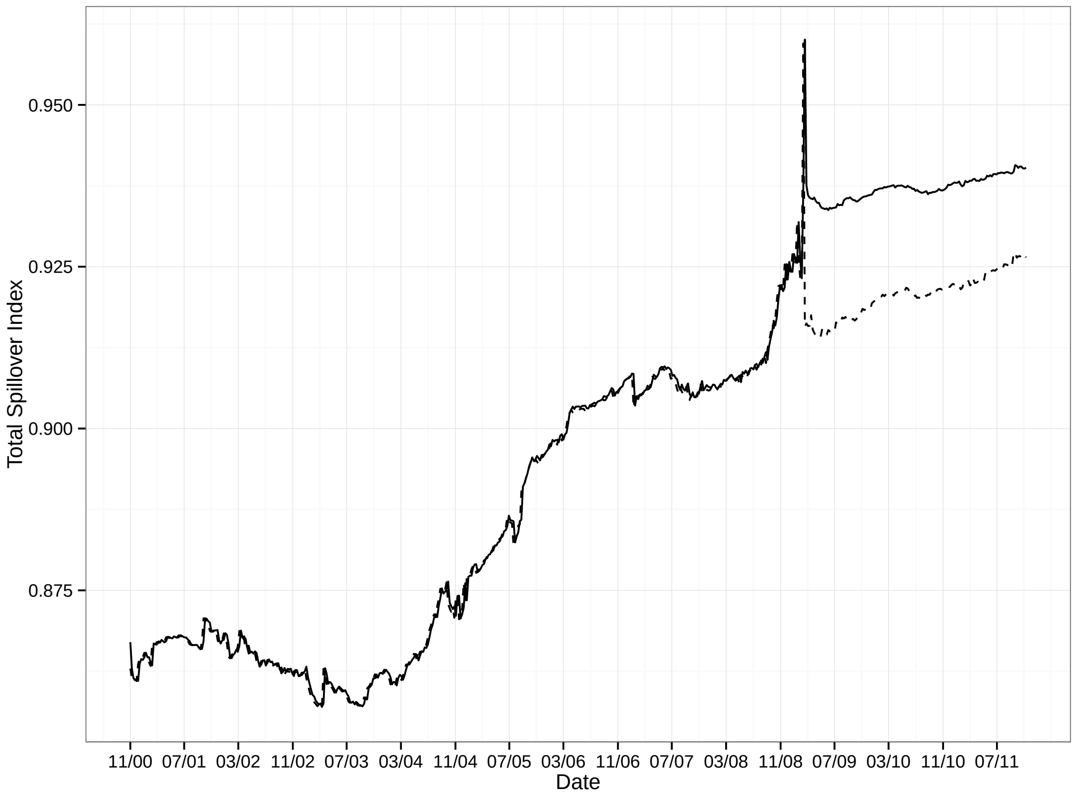
[21]The corresponding ordering of variables is (KLE, OMN, EFK, KWT, SHR, IMS, IRH, ESD, FCD, CPR, SUZ, SAM, SSL, IRL, DKN, GPL, MYA, BNL, ORT, CDQ, SSH, MBN, TPS, CBD, CLM, MNS, WTI, DBF, LYD, BRT, TJN, URL)

TABLE 4.3: Average spillover table SOT_{avg} for Friday return

	WTI	BRT	EFK	CPR	LYD	IMS	MYA	CLM	ORT	CBD	KLE	SUZ	OMN	GPL	TPS	URL	CDQ	SSL	SAM	SSH	MBN	DBF	DKN	IRL	IRH	KWT	SHR	BNL	FCD	ESD	MNS	TJN	From
WTI	21.63	5.72	2.38	2.6	2.18	7.25	3.24	5.42	4.19	2.36	1.91	2.4	1.96	1.49	0.67	4.15	1.32	1.98	1.91	1.83	1.74	1.37	1.55	1.97	2.02	1.56	2.15	2.03	2.28	2.16	0.94	3.63	78.37
BRT	7.06	15.79	3.52	1.66	1.43	3.21	2.34	2.69	1.94	3.68	3.12	3.54	2.61	1.69	0.82	6.91	1.43	2.25	2.28	2.22	2.15	1.92	2	2.42	2.5	1.9	3.34	3.21	3.72	3.47	0.99	2.15	84.21
EFK	6.57	11.83	5.8	1.38	1.47	2.92	1.99	2.6	1.81	4.24	3.58	3.97	2.68	1.64	0.7	7.44	1.52	2.19	2.17	2.09	2.16	1.95	2.08	2.34	2.45	1.88	3.85	3.62	4.41	3.87	0.93	1.86	94.2
CPR	7.97	4.64	1.68	37.22	4.5	2.64	1.53	2.52	1.35	1.74	1.35	1.81	1.99	0.99	0.68	4.44	0.98	1.34	1.29	1.24	1.32	1.18	1.51	1.42	1.62	1.16	1.9	1.53	1.76	1.62	1.63	1.44	62.78
LYD	6.55	3.78	1.43	6.48	44.56	2.49	2.96	1.69	1.5	1.39	1.21	1.38	1.23	0.84	0.49	3.96	0.72	1.27	1.39	1.24	0.92	0.86	0.95	1.14	1.29	1.2	1.17	1.39	1.46	1.21	0.63	1.24	55.44
IMS	11.31	7.71	2.8	1.86	1.91	9.14	3.31	4.57	3.59	2.93	2.47	2.9	2.2	1.78	0.78	6.32	1.43	2.1	2.11	2.07	1.99	1.62	1.79	2.13	2.25	1.79	2.66	2.56	2.79	2.71	1.01	3.41	90.86
MYA	8.92	7.42	2.17	1.52	2.16	5.11	18.74	3.32	2.77	2.6	2.26	2.46	2.11	1.74	1.06	5.1	1.47	1.9	1.97	1.98	1.88	1.5	1.68	2	2.16	1.58	2.2	2.2	2.33	2.24	0.91	2.53	81.26
CLM	11.07	6.16	2.29	1.83	1.89	5.69	3.35	13.86	4.86	2.42	1.99	2.45	2.05	1.86	0.72	6.14	1.44	2.02	1.96	1.89	1.86	1.6	1.72	2.03	2.06	1.67	2.16	2.13	2.42	2.27	1.21	2.94	86.14
ORT	10.79	5.37	2.12	1.59	1.49	5.62	3.02	5.71	18.78	2.2	1.77	2.53	1.91	1.61	0.75	4.92	1.39	1.88	1.93	1.97	1.7	1.55	1.61	1.9	2.02	1.56	2.06	2.1	2.14	2.03	1.04	2.92	81.22
CBD	7.03	11.75	3.82	1.4	1.52	2.99	2.19	2.58	1.86	5.83	3.53	3.8	2.52	1.69	0.84	7.09	1.85	2.14	2.15	2.1	2.14	1.92	2.13	2.4	2.55	1.9	3.64	3.51	4.37	3.8	1.05	1.93	94.17
KLE	6.11	11.7	4.14	1.33	1.38	2.85	2.16	2.45	1.76	4.48	8.74	3.71	2.88	1.61	0.81	6.23	1.76	2.04	2.1	2.07	2.04	1.9	2.19	2.22	2.36	1.79	3.62	3.38	3.92	3.45	0.95	1.89	91.26
SUZ	6.62	10.8	3.77	1.41	1.4	2.9	2.07	2.61	1.76	3.81	3.08	7.59	2.7	1.66	0.75	8.18	1.54	2.22	2.23	2.17	2.36	2	2.12	2.35	2.44	1.9	3.43	3.39	3.99	4.02	0.94	1.8	92.41
OMN	8.95	9.59	2.39	1.5	1.54	2.87	2.04	2.36	1.75	2.71	2.2	2.58	6.87	2.13	0.9	4.7	1.85	2.63	2.52	2.44	3.96	3.93	5.04	2.93	3.13	3.97	2.43	2.21	2.61	2.34	1.16	1.79	93.13
GPL	10.24	9.45	2.11	1.32	1.72	3.1	2.55	2.2	1.81	2.27	1.89	2.5	2.69	15.27	1.34	4.02	3.73	2.19	2.2	2.17	1.95	1.86	2.26	2.2	2.32	1.97	2.11	2.05	2.21	2.11	2.22	1.98	84.73
TPS	6.23	3.72	0.91	0.92	0.42	1.68	1.08	1.31	1.37	0.95	0.71	2.15	1.24	2.29	56.14	1.01	1.44	1.3	1.3	1.3	0.78	0.83	0.99	1.68	1.49	1.18	0.77	0.75	0.93	0.82	0.83	1.47	43.86
URL	5.17	8.67	3.1	1.75	1.98	2.34	1.81	2.08	1.41	2.82	2.35	3.12	2.11	1.14	0.7	30.98	0.98	1.54	1.57	1.57	1.71	1.44	1.52	1.71	1.87	1.43	2.71	2.5	3.03	2.71	0.64	1.54	69.02
CDQ	7.84	8.54	2.02	1.25	1.61	2.84	2.39	2.2	1.78	2.09	1.69	2.08	2.46	4.15	1.33	3.89	18.62	2.05	2.01	1.98	1.72	1.68	1.96	2.04	2.07	1.86	1.91	1.98	1.96	1.87	6.27	1.86	81.38
SSL	8.9	10.06	2.69	1.35	1.41	2.97	1.96	2.41	1.77	2.75	2.36	2.8	3.08	2.07	0.89	3.94	2.14	6.16	5.46	4.91	2.64	2.33	2.64	3.12	3.25	2.55	2.56	2.37	2.69	2.63	1.25	1.89	93.84
SAM	9.09	9.87	2.64	1.34	1.46	2.99	1.96	2.46	1.78	2.7	2.35	2.78	3.01	2.05	0.85	3.91	2.01	5.41	6.02	5.74	2.57	2.28	2.54	3.13	3.28	2.58	2.5	2.34	2.64	2.64	1.19	1.89	93.98
SSH	8.94	9.5	2.6	1.32	1.46	2.95	2	2.45	1.79	2.66	2.35	2.76	2.97	2.03	0.83	3.79	1.96	5.29	6.32	6.7	2.53	2.27	2.51	3.11	3.29	2.61	2.44	2.31	2.58	2.64	1.16	1.87	93.3
MBN	9	9.66	2.35	1.38	1.57	2.77	2.01	2.2	1.64	2.57	2.11	2.53	4.59	1.93	0.82	5.22	1.61	2.59	2.52	2.47	6.73	5.19	4.1	2.85	3.11	4.11	2.46	2.17	2.62	2.33	1.05	1.74	93.27
DBF	8.75	9.79	2.39	1.4	1.65	2.78	2.05	2.18	1.68	2.62	2.12	2.52	4.69	1.95	0.85	5.41	1.73	2.53	2.49	2.44	5.15	6.12	4.08	2.84	3.17	4.18	2.48	2.19	2.62	2.35	1.07	1.73	93.88
DKN	9.14	9.66	2.4	1.53	1.53	2.89	1.99	2.37	1.77	2.65	2.17	2.54	5.7	2.11	0.87	4.56	1.78	2.61	2.51	2.44	4.02	3.79	6.52	2.92	3.11	3.86	2.44	2.21	2.62	2.36	1.15	1.8	93.48
IRL	8.31	10.01	2.95	1.4	1.56	2.94	1.94	2.35	1.81	3.05	2.43	3.26	3.19	2.01	0.94	4.39	1.86	3.04	3.03	2.96	2.63	2.51	2.73	6.47	5.8	2.62	2.71	2.49	2.88	2.72	1.12	1.89	93.53
IRH	8.12	10.32	2.94	1.39	1.59	2.92	1.95	2.24	1.79	3.06	2.39	3.27	3.2	2.01	0.87	4.39	1.86	2.97	2.98	2.94	2.65	2.58	2.74	5.66	6.85	2.7	2.68	2.5	2.83	2.69	1.12	1.83	93.15
KWT	8.67	10.07	2.36	1.4	1.67	2.83	1.97	2.29	1.73	2.65	2.17	2.59	4.7	1.92	0.84	4.91	1.81	2.69	2.72	2.65	4.11	4.16	4.04	2.92	3.29	6.45	2.47	2.19	2.58	2.34	1.09	1.78	93.55
SHR	7.04	12.24	3.97	1.36	1.36	2.96	2.02	2.54	1.81	4.12	3.34	3.72	2.59	1.67	0.71	6.86	1.58	2.19	2.17	2.11	2.19	1.98	2.12	2.33	2.45	1.88	5.77	3.5	4.31	4.11	0.99	1.99	94.23
BNL	6.34	11.14	3.9	1.33	1.29	2.85	2	2.4	1.86	4.25	3.54	3.84	2.47	1.69	0.77	6.84	1.5	2.13	2.15	2.1	2.2	1.84	2.06	2.34	2.45	1.83	3.62	7.85	4.86	3.76	0.98	1.83	92.15
FCD	6.55	11.91	4.04	1.37	1.45	2.88	1.98	2.53	1.83	4.44	3.33	3.92	2.62	1.68	0.76	7.3	1.56	2.18	2.16	2.09	2.29	2.03	2.17	2.35	2.47	1.95	3.86	3.9	5.62	4	0.95	1.84	94.38
ESD	6.91	11.98	3.76	1.4	1.42	2.97	2.02	2.41	1.94	3.99	3.17	4.12	2.5	1.71	0.73	7.1	1.55	2.19	2.21	2.14	2.3	1.98	2.09	2.35	2.45	1.92	3.86	3.47	4.14	6.38	0.95	1.89	93.62
MNS	4.49	6.01	1.53	1.51	1.05	1.99	1.48	1.69	1.25	1.62	1.28	1.52	1.94	3.69	1.16	3.29	11.4	1.88	1.9	1.95	1.53	1.35	1.58	1.59	1.64	1.94	1.56	1.61	1.55	1.48	30.29	1.27	69.71
TJN	10.21	6.68	2.28	1.53	1.36	5.51	2.62	3.71	3.25	2.44	2.12	2.35	1.75	1.69	1.16	4.29	1.33	1.83	1.83	1.78	1.65	1.35	1.52	1.93	2	1.44	2.6	2.14	2.39	2.24	0.94	20.08	79.92
To	248.89	275.75	83.45	50.81	50.43	101.7	67.98	82.54	63.21	88.26	72.34	87.9	84.34	58.52	26.39	160.7	60.53	72.57	73.54	71.05	70.84	64.75	70.02	74.32	78.36	66.47	80.35	75.93	87.64	80.99	38.36	61.62	spillover Inex
Net	170.52	191.54	-10.75	-11.97	-5.01	10.84	-13.28	-3.6	-18.01	-5.91	-18.92	-4.51	-8.79	-26.21	-17.47	91.68	-20.85	-21.27	-20.44	-22.25	-22.43	-29.13	-23.46	-19.21	-14.79	-27.08	-13.88	-16.22	-6.74	-12.63	-31.35	-18.3	85.33%

Note: This table provides the Friday return spillover table with average entries . The number of each crude corresponds to the number in Table A.1.

FIGURE 4.14: Spillover plots comparing Wednesday returns and Friday returns



Notes: This figure provides the time series of spillover index for both Wednesday returns and Friday returns. The dashed line represents the dynamic of spillover index of Friday return while the solid line represents the spillover index of Wednesday returns. The format of the horizontal scale is "month/year", and the interval is eight months.

The spillover tables are also affected by the ordering of variables (See Table A.10 and Table A.11), which is similar to the results based on the Wednesday data. Therefore the average spillover table is used for analysis. The crudes with largest net directional spillover index (in descending order) are Brent (BRT), WTI, Russian Urals (URL) and Mexico Isthmus (IMS). Compared with the results of the Wednesday returns, benchmark crudes like Brent, WTI and Urals, still play a key role in spillover returns. WTI's role become significant and dominates Russian Urals as the second largest spillover crude. Mexico Isthmus (IMS) replaces Europe Forcados (FCD) as a return spillover crude, although the spillover effect is not obvious (10.84% of Isthmus in Table A.10 vs. 28.39% of Forcados in Table 4.1). Dubai Fateh and Oman Blend are still not return spillover crudes in these results. Therefore the basic conclusion that benchmark crudes tend to spillover returns is as robust for Friday returns as it is for Wednesday returns.

The dynamic behavior of Friday returns is then plotted and compared with that of Wednesday returns. From the Figure 4.14, dynamic spillovers based on Wednesday and Friday prices are closely matched until they reach the peak. After that the spillover index based on Friday prices remains smaller than that of Wednesday prices. This constant gap may relate to traders' strategy change after regulations on market price manipulation, because Friday price is a signal that most people refer to i.e. regulators pay more attention to it, so the traders reduce trade on Friday.

4.6.3 Alternative volatility measure: conditional volatility based on GARCH models

Another volatility measure is now applied to test the robustness of the results. The volatility of each crude has its conditional variance estimated using a uinvariate GARCH model. The order of the model is determined by AIC i.e. the model with minimal AIC from candidate models - GARCH(1,0), GARCH(2,0), GARCH(3,0), GARCH(1,1), GARCH(1,2), GARCH(2,1) and GARCH(2,2). The estimated conditional variance i.e. the GARCH volatility of some selected crudes are plotted in Figure B.6. Generally speaking, the GARCH volatility is larger than the volatility in previous sections.

Repeating the analysis in previous sections, the minimal, maximal and average total spillover indexes are $SOI_{min} = 91.46\%$[22], $SOI_{max} = 93.52\%$[23] while $SOI_{avg} = 92.56\%$.

[22]The corresponding ordering of variables is (SSL, MNS, CDQ, CPR, LYD, KWT, FCD, CLM, IRH, MBN, TPS, CBD, IRL, SAM, URL, ORT, ESD, BNL, SHR, MYA, KLE, SUZ, OMN, TJN, DBF, IMS, SSH, DKN, GPL, EFK, WTI, BRT)

[23]The corresponding ordering of variables is (GPL, OMN, SHR, MBN, BRT, SSH, KWT, WTI, EFK, CPR, SUZ, URL, ORT, BNL, MYA, TPS, DBF, CDQ, KLE, TJN, IRH, ESD, IMS, CLM, FCD, DKN, MNS, SAM, SSL, IRL, CBD, LYD)

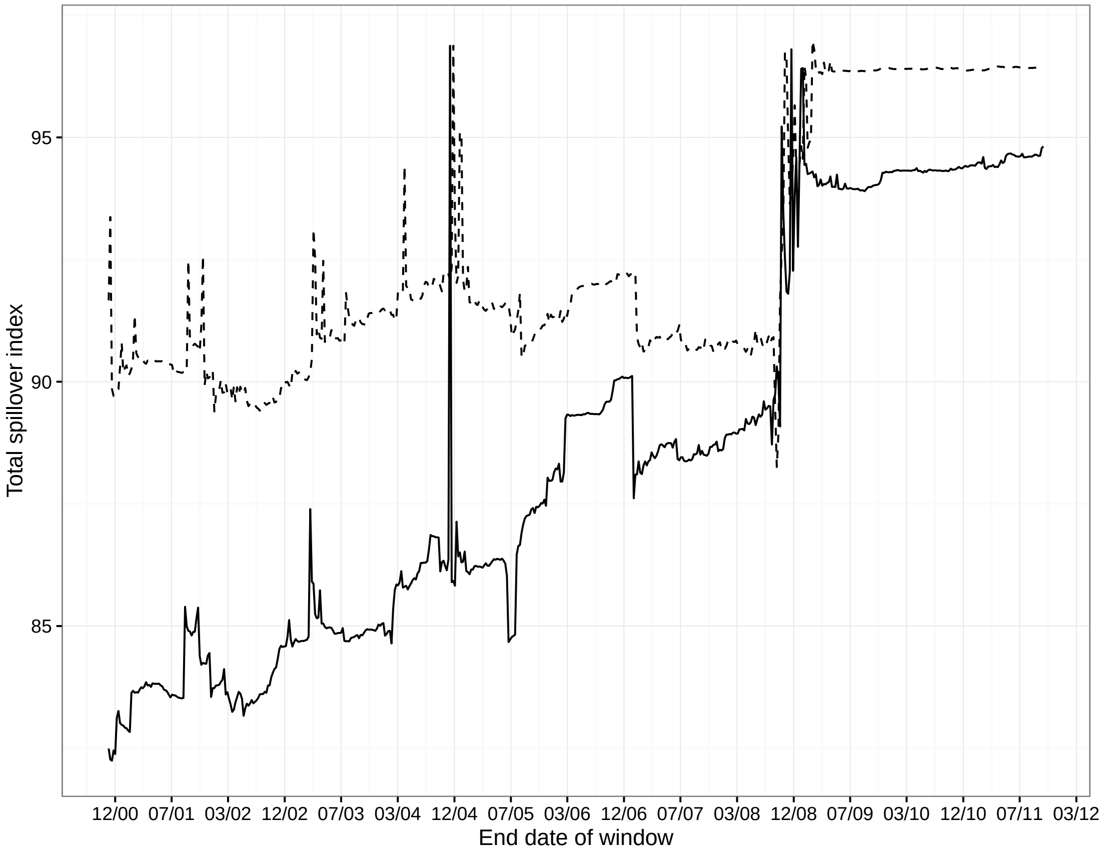
TABLE 4.4: Average spillover table SOT_{avg} for GARCH volatility

	WTI	BRT	EFK	CPR	LYD	IMS	MYA	CLM	ORT	CBD	KLE	SUZ	OMN	GPL	TPS	URL	CDQ	SSL	SAM	SSH	MBN	DBF	DKN	IRL	IRH	KWT	SHR	BNL	FCD	ESD	MNS	TJN	From
WTI	4.29	5.93	2.1	5.73	1.04	2.76	2.48	3.44	2.79	3.56	1.82	1.87	3.47	4.82	0.94	1.3	4.67	4.86	3.62	3.21	3.43	3.46	4.63	3.52	2.77	4.23	2.1	1.33	1.74	2.05	4.5	1.51	95.71
BRT	3.2	12.59	2.59	4.16	0.9	2.89	3.73	2.7	2.06	4.53	2.35	1.97	2.55	4.63	2.39	1.79	4.21	4.14	3.14	2.72	2.5	3.07	3.14	2.9	2.38	2.76	2.32	1.5	2.42	2.06	4.28	1.45	87.41
EFK	3.62	9.82	4.1	3.24	0.87	3.47	4.21	2.25	2.01	5.31	2.87	2.52	2.07	3.54	2.49	3.36	3.23	3.86	2.86	2.4	2.1	2.85	2.35	2.83	2.26	2.29	3.21	2.35	3.98	2.37	3.81	1.5	95.9
CPR	3.52	6.86	2.13	9.09	1.09	2.85	2.71	3.23	2.76	3.43	1.84	1.79	3.15	5.04	1.22	1.41	4.38	4.87	3.5	3.03	3.05	3.28	4.12	3.49	2.66	3.25	1.97	1.49	1.76	1.9	3.62	1.51	90.91
LYD	1.65	6.13	1.83	2.54	31.58	1.82	2.62	3.06	1.83	3.65	1.54	1.23	1.46	3.43	3.34	2.26	2.08	3.63	2.27	1.85	1.35	1.44	1.56	1.76	1.92	1.8	1.5	1.3	1.58	1.87	3.13	0.99	68.42
IMS	3.37	7.64	2.4	4.58	1.16	2.84	3.16	2.96	2.62	4.11	2.22	1.9	3.02	5.03	1.74	1.72	4.25	4.86	3.54	3.03	3.16	3.29	3.72	3.17	2.63	3.59	2.25	1.58	2.01	2.03	4.79	1.62	97.16
MYA	3.27	6.87	2.26	3.75	1.11	3.5	7.51	2.68	2.35	4.18	2.33	1.87	2.94	4.57	1.61	1.63	3.67	4.85	3.51	2.96	2.52	3.03	3.26	3.38	2.75	3.45	2.14	1.54	2.18	2.14	4.62	1.56	92.49
CLM	3.6	10.38	2.55	3.07	1.74	3.07	3.45	5.2	3.28	4.04	2.01	2.05	2.3	4.51	2.78	3.69	3.36	4.45	3.15	2.59	2.23	2.81	2.41	3.14	2.42	2.41	2.15	1.61	2.48	1.93	3.6	1.52	94.8
ORT	3.5	7.42	2.2	3.52	1.14	3.14	2.92	3.29	10.12	3.86	2.29	1.75	2.57	4.71	1.71	1.77	3.79	4.39	3.23	2.77	2.78	3.89	2.63	2.51	2.19	2.88	2.08	1.55	1.78	1.67	4.47	1.48	89.88
CBD	3.57	8.26	2.98	3.71	0.94	3.29	4.1	2.75	2.33	4.78	2.72	2.24	2.62	4.11	1.54	2.3	3.62	4.71	3.35	2.81	2.48	3.06	3.11	3.22	2.59	2.82	2.77	1.98	2.7	2.17	4.8	1.57	95.22
KLE	3.45	7.7	3.34	3.96	0.93	3.34	3.87	2.89	2.11	5.19	4.64	2.22	2.48	3.76	1.81	2.5	3.48	4.46	3.14	2.62	2.39	2.64	3	3.01	2.44	2.7	2.81	2.24	2.97	2.15	4.18	1.56	95.36
SUZ	4.12	7.49	3.17	3.58	0.92	3.67	4.38	2.49	2.19	4.49	2.44	2.87	2.59	3.64	1.43	2.86	3.49	4.45	3.27	2.75	2.44	3.22	3.03	3.75	2.78	2.75	2.91	2.04	3.12	2.32	3.78	1.58	97.13
OMN	3.32	6.81	2.09	4.54	0.94	2.82	3.42	3.32	2.27	3.77	2.16	1.83	3.72	5.09	1.18	1.35	4.39	4.86	3.67	3.22	3.23	3.71	4.79	3.52	2.89	3.74	2.15	1.36	1.85	2.1	4.45	1.47	96.28
GPL	2.87	9.18	2.14	3.94	1.06	2.55	3.68	3.08	2.32	3.91	2.23	1.8	2.84	7.93	1.79	1.33	4.47	4.96	3.39	2.81	2.75	3	3.75	2.56	2.25	2.95	1.89	1.5	1.72	1.74	6.25	1.37	92.07
TPS	0.99	10.14	2.65	0.86	0.65	1.31	0.77	1.49	0.72	4.61	1.57	5.18	1.45	1.7	39.26	2.14	1.62	1.03	1.11	1.07	1.73	1.44	1.9	2.99	1.66	2.1	1.15	0.86	2.77	1.21	1.28	0.59	60.74
URL	4.64	7.57	3.28	2.63	1.36	3.48	4.48	2.16	2.14	4.52	2.24	2.46	2.16	3.35	1.82	8.61	2.83	4.53	3.02	2.4	2.06	2.43	2.4	3.83	2.67	2.32	2.34	2.22	3.11	2.25	3.27	1.41	91.39
CDQ	2.68	6.91	2.32	3.48	0.97	2.64	3.21	3.03	2.37	3.79	2.7	1.87	2.8	4.71	1.1	1.35	7.34	5.79	3.7	3.12	2.69	2.75	3.23	2.79	2.43	3.1	2.17	1.52	1.87	1.73	8.29	1.56	92.66
SSL	3.21	6.49	2.19	4.23	0.97	3.15	3.25	3.03	2.87	4.03	2.3	1.94	3.35	4.92	1.22	1.4	4.22	4.64	3.62	3.22	3.37	3.46	4.3	3.29	2.83	3.73	2.43	1.5	1.88	2.21	5.13	1.63	95.36
SAM	3.21	6.18	2.22	4.2	0.99	3.04	3.28	3.16	2.76	4.09	2.29	1.93	3.3	4.84	1.16	1.38	4.17	4.93	3.74	3.34	3.31	3.41	4.23	3.39	2.87	3.82	2.37	1.49	1.86	2.18	5.25	1.6	96.26
SSH	3.19	5.83	2.23	4.17	1.01	2.99	3.28	3.24	2.77	4.1	2.29	1.93	3.28	4.76	1.1	1.36	4.13	5.08	3.84	3.49	3.27	3.38	4.21	3.47	2.9	3.88	2.35	1.49	1.85	2.16	5.36	1.59	96.51
MBN	3.47	6.88	2.02	4.5	0.93	2.98	3.74	3.27	2.28	3.69	2.18	1.83	3.54	5.1	1.02	1.35	4.31	4.84	3.7	3.27	2.98	3.77	4.55	3.85	3.04	3.72	2.13	1.32	1.83	2.15	4.31	1.46	97.02
DBF	3.37	6.91	2.09	4.32	0.96	2.94	3.68	3.2	2.35	3.85	2.25	1.83	3.47	5.02	1.21	1.39	4.28	4.87	3.68	3.22	3.11	3.99	4.37	3.64	2.95	3.7	2.16	1.35	1.87	2.11	4.37	1.48	96.01
DKN	3.49	6.95	2	4.64	0.9	2.85	3.38	3.44	2.21	3.58	2.05	1.79	3.73	5.23	0.99	1.28	4.44	4.86	3.68	3.26	3.17	3.66	5.26	3.56	2.86	3.61	2.09	1.32	1.75	2.08	4.45	1.42	94.74
IRL	3.19	7.02	2.28	4.03	0.99	2.97	3.37	3.04	2.55	4.21	2.32	1.92	3.27	4.94	1.46	1.47	4.15	4.95	3.63	3.13	3.25	3.44	4.25	3.13	2.83	3.57	2.39	1.49	1.92	2.21	5.06	1.57	96.87
IRH	3.1	6.65	2.32	3.94	1.01	2.98	3.48	3.07	2.53	4.28	2.35	1.91	3.24	4.77	1.5	1.46	4.02	5.09	3.65	3.11	3.25	3.43	4.18	3.26	3.03	3.65	2.35	1.51	1.92	2.18	5.2	1.57	96.97
KWT	3.38	6.26	2.06	4.55	0.97	2.81	3.46	3.43	2.26	3.82	2.1	1.85	3.58	4.95	1.01	1.29	4.4	4.99	3.7	3.23	3.12	3.69	4.6	3.83	3.05	4.35	2.08	1.34	1.83	2.15	4.4	1.46	95.65
SHR	3.63	8.88	3.24	3.48	0.88	3.52	4.16	2.53	2.21	4.93	2.74	2.32	2.42	3.93	1.9	2.38	3.57	4.13	3.12	2.66	2.41	3.14	2.93	2.83	2.37	2.6	3.64	2.1	3.25	2.27	4.3	1.55	96.36
BNL	2.87	7.85	3.47	2.31	0.98	3.33	5.36	2.3	1.95	5.45	3.46	2.36	1.72	3.49	2.19	2.56	2.97	4.63	2.95	2.5	1.86	2.35	1.77	2.67	2.11	2.54	2.89	6.51	3.5	2.22	5.53	1.35	93.49
FCD	3.55	9.88	4.19	2.78	0.79	3.8	4.97	2.07	1.77	5.52	2.92	2.65	1.87	3.01	2.64	3.65	2.89	3.65	2.73	2.29	1.86	2.73	2.02	2.71	2.16	2.2	3.31	2.49	5.51	2.44	3.52	1.45	94.49
ESD	3.7	8.38	2.91	3.98	0.86	3.5	3.88	2.79	2.53	4.4	2.52	2.27	2.63	4.14	1.75	2.11	3.8	4.41	3.29	2.81	2.7	3.48	3.18	3.08	2.49	2.82	2.81	1.86	2.78	2.36	4.24	1.53	97.64
MNS	2.27	7.34	2.34	2.39	0.83	2.35	3.64	2.29	1.98	4.04	2.6	1.74	2.2	4.36	1.44	1.27	7.45	5.44	3.27	2.72	2.48	2.28	2.58	2.13	1.92	2.69	1.88	1.39	1.73	1.47	15.96	1.5	84.04
TJN	3.39	7.31	2.35	4.39	1.13	2.8	3.25	2.79	2.34	3.83	2.08	1.82	2.99	4.91	1.61	1.67	4.24	4.93	3.54	3	3.31	3.44	3.84	3.37	2.68	3.46	2.17	1.48	1.95	1.94	5.13	2.86	97.14
To	100.39	233.92	77.94	115.2	31.02	92.61	109.37	88.47	71.51	130.77	71.78	64.64	85.06	135.01	51.09	58.78	120.58	141.5	101.87	87.12	83.36	95.03	104.04	97.45	78.75	95.13	71.32	50.1	69.96	63.46	139.37	45.41	**Spillover Index**
Net	4.68	146.51	-17.96	24.29	-37.4	-4.55	16.88	-6.33	-18.37	35.55	-23.58	-32.49	-11.22	42.94	-9.65	-32.61	27.92	46.14	5.61	-9.39	-13.66	-0.98	9.3	0.58	-18.22	-0.52	-25.04	-43.39	-24.53	-34.18	55.33	-51.73	**92.57%**

Note: This table provides the average spillover entries for volatility measures based on the univariate GARCH model. The crudes' names are abbreviated. Refer to Table A.1 for the full names.

Similarly, the ordering does not change total spillover index to a significant degree. Compared with volatility in previous sections, the total spillover index is large.

FIGURE 4.15: Spillover plots of volatility and GARCH volatility



Notes: This figure provides the time series of spillover indexes for both volatility and GARCH volatility. The dashed line represents the dynamic of spillover index of GARCH volatility while the solid line represents the spillover index based on original volatility. The format of the horizontal scale is "month/year", and the interval is eight months.

Again, spillover tables are severely affected by the ordering of variables. Compared Table A.12 and Table A.13 , there are significant differences between the maximal spillover table and the minimal spillovers. Therefore average GARCH volatility spillover table (Table 4.4) is referred to, to make an analysis. The net directional spillover index shows that the top GARCH volatility spillover crudes are Brent (BRT), Indonesia Minas (MNS) and Saudi Arabia Saudi Light (SSL), which is different from previous findings which showed WTI, Mexico Isthmus (IMS) and Brent (BRT) to be the volatility spillovers crudes. Prasad et al. (2014) also found that GARCH volatility gives gives different results to other volatility measures such as realized volatility or range-based volatility on directional spillover analyses.

The model is estimated using 200-week rolling samples to obtain the dynamic spillover index in order to check the evolution of spillovers. Figure 4.15 displays the dynamic spillover index of volatility and GARCH volatility. Generally these two volatility measures show similar patterns, especially in the timing of spikes, which implies that the analysis of dynamic total spillover indexes are robust under different volatility measures. The difference is that GARCH volatility tends to give a larger spillover index.

4.7 Conclusion

This chapter investigated the return and volatility spillover effects among 32 crude varieties. A VAR forecast error variance decomposition method was employed to construct various spillover measures, and re-estimate the model with a rolling-window to take dynamics into account. In order to make a solid analysis, the average measures calculated over large number of randomly created ordering permutations were used to overcome the ordering-variant deficiency under the Cholesky-factor identification of VARs.

The static analysis shows that the crude market has the largest spillover indexes in the literature (87.1% for return and 80.57% for volatility), even when compared to the global stock market (40% according to Diebold and Yilmaz (2009b) for developed stock markets, and 68.1% according to Prasad et al. (2014) when emerging stock markets taken into account). This indicates a high degree of integration. The reason may be that the crude oil market is vulnerable to a lot of shocks, not only crude specific shocks but also shocks on other markets (e.g. FX or stock markets). The spillover tables generally confirm the benchmark role of WTI and Brent, in terms of transmitting return and volatility shocks to other crudes. The potential benchmark, Urals, proposed by Wlazlowski et al. (2011) is supported in this analysis. However, other benchmark crudes such as Dubai Fateh and Oman, were not found to have any role in transmitting shocks.

The dynamic analysis shows that return and volatility spillover indexes have different dynamics. Return spillovers display gradually evolving trends but no bursts, whereas volatility spillovers display clear bursts that correspond closely to events such as the 9/11 terrorist attack, the invasion of Iraq in 2003, China's rapid development and the 2008 financial crisis. The volatility spillover index remained low and stable from early 2007 until the crude oil price reached a peak in summer 2008, then it jumped and has maintained a high and stable state since. This implies that the 2008 financial crisis may have profoundly changed the spot crude oil market, making it more vulnerable to system risk. The reason for this change requires further research.

Further dynamic analysis revealed spillover patterns at different levels. First, the individual and pairwise directional spillover study shows that WTI and Brent are dominant return spillover transmitters over the whole sample period, which is consistent with their roles as benchmark crudes. Compared with WTI, Brent is a more influential transmitter, especially from 2005 to 2008. Russian Urals used to have large net return spillover effect to other crudes, but this effect disappeared in 2005. Although these benchmark crudes also behave as transmitters in terms of volatility, the pattern is different to that of the return spillover. Brent and Russian Urals only had volatility transmission effects before the middle of 2005. WTI became a dominate volatility transmitter in 2007, and this effect was most remarkable when crude oil price collapsed in 2008. The reason for this is possibly that the origin of the 2008 crisis was in the United States, the location of WTI production. Pairwise directional spillover provides similar but more detailed results of individual directional spillovers.

In the group level, the non-OPEC group is a return transmitter to the OPEC group, although the OPEC group's influence on the non-OPEC group has been increasing over time. However, there is no consistent pattern for the volatility spillover between the OPEC and non-OPEC groups. With respect to quality, the light sweet group is a return transmitter to all other groups, and has had the largest impact on the medium sour group since 2004. Although the low quality of medium sour crudes occupy a large share of the market, they fail to have a large and stable influence over other crudes. Light sour and heavy sour crudes are generally receivers. In terms of volatility, there is no constant receiver or transmitter, but the light sweet group has been a net volatility transmitter to other groups since 2007. With respect to geographic regions, the Europe group is the net return transmitter to all the other groups, followed by the American group. Asia and Africa region and Sub-Saharan Africa regions are generally receivers, but had some transmission effect to the MENA group during and after the 2008 financial crisis. In terms of volatility, the roles of each group is time varying. Recently the America region became a net transmitter to other regions, but this was mainly due to the dominant transmission effect of WTI.

The robustness of our conclusion was checked by changing the parameters of the model, but the basic conclusions remain. The alternative return measure based on Friday price indicates that after the 2008 financial crisis, spillovers reduces. This is attributed to the reduction of speculative trade on Friday due to regulation. The alternative volatility measure based on the conditional variance of the GARCH model show generally similar pattern to our original volatility measure.

In sum, this analysis supports the benchmark roles of WTI and Brent, in terms of transmitting return and volatility shocks. Moreover, the dynamic analysis reveals that their transmitting patterns are different and time-varying. Brent is more influential with respect to return while WTI is more influential regarding volatility, especially since 2007. Therefore this analysis reconcile the debate of Kao and Wan (2012) and Elder et al. (2014) over the benchmark roles of Brent and WTI. In practice, market participants could treat these two benchmarks differently according to their objectives and strategies, because they may reveal different information.

Chapter 5

Determinants of return and volatility spillover

5.1 Introduction

Financial market spillover is broadly defined as changes in one market which respond to changes in factors in other markets. It usually appears as comovement of return or volatility across markets. During crisis the spillover of shocks is quick and in large scale, leading to "contagion", which is reflected as sharply increased spillover. In the crude oil market, which was proposed to be "one great pool" by Adelman (1984), implying a high degree of integration, spillover effects are particularly prevalent. Although there are various studies investigating the direction and patterns of spillover effects in the crude oil market (e.g. Feng-bin et al., 2008; and Kaufmann & Ullman, 2009), few studies explore factors driving such spillover effects. The empirical work here shows that crudes in some countries tend to spread return or volatility shocks, while others are prone to receiving these shocks. The dynamic spillover plots in Chapter 4 further show that even though some crudes were receiving shocks, the amount received is different between the crudes and crude producing regions. This leads to the fundamental question: what determines the extent of spillover among crudes in different countries?

Market participants and policy makers in the international crude oil market need to understand the forces behind the spillovers in order to assess the potential risk of exposure to their portfolios and the potential benefits of crude diversification. For example, if crudes in two countries have similar statuses in transmitting or receiving shocks, investing in these two crudes cannot have diversification benefits. Likewise, policy makers need to understand the driving forces of spillover to make informed decisions with regard to production and trade. For example, they may want to know the channels through which the shock from another country could affect the return or volatility of their country, and hence take steps to mitigate against the rising risks of market spillovers. Can the amount of shocks transmitted among crudes in different countries be explained? This calls for an examination of the factors that influence the relationships and linkages between crudes in different countries. Such insights will provide a better understanding of the functioning of the crude oil market.

The purpose of this study is to examine the factors that influence the return and volatility spillover among crudes in different countries. Although there are various studies which investigate the channels through which shocks are transmitted in stock, bond or foreign exchange markets, there has been limited work conducted in the area of crude oil markets. This research therefore fills this gap in the literature. Combining the analysis logic in other financial markets and features of the crude oil market, five types of variables that may influence the return and volatility spillovers are identified. These are: international trade variables, fundamental variables, country risk variables, global risk factors and time trends which can capture the effect of increasing globalization over time.

The spillover effect of a country to all the other countries is modelled first. The empirical work shows that international trade variables are important factors which influence return and volatility spillovers. Fundamental variables are more important for return spillovers than volatility spillovers. Country and global risk factors can also explain spillovers, although they are not all significant. In order to investigate the role of OPEC membership, the sample is split by OPEC/non-OPEC membership, and the findings show that the variable given above have different effect on these two sub samples. Generally, the explanatory variables have more explanatory power in non-OPEC samples. Then the regression was applied to the pairwise spillover index i.e. the spillover from one country to another country. Generally international trade variables, fundamental variables and country risk variables have similar effects as they do in individual spillover determinant models, but global risk factors show more effect than those in individual spillover models. Again the effect of OPEC membership was studied, and the variables were found to have different effects on OPEC and non-OPEC pairs. Upon examining whether distance has any impact, there was no strong evidence to support the argument that the variables' impact on spillover would be enhanced if countries in a pair are geographically close to each other.

The key contribution of this study is that it is the first attempt to provide a systematic analysis ofvarious factors that could influence the return and volatility spillovers. Moreover this analysis is not limited to several so-called "benchmarks" in the crude oil market, but it is extended to 32 crudes from 25 countries. Therefore this research provides a comprehensive understanding of spillover mechanisms in the rude oil market.

The remaining part of paper is structured as follows: Section 2 provides a literature review of the relevant studies on the determinants of spillover effects in different markets. Section 3 describes the data and variables applied. Section 4 presents the empirical analysis, including the methodology and discussion of the empirical results. Section 5 summarizes the findings and concludes. Discussion about the limitation of the research and potential future studies are summarized in Section 6.

5.2 Literature Review

Various studies analyse the cross-border spillover of financial shocks, especially during in crisis periods when spillovers increase significantly. Most of these studies focus on stock and bond markets, with little attention paid to the spot crude oil market. Although different markets have different ways of functioning, they share something similar in the way shocks are transmitted. The theory of and method of analysis in stock and bond market shocks could therefore shed light on the crude oil market, therefore, this literature review is not constrained to the crude oil market.

Dornbusch et al. (2000) identify two categories of causes of contagion transmission. The first category emphasizes the spillovers that result from normal interdependence among markets. This interdependence leads shocks, whether global or regional, to be transmitted across countries because of real and financial linkages. Calvo and Reinhart (1996) called such spillover "fundamentals-based". This type of cause includes macroeconomic shocks that have an impact on an international scale, local shocks transmitted though trade links, competitive devaluations, and financial links. Corsetti et al. (1999) found that the strengthening of the US dollar against the yen in 1995-96 was an important factor in the export downturn in East Asia and that this caused subsequent financial difficulties there. A common macroeconomic shock generally leads to comovement in asset prices or capital flows.

Local shocks, such as a crisis in one economy, can affect the economic fundamentals of other countries through trade links and currency devaluation. Diebold and Yilmaz (2015a) point out that trade flows play a key role in the transmission of shocks across countries. If the demand of one country takes hit, its import demand is affected as well, and the domestic shock is transmitted to its exporters via trade links. Competitive devaluation can also serve as a channel for transmitting spillovers. Devaluation in one country reduces the export competitiveness of its competitors, putting pressure on the currencies of these countries, especially when those currencies do not float freely. Corsetti, Pesenti, Roubini, and Tille (2000) point out that competitive devaluation can induce a sharper currency depreciation than that required initially by fundamentals. Moreover, the non-cooperative nature of the devaluation can result in greater depreciation compared to that which can be attained in a cooperative equilibrium. For example, in 1997, exchange rates depreciated substantially in economies such as Singapore and Taiwan, whose fundamentals are not so vulnerable to have deep depreciation.

Financial links are another channel to transmit shocks. Financial crisis in one country could lead to reductions in trade credits, foreign direct investment, and other capital flows abroad.

The other category of causes of contagion identified by Dornbusch et al. (2000) is investors' behavior. They point out that crisis in one country may cause investors to sell off equity on several other markets at the same time in order to reduce the overall exposure of their portfolios. In particular, leveraged investors may have to sell their asset holdings in other markets when confronting liquidity problems. Investors' panics, herd behavior and loss of confidence are all reasons why crisis in one market can spread to other markets.

Pretorius (2002) used a cross-sectional analysis and found that bilateral trade and industrial production growth differentials could explain the co-movement of stock markets between two countries, measured by the correlation of the markets.

In addition, countries in the same region were more correlated than countries in different regions. On the time-series basis, the impact of the 1998 crisis was significant. Because the model used by Pretorius (2002) explained 40% of variations in correlation coefficients, he concluded that a substantial proportion of interdependence among emerging stock markets can be explained by fundamentals rather than contagion.

Syllignakis and Kouretas (2011) also emphasize the impact of macroeconomic fundamental factors on the correlation between central European and Germany stock markets. They calculated the time-varying conditional correlation of seven stock markets in central and Eastern Europe, using a Dynamic Conditional Correlation (DCC) multivariate GARCH model. A significant increase in conditional correlations was found during the 2007-2009 financial crisis, implying a spillover of external shocks. They attribute this to investors' herding behavior. In times of severe stress in 2008, disparate markets all tumbled together as investors scrambled to sell assets and move into cash. An additional explanation is financial liberalization in central and East European countries, which facilitated not only foreign ownership, but also the spillover of external shocks. Syllignakis and Kouretas (2011) identify several macroeconomic factors to explain the time-varying correlation coefficients (including a time-varying conditional correlation in monthly growth rates of industrial production) in the three-month interbank rate and the monthly rate of change of Harmonized index of consumer prices, which are proxies for the convergence of business cycles, monetary policy convergence and inflationary environment convergence respectively. They also used conditional volatility of exchange rate as a proxy for the currency risk premium and Standard and Poor's credit rating as a proxy for sovereign risk. Using rolling regression, they found that during the 2007-2009 crisis, macroeconomic fundamentals played a key role, while in other periods, the explanatory power of fundamental was limited. Monetary convergence therefore has strong positive relationship with stock returns' correlation, while the impact of other factors' varies across their sample. Their study provides evidence that contagion in the 2007-2009 crisis, reflected by increased conditional correlation, has a fundamental basis other than investors' behavior.

Similar to Syllignakis and Kouretas (2011), Hwang, Min, Kim, and Kim (2013) also investigated the determinants of dynamic conditional correlations in emerging stock markets. They used risk factors in financial markets, including sovereign CDS spread, VIX indexes for the US stock market, information on foreign institutional investments, TED spreads (the difference between the London Interbank Offered Rate and the specific country's short term interest rate) and one month's volatility index. Their results show that increases in CDS spread and TED spread decreased conditional correlation, while the other factors increased conditional correlation.

Shinagawa (2014) identified three transmission channels: bilateral portfolio investment, bilateral trade and geographical preference of portfolio investments. Larger portfolio exposure between countries was found to be associated with larger spillovers. This was also demonstrated by K. J. Forbes (2012), who firstly showed that advanced economies have increased international investment positions and portfolio inflows since the late 1990s, suggesting this this is a factor causing increased spillover over time. Second, he showed that if countries trade more intensely, they become more vulnerable to income shocks that could adversely affect aggregate demands and lead to weaker returns on assets in that country. Thirdly he showed that international portfolio diversification could also affect financial spillovers i.e. if a country has a diversified portfolio, it should be more resilient against shocks, because diversifying portfolio assets can help the country to reduce the concentration of risks of holding exposure to one country. In contrast, a country with a strong home bias would be less affected by financial spillovers because of its lower financial-market exposure to external shocks.

Didier, Love, and Martinez Peria (2010) analyzed the comovement between the US and other countries. They argue that a countries' correlation with the US market is interacted with country-level characteristics that affect comovement, such as real and financial linkages. These country-level measurements include trade indicators, financial indicators, capital account openness indicators and stock market size and liquidity. They found that during the 2007-2008 crisis, the main channel of transmission was financial.

K. J. Forbes (2012) also found that if a country has a more leveraged banking system, greater trade exposure, weaker macroeconomic fundamentals and larger international portfolio investment liabilities, it would be more vulnerable to spillovers. If countries have larger international financial portfolio investment assets as buffer against shocks, and are less reliant on debt for international financing, they would be less vulnerable to spillovers.

Most of these studies use correlation or conditional correlation as proxy for spillovers. Therefore the determinants of spillovers are investigated based on a bilateral basis. Unfortunately, these the correlations are not able to specify the direction of the spillovers. The directional spillover indexes of Diebold and Yilmaz (2015a) can be aggregated to show spillovers at different levels, and also indicate the direction of spillovers. Prasad et al. (2014) applied directional spillover indexes as dependent variables to study the stock markets in 16 countries. They observed that exceptional increases or decreases in volatility are often associated with significant over/under performance in terms of returns, and lead to a particular market becoming a transmitter of shocks. Hence they propose that a relatively more volatile market will have more spillovers to others. Their empirical work supports this hypothesis. Their other determinants include return and volatility in bond and foreign exchange markets and macro news surprise. Bond yield was found to be associated with higher spillover transmission from the 2008 global crisis onwards. This is because bond yield rose for markets considered to be risky, especially during the crisis, and this further increased stock market volatility and spillover. Foreign exchange volatility, however, has the opposite effect, although it was insignificant during the 2008 global financial and European debt crises. This suggests that higher exchange rate volatility during relatively tranquil periods leads to withdrawals of capital away from some markets, and thus leads them to becoming more isolated and less able to contribute to spillovers. Macroeconomic news surprise, which is the difference between expectations and actual value, was significant during tranquil periods, but not in crisis periods. They explained that this was due to the different way that market participants perceived and acted on news announcements during tranquil and crisis periods. Macroeconomic news in crisis periods could reduce information uncertainty in crisis periods, and therefore reduce the volatility and spillovers.

Fernández-Rodríguez et al. (2015) also use the directional spillover indexes of Diebold and Yilmaz (2015a) as dependent variables. They investigate the volatility spillovers in EMU sovereign bond markets. They model the pairwise spillover between countries using two types of explanatory variables: fundamental-based variables and investor behavior-based variables. The former includes government debt-to-GDP and deficit-to-GDP, liquidity difference between markets, foreign debt and the net position of the country towards the rest of the world, and inflation as a proxy of the country's loss of competitiveness. With respect to market sentiment proxies, they use a consumer confidence indicator to gauge economic agent's perceptions of future economic activity, and also the standard deviation of equity returns to capture the local stock market volatility. Their results show that macroeconomic fundamentals are significant with expected signs. Variables that gauge market participants' perception are more significant in the case in peripheral countries, but not in central countries. They also observe that all marginal effects register an increase in crisis periods as compared to pre-crisis periods, suggesting that the market participants reassess the relevance of the variables as crises unfold.

Based on these studies, it can be concluded that macroeconomic fundamentals that measure real and financial linkages between countries are important factors which impact spillovers. In addition, investors' behavior is also important, especially in crisis periods. However, this logic should be combined with the features of crude oil markets to study spillovers in these markets. Although there are few studies investigating the driving forces of spillover in crude oil markets, researches from other angles could shed light on this research.

Ji et al. (2014) apply complex network theory to identify patterns in global oil trade. They point out that in 2011, more than 60% of global oil consumption was met by imports, which play a core role in supporting the consumers' oil demand. Obviously global oil trade patterns result from interactions between oil-exporting and oil-importing countries on a global scale. In fact exports could change the trade pattern in a region. For example, Christy (2004) found that Russian oil exports changed trade patterns and improved Russia's position in the world crude oil market and decreased oil-importing countries' dependence on Middle East oil. By using the complex network method, Christy (2004) identified three trading blocs in the global trade network, including the 'South America-West Africa-North America' trading bloc, the 'Middle-East-Asian-Pacific region' trading bloc, and 'the former Soviet Union-North Africa-Europe' trading bloc. Geopolitics and diplomatic relations are the two main reasons for this regional oil trade structure. Moreover, the global oil trade network presents a 'robust but fragile' characteristic, and the impacts of trade interruption always tend to spread throughout the whole network, even if export disruption is localized.

H.-Y. Zhang, Ji, and Fan (2015) further explored what drives global oil trade patterns. They constructed four different kinds of spatial econometric models; a base model, an export-oriented model for exporters, an import-oriented for importers, and an import-export interaction model. They apply six types of explanatory variables to model the trade flow between countries using a cross-sectional analysis. These explanatory variables are economic factors, supply and demand factors, political factors, technological factors, alternative energy factors and interactive factors. The results show that distance is the most significant factor impeding trade, while sharing same language is much more likely to promote trade. An importers' economy could influence oil trade flow, but exporters' cannot, indicating that current trade patterns are oriented by demand, but supply factors such as oil reserves and production have significant positive impacts on oil trade. Moreover, geopolitical risks to oil exporters is one of the most important factors affecting the formation of trade patterns. Consumption by importers has a positive influence on the oil trade, while the technology of importers could significantly restrict the growth of oil trade. González, Landajo, and Presno (2014) point out that research and development has a significantly negative influence on oil trade, because it is a main tool used to lower energy consumption, which effectively reduces the demand for oil imports. The energy intensity of importers is also an important factor for enhancing oil trade. Despite the rapid development of the natural gas industry, alternative energy does not have significant effect on oil trade.

H.-Y. Zhang et al. (2015) also examine the spillover effects in their data i.e. changes in the explanatory variables related to one trade flow may also affect other trade flows. They found limited spillover effects in oil trade flows. Hence they ignore it when considering the estimated parameters as the impacts of factors on oil trade. However, as illustrated in Chapter 4, spillover effect of return and volatility are huge and cannot be ignored. The reason for this difference is that H.-Y. Zhang et al. (2015) study trade flows but I study return and volatility. Trade flow was found to be less flexible than return and volatility because it is restricted by the facilities availability, such as pipelines or transportation vehicles, so it is not as sensitive to the market condition as price/return/volatility. Therefore although the factors affecting trade are included in this analysis, they are not expected to have same effect on trade flows.

Giulietti et al. (2014) investigated the impact of physical characteristics of crude oil, and the countries' institutional memberships on price differentials between crudes. They found that crudes with similar physical characteristics tend to return to equilibrium more quickly. They also found that, if crudes belong to OPEC membership countries, they will be slow to return to equilibrium after shocks. Hence they conclude that OPEC membership does help to reduce the effect of global price competition when exogenous shocks move prices away from the long term equilibrium. Therefore OPEC membership could also serve as a factor to impact the effect of market variables, and hence spillovers.

This analysis aimed to identify the determinants of return and volatility spillovers of crude oil in different countries. Combining the logic of financial markets with features of crude oil markets, macroeconomic fundamentals such as tradeand supply and demand are relevant factors are in addition to country-level characteristics. Investors' behavior and attitudes towards risks is also an important category of spillover channel. Although major events, such as political and weather-related events, as well as macroeconomic news, have been found to impact on spillovers in the stock market (e.g. Prasad et al., 2014), they are not included in this analysis directly; firstly because it is difficult to evaluate what types of events could have an impact on spillover in the crude oil market. Events like wars, hurricanes, wildfires, strikes, OPEC production cut announcements and stock reports different from the market's expectation, are all related to the crude oil market, but it is unrealistic to include them all in the full model and selective choice would inevitably be arbitrary. Secondly, the impact of events will, to some extent, be reflected in the market variables or investors' emotional variables. Therefore, this research will focus on macroeconomic fundamentals and investors' behaviors.

5.3 Data and variables

This section discusses the potential driving factors of spillover effects in the crude oil market. As discussed in Chapter 4, the spillover index is a measure of forecast error variance that can be explained by shocks in other markets. How can shocks in one market effect other markets? The main reason is that markets are interdependent; cross-market linkages, including trade and finance, cause the shocks transmit from one market to another. Under extreme market conditions, such linkages will sharply increase or decrease and lead to contagion or crisis. Therefore, besides factors that may affect the extent of interdependence, this study also considers the market conditions, whether nationally or globally, which may also contribute to the spillover effects. Moreover, the market interdependence may also increase because of globalization processes, such as the development of transportation and communication. These effects are gauged by time trends. The details of each variable are discussed as follows.

5.3.1 International trade variables

Trade flow is an important channel for the transmission of shocks. When there is a shock to domestic demand in country i, it is transmitted to other countries through the trade channels. If the aggregate demand in country i takes the hit, the demand for imports is affected as well, so the domestic shock is transmitted to those exporters of country i. Diebold and Yilmaz (2015a) examined the relationship of spillover and trade balance for six developed countries[1], and concluded that countries with trade surpluses tend to be net recipients of shocks, while countries with trade deficits are likely to be net transmitters. This is reasonable, because if a country has more exports than imports (trade surplus), its counter-party countries' shocks will transmit to it via trade channels, making it a net receiver. Diebold and Yilmaz (2015a) found that Germany, which runs a trade surplus, was receiving shocks from the other countries. Therefore, the difference between export and import could serve as an explanatory variable to our net spillover index. In practice the net energy import index from the World Bank was used, which is estimated as energy use less production, both measured in oil equivalents. A negative value means this country is a net exporter. According to the argument of Diebold and Yilmaz (2015a), the expected sign is positive, because more imports than exports implies more spillover to other countries.

[1] That is France, Germany, Italy, Japan, United Kingdom and United States.

On the other hand, the dependence of a particular country on international interactions is also a function of its relative market size. A country which has a huge market share in the international market is more important than a small one, and tends to spread its influence to other countries, regardless of whether it is an exporter or importer. In the crude oil market, participants closely monitor the movement of Middle East countries, because these countries make up a significant share of the global crude oil exports. Any shocks in this region, such as war or strikes, will spread to the global market, cause tension to trade participants and a response in crude oil price. Similarly, large importers will also provide large spillover effects to the international market. Therefore export share and import share measures are constructed to measure the role of the country in the crude oil market, that is, the export (import) of the country divided by the export (import) of the world. The export and import data is obtained from the OPEC library, and converted from a yearly to a quarterly figure[2]. According to above analysis, a positive sign is expected.

In sum, this research takes into account two dimensions of trade: the country's role in the international crude oil market (export and import share), as well as the role of international crude oil market on a country (a country's dependence on the international market, measured by net energy import index). If only one aspect is taken, one may get misleading conclusion. For example, according to Diebold and Yilmaz (2015a), if a country has a trade surplus (e.g. Germany), it is more likely to be a net receiver of shocks. This rule applies in their empirical work of six developed industrial countries. But for the crude oil market, countries are not similar: some countries are dominant exporters while some are large importers. This conclusion does not apply in such market.

[2] The conversion is applied by conversion method 'low frequency to high frequency - quadratic: match sum' in Eviews 8.0. For import, if the import for the year is zero, assign quarterly import to zero, so that to avoid converted negative values.

For example, Libya is a country which exports much more crude oil than it imports. It should be a net receiver of shocks according to Diebold and Yilmaz (2015a). However, the Libyan crisis shocked the market. The reason is that Libya is an important exporter in the international crude oil market. Therefore it is better to consider both aspects, especially in a market with heterogeneous participants.

5.3.2 Fundamental variables

Diebold and Yilmaz (2015a) examined connectedness[3] patterns across asset classes (stocks, bonds, FX and commodity) and across countries. They found that the bulk of connectedness takes place within the same asset class and across countries rather than across different asset classes within the same country. In other words, the same asset class in different countries is more closely connected than different assets in the same country. This implies that the driving force of connectedness is basically the fundamental factors of the certain asset class. Dornbusch et al. (2000) make a survey of the literature related to the causes of market disturbance spread, and point out that the first category of spillover is "fundamental-based". Therefore fundamental factors have to be taken into account.

Supply and demand are the basic fundamental factors of energy. Therefore they should be considered as underlying determinants of spillover effects. Oil production and consumption are therefore used to represent supply and demand. Oil production has a substitution effect on imports. If a country produces more oil, it needs to import less, its domestic demand shock is therefore less likely to be transmitted to other countries, which implies a negative relationship with net spillover indexes. For consumption, the

[3] In their early work,e.g.Diebold and Yilmaz (2012), they use the term "spillover". When they develop the model and link it to network theory, they use the term "connectedness". The essence is the same. So these two terms are viewed as interchangeable. In this thesis, "spillover" is used to keep consistency.

opposite is true and the sign is expected to be positive. Specifically, more consumption implies more need of imports, which is more likely to spread that country's demand shock to other countries. Similar to trade variables, production and consumption shares are used rather than absolute values. A large producer will be less likely to spread spillovers, while a large consumer is more likely to spread its own demand shocks.

Production and consumption data for each country are obtained from the EIA[4], and annual data is converted to quarterly data in the same way as for trade data.

Oil stock is an indicator of the buffering ability of a country. If a country has more stock, the effect of outside shocks could be mitigated, which means that the spillover received from others is likely to be smaller. If the shock is generated from within, stock could also help to mitigate the spillover to others. The overall effect is not clear. The data of oil stock is available for only a few countries, therefore oil reserve data is used instead. Reserve has a similar buffering effect as stocks, but it takes time to become available. Annual reserve data is obtained from the OPEC library[5], and converted to quarterly data[6].

5.3.3 Country risk variables

Geopolitical risks have become the focus of the the oil trade. The instability of political environments significantly enhances the uncertainties of supply in the oil trade (Sun, Gao, & Shen, 2014). H.-Y. Zhang et al. (2015) found that the geopolitical risks of oil exporters is one of the most important factors affecting the formation of oil trade

[4]According to EIA, production data includes crude oil and lease condensate; consumption data is total petroleum consumption.

[5]Reserve of Cameroon is from EIA because it's missing in OPEC library. World reserve data from OPEC library is adjusted accordingly, i.e. Cameroon's reserve is added.

[6]Since reserve is a stock variable rather than a flow variable, the conversion method is averaging observations. The conversion is applied by conversion method 'low frequency to high frequency - quadratic: match average' in Eviews 8.0.

patterns. In their research it was found that the higher the political risk, the more likely it was that the country was a shock generator and transmitter. To measure the geopolitical risk of the country, the percentile rank in the political stability and absence of violence/terrorism indicator published by Worldwide Governance Indicators is used. Political stability and absence of violence/terrorism measures perceptions of the likelihood of political instability and/or politically-motivated violence, including terrorism. Percentile rank indicates the country's rank among all countries covered by the aggregate indicator, with zero corresponding to the lowest rank, and 100 the highest. The lower the rank, the higher the risk, and more likely a country is to be a transmitter. Therefore a negative relationship with net spillover index is expected. This is not a flow variable, therefore is averaged to convert to the quarterly data[7].

The second country risk variable is the share of oil revenue to GDP. If a country's output relies more on oil production, the external shocks could provide more severe impacts to the domestic market. Hence this country will prone to "receive" spillovers from other markets. Therefore a negative relationship with net spillover index is expected. However, in reality, such a country could also be a large supplier, which could spread its influence to other countries, especially in an over-demand market. Thus the direction could be the opposite. The overall effect should be analyzed together with market conditions.

The third country risk variable is exchange rate. Oil benchmarks are traditionally priced in U.S. dollars, but most oil production takes place in countries other than the US. If the local currency is depreciating, export is competitive compared to other countries. This is because the revenue is in U.S. dollars but cost is in a depreciated local currency. Higher profit in producing crude oil leads to more production. Therefore it is expected to have the same sign as production, i.e. negative. Daily exchange rate data is retrieved from

[7]Data of 2001 is missing , and is filled by averaging data of previous and following year.

Datastream and is expressed as the local currency per U.S. dollar[8]. Depreciation means a positive change in exchange rate. Daily data is converted to quarterly by averaging observations. The changes in exchange rate is the difference in the natural logarithm of exchange rates on consecutive quarters.

The fourth country risk variable is volatility in the country. Prasad et al. (2014) proposed a hypothesis that if one market transmits volatility to others, this may be due to something exceptional about that market, for example, its large volatility relative to other markets. They explored the events occurring during various spillover cycles in international stock markets, and found that in the majority of these cases the market transmitting was exceptionally volatile. Their empirical work shows that volatility is the major driver of increased volatility spillovers to other markets. This hypothesis implies a positive relationship of volatility and spillover. In this study, the validity of this hypothesis will be tested in relation to the crude oil market. Data is the calculated volatility in Chapter 4.

5.3.4 Global risk factors

The crude oil market is not isolated from other markets, thus this study also takes into account the global risk factors as control variables. Moreover, the spillover could not only result from macroeconomic or fundamental changes, but also from the "irrational" behavior of investors or other financial agents, such as financial panics, herd behavior, loss of confidence, and increased risk aversion (Dornbusch et al., 2000). Diebold and Yilmaz (2015a) suggest exploring the correlation between spillover and the VIX, which is the implied volatility of the S & P 500 index options. VIX is often referred to as

[8]Cameroon has missing data for 15 specific dates, which is filled by averaging the prices of previous and subsequent dates.

the fear index, representing one measure of the market's expectation of stock market volatility over next 30-day period. Various studies suggest that spillover may increase during crisis, because everyone runs for the exits simultaneously. The higher the VIX is, the more the investors fear, and the more spillover there is in the market. Therefore a positive relationship is expected between VIX and spillover. Data are collected from Bloomberg and averaged to quarterly.

Another global risk factor is gold price (Leelahaphan, Prukumpai, & Sethapramote, 2015). Gold is viewed as safe-haven asset, and its price will be higher when investors' risk tolerance is low. According to risk-on risk-off theory, investors' appetites for risk rises and falls over time. Sometimes investors are more likely to invest in higher-risk instruments but sometimes they prefer safe-haven assets. Therefore gold price could reflect investors' attitude towards risk. Similar to VIX, a positive relationship is expected between gold price and spillover. Although VIX and gold price are both high during crises, they are not the same. The former is volatility and the latter is asset price, the correlation between which is only 0.16 in the sample.

I also consider two global risk factors that are specific to the crude oil market, OPEC spare capacity and OECD oil stocks. OPEC member countries produce about 40 percent of the world's crude oil, and their oil exports represent about 60 percent of total petroleum traded internationally (EIA). Because of its market significance, OPEC's action can influence the international oil market. The extent to which OPEC member countries utilize their production capacity is often used as an indicator of the tightness of global oil markets. It provides a measurement of the world oil market's ability to respond to potential crises that reduce oil supplies. The condition of the crude oil market is critical for this analysis. For example, Fattouh (2007a) points out that the impact of political factors are not independent of the oil market. The oil price shock in 1990, owing

TABLE 5.1: Determinants of net directional spillover

Variables	Description	Definition	Original frequency	Frequency conversion method	Source
1. International trade variables					
ES	Export share	$export_{i,t}/export_{w,t}$	Yearly	quadratic-match sum	OPEC library
IS	Import share	$import_{i,t}/import_{w,t}$	Yearly	quadratic-match sum	EIA
NI	Energy net import	energy net import , % of energy use	Yearly	quadratic-match sum	World Bank
2. Fundamental variables					
PS	Production share	$Production_{i,t}/production_{w,t}$	Quarterly	-	EIA
CS	Consumption share	$Consumption_{i,t}/consumption_{w,t}$	Yearly	quadratic-match sum	EIA
RS	Reserve share	$Reserve_{i,t}/reserve_{w,t}$	Yearly	quadratic-match average	OPEC library
3. Country risk variables					
GR	Geopolitical risk	Percentile rank in political stability and absence of violence/terrorism	Yearly	quadratic-match sum	Worldwide Governance Indicators
OG	Oil revenue to GDP	Oil revenue (% of GDP)	Yearly	quadratic-match sum	World bank
EX	Exchange rate changes	$ln(exchangerate_{i,t}) - ln(exchangerate_{i,t-1})$	Daily	average	Datastream
V	Volatility	$volatility_{i,t}$	Daily	average	calculated from Chapter 4
4. Global risk factors					
VIX	VIX	VIX index, take natural logarithm	Daily	average	Bloomberg
GOLD	gold	Gold price, take natural logarithm	Daily	average	Bloomberg
OPECSC	OPEC spare capacity	OPEC spare capacity	Quarterly	-	EIA
OECDS	OECD stocks	OECD stocks	Quarterly	-	EIA
5.Other variables					
TD	Trend	1 for period 1, 2 for period 2,. . . etc			

Note: This table presents the abbreviation of names, description, definition, frequency, frequency conversion method and sources of individual net spillover determinants, divided into five groups: international trade variables, fundamental variables, country risk variables, global risk variables and other variables. The last two groups are pure time-series variables, i.e. they are cross-sectional invariant. The other variables are panel data, both vary in times series and cross section. The sample period is from 2000Q1 to 2011Q4, for all variables.

to the Iraq Invasion of Kuwait, would have had a much bigger impact if it had occurred in the tight market conditions of 2004. Therefore shocks are normally magnified in a tight market, hence OPEC spare capacity is expected to have a negative relationship with net spillover.

OECD countries are the main consumers of crude oil. Their inventories are a good measure of the supply-demand balance. A large over-supply will decrease price, while under-supply will push prices upward. Meanwhile, low inventories implies a low cushion, which will increase the potential for price volatility and hence generate and transmit shocks. Therefore a negative relationship is expected with spillover. OECD stock, as a measure of demand-side risk, together with OPEC spare capacity, which is a supply-side risk factor, will serve as the global crude oil market risk factors in the model.

Finally, as stated at the beginning of this section, a trend variable is used to gauge the other variables that may enhance globalization and hence increase spillover over time, such as development of communication and transportation. All of the variables are summarized in Table 5.1.

Although 15 variables are included, the model may not take account of all the variables that could possible affect spillovers. However, the chance of omitting a relevant variable is not a severe threat due to the methodology, which will be discussed in the next section.

5.4 Empirical analysis

5.4.1 Methodology

The explanatory variables discussed in the last section will be used to model net spillover indexes for both return and volatility. Because the explanatory variables are at country level, the net spillover indexes at crude level are aggregated by country level as well. If two crudes are from the same country, their spillover indexes are summed. Because a number of the crudes are from the same countries the spillover table's dimensions are reduced from 32×32 to 25×25. From the analysis in Chapter 4, the spillover table is still informative after aggregating. The net spillover index from country i to country j is calculated by subtracting the spillover from j to i from the spillover from i to j. Applying this operation to each weekly spillover table, results in the dynamic net spillover tables with 576 results for returns and 577 for volatility. To match the quarterly frequency of explanatory variables, the weekly net spillover indexes are averaged to quarterly frequency.

There are two types of spillover index, as discussed in Chapter 4 the individual net spillover index and the pairwise net spillover index. The former measures the contribution of an individual crude to the forecast error variance of all others, while the latter measures the contribution of an individual crude to the forecast error variance of another. Models are set up separately. First, the explanatory variables in Table 5.1 are used to model the individual net spillover index. Second, to model the pairwise net spillover index, the same explanatory variables are used, but in relative terms, representing the difference between their values in the two countries involved in the net directional spillover. For example, when modeling the net spillover from country i to country j, the export share (ES) variable would be the export share of country i minus ES of country j. A similar operation applies to the other trade variables, fundamental variables and country risk variables. The same logic discussed in the previous section applies to the variables in relative terms. For example, if country i has a greater export share than country j, it should have a greater spillover to country j because this. Therefore the positive/negative relationship discussed in the previous section is expected to be valid in relative terms here as well.

However, global risk factors and trends, reflect the global market condition, not those specific to any one country, so they are given still in absolute terms in the pairwise analysis. Their relationships with the net spillover index, are expected to be valid as well.

Panel analysis is applied because it is suitable for data varying both over time and cross-sectionally. It is a standard method and is widely used in similar studies. For example, Fernández-Rodríguez et al. (2015) used panel regression to study the determinants of volatility spillovers in European sovereign bond markets. Similarly panel tests and regression are applied here in the individual and pairwise net spillover models. The analysis tool is the 'plm' package in R software.

5.4.2 Model individual net spillover index

In this section the impact of a country on the whole system is modelled. The dependent variable is net spillover of an individual country contributes to other countries. The individual net spillover of country i is the forecast error variance of all the other countries due to shocks from i. That is, country i's net impact on all the other countries. What determines country i to have this contribution to other countries' forecast error variance? In this section whether or not the selected variables have explanatory power in the panel regression will be tested.

5.4.2.1 Model selection

First, diagnostic tests are applied to select the appropriate regression model. Table 5.2 presents the results of various statistical tests to select the appropriate panel regression model from the fixed effects (FE) model, the random effects (RE) model and the pooled-OLS model. Specifically, the F test is used to check the stability of the coefficients of the panel model. The null hypothesis is that the same coefficients will apply to each country. It compares the model obtained from the full sample with the model based on the estimation of an equation for each individual, i.e. each country in our case. If the null hypothesis is rejected, the pooled OLS model is not appropriate because the coefficients are not stable over countries.

Second, the Lagrange multiplier of Breusch and Pagan (1980) is used to test for the presence of unobserved time and individual heterogeneity effects. The null hypothesis is that no such effects exist while the alternative hypothesis is these effects are significant. Rejection of the null hypothesis implies heterogeneity across time, that individuals are too significant to be ignored, and that the pooled OLS model is not appropriate. Therefore a random effects model is to be favored. An F test is then used to compare the fixed effects and pooling OLS models. A fixed effects model is to be favored if the null hypothesis is rejected. Finally a Hausman test is applied to choose between the fixed effects and random effects models. The Hausman test basically tests whether the unique errors are correlated with the regressors. The null hypothesis is that they are not correlated. Rejection implies that the fixed effects model is to be favored.

Table 5.2 shows that for the full sample, the pooling OLS method is not appropriate because the poolability test results reject the null hypothesis of there being the same coefficients for all countries. The Breusch and Pagan LM tests reject the null hypothesis of pooling OLS and favor the random effects model. The F test results show that the individual and time effects are significant, rejecting pooling OLS and favoring the fixed effects model. Finally the Hausman test indicates that fixed effects models are more appropriate.

Table 5.2: Individual net spillover determinants panel diagnostic test results

Test	Full sample		OPEC		Non-OPEC	
	NETRT	NETVT	NETRT	NETVT	NETRT	NETVT
Tests of poolability (F test)	19.302***	13.121***	9.655***	12.487***	20.286***	10.312***
Tests for individual and time effects (Breusch and Pagan LM test)	4837.8***	334.77***	12.407***	14.946***	346.49***	26.254***
F test (individual and time effects)	29.29***	6.687***	1.3033*	1.745***	8.8531***	3.658***
Hausman test	164.07***	158.13***	35.588***	34.883***	330.33***	122.9***
selected model	Fixed Effects	Fixed Effects	Fixed Effects	Fixed Effects	Fixed Effects	Fixed Effects
Wooldridge test for serial correlation	876.68***	641.68***	335.12***	272.39***	528.91***	349.05***

Note: This table presents the diagnostic test results of the individual net spillover determinants panel. NETRT represents net return spillover while NETVT represents net volatility spillover. The IS variable is not included in the sub-samples because it is zero or close to zero for the OPEC countries. *** significant at 1%; ** significant at 5%; * significant at 10%.

Moreover, this data is a macro panel with a time dimension (44 quarters) larger than that of the cross-section (25 countries). Schmidheiny (2015) points out that in practice, when there are more than two periods, the idiosyncratic errors are often serially correlated. This is confirmed by the Wooldridge test for serial correlation. All tests reject the null hypothesis of no serial correlation in the idiosyncratic errors. Bertrand, Duflo, and Mullainathan (2002) show that the usual standard errors of the fixed effects estimator are drastically understated in the presence of serial correlation. It is therefore advisable to always use robust standard errors for the fixed effects estimator. Therefore in this analysis, autocorrelation-robust covariance estimators (also known as 'sandwich estimators') are applied instead of standard fixed effects estimators.

The fixed effects model has the benefit of controlling the average differences across countries in any observable or unobservable predictors, because fixed effect coefficients soak up all of the across-country action, therefore the threat of omitted variable bias is greatly reduced. However, this also has a significant limitation. One cannot assess the effects of cross-sectional variables in a fixed effects model. For example, one cannot assess if OPEC membership has any impact on the net spilllover index. To do so, it is necessary to split the sample based on OPEC membership, and then run regressions over the sub-samples to determine if there are any difference in the regression results. Because OPEC member countries are mainly crude oil net exporters, their import shares (IS) are zero or very close to zero, resulting in a meaningless coefficient estimation. Therefore the IS variable is excluded in sub-sample of OPEC countries. To make a fair comparison, the IS variable is not included in non-OPEC sub-sample either. Table 5.2 also displays the diagnostic test results for the sub-samples. Following a similar to the above analysis, it can be concluded that the fixed effects model is also appropriate for the sub samples.

The panel regressions for individual net spillover indexes is as follows:

$$\begin{aligned}
\text{Individual net spillover index}_{i,t} = {} & \alpha_1 ES_{i,t} + \alpha_2 IS_{i,t} + \alpha_3 NI_{i,t} \\
& + \alpha_4 RS_{i,t} + \alpha_5 CS_{i,t} + \alpha_6 PS_{i,t} \\
& + \alpha_7 GR_{i,t} + \alpha_8 OG_{i,t} + \alpha_9 EX_{i,t} + \alpha_{10} V_{i,t} \\
& + \alpha_{11} VIX_t + \alpha_{12} GOLD_t + \alpha_{13} OPECSC_t + \alpha_{14} OECDS_t \\
& + \alpha_{15} TD_t + \mu_{i,t}
\end{aligned}$$

where all variables[9] are in absolute terms.

[9]See 5.1 for full names of variables.

The panel regression for pairwise net spillover indexes is as follows:

$$\begin{aligned}
\text{Pairwise net spillover index}_{ij,t} = {} & \alpha_1 ES_{ij,t} + \alpha_2 IS_{ij,t} + \alpha_3 NI_{ij,t} \\
& + \alpha_4 RS_{ij,t} + \alpha_5 CS_{ij,t} + \alpha_6 PS_{ij,t} \\
& + \alpha_7 GR_{ij,t} + \alpha_8 OG_{ij,t} + \alpha_9 EX_{ij,t} + \alpha_{10} V_{ij,t} \\
& + \alpha_{11} VIX_t + \alpha_{12} GOLD_t + \alpha_{13} OPECSC_t + \alpha_{14} OECDS_t \\
& + \alpha_{15} TD_t + \mu_{ij,t}
\end{aligned}$$

where all variables[10] are in relative terms, except global risk factors.

5.4.2.2 Estimation results

Table 5.3 displays the results of regression of the individual net spillover determinants models. The left part of the table gives the result of regression of the full sample, while the right part of the table shows the results for the sub-samples: OPEC and Non-OPEC countries.

For the full sample, the international trade variables, including export (ES), import (IS) and net energy import (NI) shares, are all significant, both for return and volatility net spillovers. Export share (ES) and import share (IS) are positive as expected, confirming that countries with larger market shares tend to spread their influence to other countries. The energy net import (NI) variable is positive for volatility net spillover, but negative for return net spillover. As discussed above, a country which exports more than it imports will tend to receive spillovers from other countries because it is exposed to the other countries' demand shocks. The empirical result shows that this hypothesis only valid for volatility. For returns, the relationship is reversed; that is, a country which

[10] See 5.1 for full names of variables.

TABLE 5.3: Individual net spillover determinants models

	Full sample		OPEC		Non-OPEC	
	NETRT	NETVT	NETRT	NETVT	NETRT	NETVT
1. International trade variables						
ES	1.1372***	1.8106***	0.1992	0.8641	0.8943**	1.5515***
	(4.325)	(5.3547)	(0.9141)	(1.5219)	(2.5549)	(3.2859)
IS	0.7130***	1.7277***				
	(3.7709)	(3.5883)				
NI	-0.0337***	0.0149**	-0.0269***	0.0667***	-0.0474***	-0.0191*
	(-10.1817)	(2.02)	(-4.9561)	(5.8095)	(-9.5198)	(-1.9007)
2. Fundamental variables						
RS	0.0846**	0.0918	0.1251***	0.0165	5.4348***	7.4785***
	(2.0627)	(1.5476)	(5.6762)	(0.4553)	(4.4983)	(4.3627)
CS	0.5447*	-1.0686	4.0786***	-3.4877***	1.1635***	0.8011**
	(1.6956)	(-1.2849)	(3.772)	(-2.6197)	(8.1719)	(2.549)
PS	-5.5028***	-4.3983***	-1.8103***	0.9653	-7.0924***	-6.9766***
	(-12.8081)	(-7.2463)	(-6.0352)	(1.6192)	(-12.3659)	(-7.5693)
3. Country risk variables						
GR	0.0474***	0.0339	0.0220*	0.0349	0.0537**	0.0396
	(4.2385)	(1.6479)	(1.8813)	(1.5697)	(2.4872)	(1.4715)
OG	0.0850	0.6260***	0.1078*	0.5834***	-0.2973**	0.2554**
	(1.0506)	(4.6184)	(1.6824)	(3.6079)	(-2.1788)	(2.0234)
EX	-0.0113	-0.0017	0.0032	0.0110*	-0.0536**	-0.0468
	(-1.5671)	(-0.1975)	-0.8107	(1.6982)	(-2.4368)	(-1.6475)
V	-0.0466	1.3016**	-1.4126***	-2.0556***	0.6922***	3.1619***
	(-0.2977)	(2.4575)	(-6.5286)	(-2.8538)	(3.0516)	(3.8952)
4. Global risk variables						
VIX	0.0007	0.0000	0.0046***	-0.0058	-0.0010	0.0049
	(0.9702)	(-0.0011)	(2.9655)	(-0.743)	(-0.4579)	(0.8902)
GOLD	-0.0031	-0.0096	0.0288***	0.0355	-0.0282***	-0.0430***
	(-0.7408)	(-1.3134)	(2.8296)	(1.3727)	(-2.6622)	(-2.5853)
OPECSC	0.0005	0.0027***	0.0002	0.0046***	0.0013*	0.0025***
	(1.2301)	(4.0968)	(0.2612)	(2.6574)	(1.7982)	(3.39)
OECDS	-0.0307**	-0.0743***	0.0687*	0.1076*	-0.1345***	-0.2414***
	(-2.2779)	(-2.5835)	(1.7467)	(1.6716)	(-3.2437)	(-4.5926)
5. Other variables						
TD	0.0003	0.0005	-0.0014***	-0.0014	0.0019***	0.0026***
	(1.4127)	(1.3877)	(-2.7327)	(-1.2014)	(3.5618)	(3.4901)
R square	0.2756	0.1422	0.1561	0.1853	0.5043	0.3053

Note: This table presents the results pf the regression of individual net spillover determinants models using the fixed effects model. NETRT represents net return spillovers while NETVT represents net volatility spillovers. They are scaled by 1000 to make the results more presentable. The IS variable is not included in the sub-samples because this variable is zero or close to zero for OPEC countries. In parenthesis below each parameter estimate is the corresponding t-statistics, computed using robust standard errors. *** significant at 1% ; ** significant at 5%; * significant at 10%.

imports more it exports tends to receive return spillovers. This may reflect the fact that in the crude oil market, the supply side (net exporters) has more pricing power, and spreads this influence to demand side (net importers). The net importers have no choice but to receive. This is different from Diebold and Yilmaz (2015a), who studied the industrial product trade, which is more likely to result in free trade than the crude oil market.

The fundamental variables such as production (PS), consumption (CS) and reserve shares (RS) are all statistically significant for return net spillovers. The production share variable is negative, and the consumption share variable is positive as expected. It was not possible to predict the sign of the reserve share variable in the previous section because reserve, as potential supply, could mitigate spillover from other countries and to other countries at the same time. The overall effect is not clear. The regression shows a positive relationship, implying that the dominant effect of reserve reduces the spillover effect from other countries, and hence makes the overall effect positive with regard to net return spillovers.

However, for volatility net spillover, production share (PS) is the only significant fundamental variables, which has the effect of decreasing the net volatility spillover to other countries. Consumption and reserve do not have a significant impact on volatility spillovers.

In the category of country risk variables, geopolitical risk (GR) is the only significant variable for return net spillovers, and is surprisingly positive. A risky country was expected to transmit shocks rather than receive them. However, the dominant return spillover crudes in Chapter 4 (Brent and WTI) are both are located in safe countries, the US and the UK which have high political stability percentile ranks. Therefore a positive relationship in the regression can be explained. This result is different from that of H.-Y. Zhang et al. (2015), who found that the geopolitical risk of oil exporters was a significant factor affecting the formation of oil trade patterns. They argued that oil importers gradually shift their import sources from high-risk regions to low-risk regions to avoid supply disruption threats, therefore stable political environments have a positive effect on promoting oil trade, which implies that high-risk regions are less likely to transmit shocks. The reason for the difference between these studies is that the object of their study was oil trade flows, not price or returns, so pricing mechanisms had little impact on their results. Therefore, although there are different conclusions, both are reasonable under their corresponding analysis frameworks.

In the case of volatility net spillover, geopolitical risk (GR) is nonsignificant. Instead, oil revenue's contribution in GDP (OG) and volatility (V) are found to be two important factors. As discussed in Section 5.3.3, a country's dependence on oil could have mixed effect. A high dependence on oil production makes it prone to receive demand shocks from other countries, but if it is also a larger supplier it will tend to spill over shocks. The significant positive result indicates that the latter effect dominates in terms of volatility spillover.

Volatility is significantly positive in the full sample regression. Thus this analysis supports the hypothesis of Prasad et al. (2014) that volatility is the major driver of increased volatility spillovers to other markets. This hypothesis is not only valid in the stock market, but in the crude oil market as well.

Finally, in the global risk factor category, OECD stock (OECDS) is a significant variable for both return and volatility net spillovers, and is negative as expected. This implies that cushion from stock will help to reduce spillovers. However, OPEC spare capacity (OPECSC), has an unexpectedly positive relationship with net volatility spillovers, which implies that volatility spillover is small in tight markets. One possible explanation of this is that OPEC countries use their production ability strategically. Since the early 1990s, the year-to-year increase in global oil demand has outpaced the increase in non-OPEC supply. According to Fattouh (2007a), over the period 1990–2004, global demand for oil increased by around 16 mbd, while the increase in non-OPEC supply amounted to only around 6 mbd. OPEC countries increase production to meet the difference between the increase in global demand and non-OPEC supply. From 1990–2004, OPEC countries supplied the additional 10 mbd, with production in 2004 reaching around 33 mbd. Therefore OPEC countries absorb the demand shock by using their spare production capacity, leading to less shock transmission.

Trend (TD) is non-significant in either return or volatility net spillover. A country's spillover to other countries does not therefore increase or decrease over time.

The right hand part of Table 5.3 shows the regression results across OPEC countries and non-OPEC countries, in order to determine whether or not OPEC membership has any impact on spillover. The analysis only focuses on the difference between groups.

International trade and fundamental variables in non OPEC countries are generally more significant than in OPEC countries, especially for the export share (ES) variable, which demonstrates enhanced spillover for non-OPEC countries, but not OPEC countries. The reason for the difference, could be that non-OPEC countries are more globalized, therefore the trade and market variables play a more important role for non-OPEC countries than OPEC countries. Another difference is the consumption share (CS) of OPEC countries will significantly reduce their ability to give volatility spillovers, but this is not the case for non-OPEC countries. As discussed in Section 5.3.2, a greater consumption share will allow a country to spread its demand shocks to other countries. However, if the country belongs to the OPEC group, more consumption will limit its volatility spillover, possibly because it is a big producer as well; it could therefore soak up its demand shocks and hence reduce the amount of shocks spread it gives.

In the country risk variables, there are several notable differences: first, if a non-OPEC country's GDP relies more on the oil industry (OG), it is vulnerable to shocks and tends to receive return spillovers. However, if it is an OPEC country, the situation is the opposite. i.e a greater share of oil output in GDP makes it more able to give spillovers. Second, exchange rate (EX) has opposite effects for OPEC and non-OPEC countries. Depreciation of local currency in non OPEC countries will enhance their competitive advantage, promoting production, therefore limiting its ability to spread demand shocks to others, as expected from Section 5.3.3. However, in contrast an OPEC country's currency depreciation does not have this effect. Currency depreciation in these countries was found to slightly increase their volatility spillover. This may be due to the fact that OPEC countries are mainly net exporters and depreciation will increase their export advantage and enhance their influential power.

Third, the volatility (V) of OPEC countries will decrease their net spillover, while volatility of non OPEC countries will increase net spillover. Both effects are significant. Although our full sample regression supports the hypothesis of Prasad et al. (2014) that volatility is the major driver of increased volatility spillovers to other markets, the subsample regression shows that this hypothesis is only valid for non-OPEC countries.

In the global risk factors, there are also remarkable differences between OPEC and non-OPEC countries. First, VIX only significantly increases return net spillover for

OPEC countries. Gold price (GOLD), which gauges investors' attitude towards risk, has opposite effects on OPEC and non-OPEC countries' net spillover. When investors' risk tolerance is low (high gold price), OPEC countries' spillover increases while non-OPEC countries' net spillover decreases. Second, the cushion effect of OECD stocks only seems to be effective to non-OPEC countries, with more stock associated with less spillovers. To OPEC countries, more OECD stock enhances net spillover. This may due to the fact that in order to keep profits high OPEC countries used to reduce their production targets when they observed more OECD stocks.

Finally, the trend variable (TD) also has opposite relationships for OPEC and non-OPEC countries. OPEC countries' net spillover decreases over time, while the non-OPEC countries' net spillover is increasing. This may imply that non-OPEC countries' influence is increasing while OPEC countries' influence is decreasing.

The range of R-squared of these determinant models is from 0.15 to 0.5, which indicates that a reasonable amount (15-50%) of the variation in the net spillover is able to be explained by variation in our selected explanatory variables. Comparing the R-squared of OPEC and non-OPEC countries, models of non-OPEC countries have a better fit than those of OPEC countries, implying that these determinants are more relevant for non-OPEC countries. Comparing the R-squared of return and volatility spillover, models of return spillover have better fit than those of volatility spillover. This observation is consistent with the discussion regarding the difference of return and volatility spillover in Chapter 4. Return spillover generally reflects the integration of market, but volatility spillover does not. Instead, volatility spillover is small in tranquil periods, but is often magnified by events, especially crisis periods. Since events are not included in the determinants, the explanatory power of volatility spillover is smaller than that of return spillover.

5.4.3 Model pairwise net spillover index

In this section, I model the pairwise net spillover index. The dependent variable is the net spillover from one country to another country. It measures the amount of country i's forecast error variance due to shocks from country j. When a shock takes place in country j, it does not transmit equally to all other countries. Rather, the shock is distributed to other countries depending on "how connected these markets are with the market that was subject to the shock in the first place." (Diebold & Yilmaz, 2015a). This pairwise analysis will explore whether or not the selected explanatory variables can explain the level of shocks transmitted between countries.

5.4.3.1 Model selection

Similar to the individual net spillover models, diagnostic tests are applied first, to select an appropriate regression model. The left hand part of Table 5.4 presents the test results for the full sample. Following a similar analysis process to the individual net spillover models, a fixed effects model is appropriate for both return and volatility net spillovers. As stated above, a fixed effects model cannot assess the effect of pure cross-sectional variables. So the sample is again split into OPEC/non-OPEC membership to investigate whether OPEC membership has any impact on the model. If both countries in a pair belong to the same membership group, whether OPEC or non-OPEC, the pair is classified in a "same membership" sub sample. If a pair belong to different membership groups, i.e. one belongs to OPEC but the other not, this pair is classified in a "different membership" sub sample. The right hand part of Table 5.4 provides the diagnostic results for sub-samples. Again a fixed effects model is chosen as the most appropriate regression method. Moreover, it would be beneficial to know even if two countries in a pair belong to the same membership group, is there a difference if they belong to either the OPEC or the non-OPEC group. Therefore the "same membership" sub sample is further split into "same OPEC" and "same non-OPEC" samples. Table 5.5 presents the diagnostic test results for the same OPEC and same non-OPEC sub-samples. Again, the fixed effects model is selected as the appropriate model. Wooldridge serial test results also suggest the need to apply autocorrelation-robust covariance estimators.

Table 5.4: Results of pairwise net spillover determinants panel diagnostic: full sample and same/different membership

Test	Full sample		Same membership		Different membership	
	Return	Volatility	Return	Volatility	Return	Volatility
Poolability (F test)	27.829***	12.107***	28.06***	11.94***	27.672***	12.183***
Tests for individual and time effects (Breusch and Pagan LM test)	64417***	6550.2***	18505***	3747.3***	39395***	2642.5***
F test	61.722***	15.549***	41.853***	15.819***	60.279***	11.93***
Hausman test	1379.1***	1549.9***	847.05***	930.9***	453.56***	703.95***
Selected model	Fixed Effects	Fixed Effects	Fixed Effects	Fixed Effects	Fixed Effects	Fixed Effects
Wooldridge test for serial correlation	10631***	8286.1***	5351.6***	4285.9***	5252.7***	4013.3***

Note: This table presents the results of the pairwise net spillover determinants model diagnostic test. The left hand part of the table shows the results for the full sample. The right hand part of the table shows the results for the sub-samples separated by OPEC membership i.e. whether the countries in the pair belong to the same membership group or different groups. *** significant at 1% ; ** significant at 5%; * significant at 10%.

5.4.3.2 Estimation results

Table 5.6 presents the results of the regression of the pairwise net spillover determinants models for the full sample and the sub-samples, as separated by same/different OPEC membership.

TABLE 5.5: Results of pairwise net spillover determinants panel diagnostic test: OPEC and non-OPEC groups

Test	Same OPEC		Same NonOPEC	
	Return	Volatility	Return	Volatility
Poolability (F test)	20.05^{***}	10.165^{***}	26.658^{***}	10.642^{***}
Tests for individual and time effects (Breusch and Pagan LM test)	21.923^{***}	605.62^{***}	6314^{***}	1011.6^{***}
F test	3.6801^{***}	6.2498^{***}	27.155^{***}	11.702^{***}
Hausman test	171.97^{***}	98.513^{***}	684.66^{***}	1102.3^{***}
Selected model	Fixed Effects	Fixed Effects	Fixed Effects	Fixed Effects
Wooldridge test for serial correlation	1531.6^{***}	1254.4^{***}	3820.8^{***}	2979^{***}

Note: This table presents the results of the pairwise net spillover determinants model diagnostic test on sub-samples. Countries in a pair both belonging to OPEC are classified into the "Same OPEC" sub-sample, while if both belong to non-OPEC are classified into the "Same non-OPEC" sub-sample. *** significant at 1% ; ** significant at 5%; * significant at 10%.

As stated in the methodology, all of the explanatory variables are in relative terms except global risk factors and trends, and these are expected to have the same sign as the absolute terms. In the full sample, international trade variables such as export and import shares are significant positive as expected, whether for return or volatility pairwise net spillovers. This implies that if a country i has a greater share of the international trade market than country j, it would tend to spread shocks to j. The energy net import variable has a positive effect on volatility pairwise net spillovers as expected, but a negative effect on return net spillovers. This is the same as in the individual net spillover models. Similarly the negative relationship could be attributed to the pricing power of the supply country (net exporters) because the country with more net imports has to receive the spillover from exporters.

The fundamental variables have the same expected signs and significance as those in the individual net spillover models, with the exception of consumption on pairwise volatility net spillovers, which are non-significant. The country risk variables, including geopolitical risk (GR), oil revenue in GDP (OG), exchange rate change (EX) and volatility (V), have the same sign as in the individual net spillover determinants models. Therefore the argument for the individual net spillover determinants models applies in the pairwise models as well.

However, the effects of global risk factors are not the same as in the individual net spillover determinants models. VIX and gold price, which are non-significant in the individual net spillover models, have significant effects in the pairwise net spillovers models. VIX, as expected is positive in the pairwise volatility spillover, but has an unexpected negative relationship with return spillover. Gold price is also unexpected negative, especially for volatility spillover. This finding is different from that in equity markets. Leelahaphan et al. (2015) found VIX and gold were significant able to explain the spillover for both return and volatility in their sample of 19 equity markets. They argue that VIX index, which was calculated from implied volatility embedded in option price based on the S&P Index, can be an indicator of financial turmoil, not only for the US market, but also for all other international equity markets. Gold price has similar effect as an alternative indicator of global instability. However, in the crude oil market, VIX and gold price do not show this effect. Further research is needed to investigate the interaction between equity, crude oil and other commodity markets.

The result of crude oil market specific risk factors is encouraging. OPEC spare capacity (OPECSC) and OECD stock (OECDS) are significant and negative as expected.

Finally, the trend variable is positive and significant for the volatility pairwise net spillover, implying that one country can easily give greater volatility shocks to the other over time. This effect is non-significant for return pairwise spillovers.

Table 5.6: Pairwise net spillover determinants models: full sample and grouped by same or different OPEC membership

	Full sample		Same membership		Different membership	
	NETRT	NETVT	NETRT	NETVT	NETRT	NETVT
Model	FE	FE	FE	FE	FE	FE
1. International trade variables						
ES	0.0431***	0.0705***	0.029***	0.0622***	0.0548***	0.0743***
	(4.1277)	(5.3859)	(2.6964)	(4.4583)	(5.1344)	(5.3529)
IS	0.0262***	0.0687***	0.0331***	0.0853***	0.0252***	0.0582**
	(3.4002)	(3.6148)	(4.5739)	(5.0555)	(2.7138)	(2.5755)
NI	-0.0014***	0.0008***	-0.0011***	0.0009***	-0.0015***	0.0009**
	(-9.3759)	(2.7921)	(-8.4579)	(3.8126)	(-9.707)	(2.5322)
2. Fundamental variables						
RS	0.0046**	0.0065**	0.0057***	0.008***	0.0035*	0.0049*
	(2.4842)	(2.4278)	(3.4477)	(2.8846)	(1.658)	(1.8543)
CS	0.0216*	-0.0506	0.0043	-0.078***	0.0311**	-0.0338
	(1.7112)	(-1.533)	(0.3801)	(-2.7473)	(1.9713)	(-0.8459)
PS	-0.2212***	-0.1775***	-0.1967***	-0.1737***	-0.2429***	-0.1724***
	(-12.4279)	(-7.1491)	(-12.1906)	(-7.251)	(-12.1031)	(-6.3861)
3. Country risk variables						
GR	0.002***	0.0013	0.002***	0.0009	0.0019***	0.0014
	(4.5683)	(1.5463)	(5.2034)	(1.1604)	(3.8334)	(1.5999)
OG	0.0045	0.031***	0.0053	0.0339***	0.0033	0.028***
	(1.0415)	(4.5786)	(1.3356)	(4.8815)	(0.7178)	(3.9121)
EX	-0.0005	0.0003	-0.0004	0.0001	-0.0005	0.0005
	(-1.4449)	(0.5776)	(-1.2256)	(0.1165)	(-1.441)	(0.8712)
V	0.0104	0.303*	0.0081	0.2584*	0.0133	0.3506*
	(0.2503)	(1.8046)	(0.2038)	(1.8139)	(0.3058)	(1.7942)
4. Global risk variables						
VIX	-0.0001**	0.0004***	-0.0002***	0.0004***	-0.0001	0.0004***
	(-2.2625)	(3.1092)	(-3.3123)	(2.7666)	(-1.3188)	(3.2404)
GOLD	-0.0001	-0.002***	-0.0003	-0.0025***	0.0001	-0.0016***
	(-0.233)	(-3.2152)	(-0.8028)	(-3.3684)	(0.3001)	(-2.8962)
OPECSC	-0.0001***	0.0000	-0.00004*	0.0000	-0.0001***	-0.0001*
	(-2.8529)	(-0.996)	(-1.8347)	(0.0807)	(-3.6392)	(-1.859)
OECDS	-0.0031**	-0.007***	-0.0041***	-0.0106***	-0.0021	-0.0035**
	(-2.3184)	(-4.1714)	(-3.1969)	(-5.8949)	(-1.4562)	(-2.0761)
5. Other variables						
TD	0.0000	0.00008***	0.0000	0.0001***	0.0000	0.00007***
	(0.2936)	(2.9065)	(0.5579)	(2.9994)	(-0.024)	(2.5768)
R square	0.2144	0.1326	0.2498	0.1720	0.1948	0.107

Note: This table presents the results of the regression of pairwise net spillover determinants models using fixed effects model, for the full sample and sub-samples separated by same/different membership. The dependent variables are return/volatility net spillovers from country i to country j, represented by NETRT and NETVT respectively in the table. They are scaled by 1000 to make the results more presentable. In parenthesis below the parameter estimates are the corresponding t-statistics, computed using robust standard errors. *** significant at 1% ; ** significant at 5%; * significant at 10%.

In order to explore whether the OPEC membership has any impact on pairwise spillovers, the regression is repeated on sub-samples separated by membership. The right hand part of Table 5.6 presents the results. This analysis will focus on the difference between the sub-samples.

The international trade variables, fundamental variables and country risk variables have similar signs across the sub-samples, implying that whether or not the countries of a pair belong to the same or a different membership group, makes no difference to the determinants of pairwise spillover.

There is a slight difference in the global risk factors between the two sub-samples, reflected by the fact that VIX is significant for return net spillover in same membership sub-sample, but not so in the different membership sub-sample. Moreover, OPEC spare capacity's negative impact on volatility pairwise net spillover is non-significant for the same membership sub-sample, but significant for the different membership sub-sample. OECD stock is non-significant for the return pairwise spillover in the different membership sub-sample, although it is negative as expected. Overall, there is no remarkable difference, such as significantly opposite signs, between these two sub-samples.

The R-squared of these pairwise net spillover determinants models ranges from 0.1 to 0.25. The models of different membership sub-samples have better fits than the same membership sub-samples.

Whether or not the countries in a pair belong to the same membership group was explored to discover if there is any difference if they belong to the OPEC or non OPEC group. The same membership sub sample is therefore split further into a same OPEC and same non OPEC groups. Table 5.7 presents the regression results.

From Table 5.7 it can be seen that the difference between the OPEC and non OPEC groups is greater than same and different memberships in Table 5.6. The international trade variables and fundamental variables of the non-OPEC countries are generally more significant than that of OPEC countries, except for net energy import (NI) for volatility spillover and consumption (CS) for return spillover. The greater relevance of trade and fundamental variables for non-OPEC countries is similar to the observation in the individual net spillover analysis.

For the country risk variables, only exchange rate depreciation is negative, as expected, for return net spillover between non-OPEC countries, but not for between OPEC countries. Volatility also has the opposite effect on OPEC pairs and non-OPEC pairs. These differences were also observed in the individual net spillover analysis, and a similar logic applies.

For the global risk factors, non-OPEC pairs' spillover is generally more sensitive to VIX and gold price than OPEC pairs, as reflected by the significance of these two variables in the nonOPEC sub sample. Regarding risk factors that are specific to the crude oil market, OPEC pairs' return spillovers are more sensitive to OPEC spare capacity than non-OPEC pairs, while non-OPEC pairs are more sensitive to OECD stock than OPEC pairs.

Finally, the volatility spillover between non-OPEC countries is increasing over time, but this is not the case for OPEC countries. This is consistent with the observation in Figure 4.8 in Chapter 4.

The R-squared shows that our explanatory variables could better explain variations of spillover between non-OPEC countries than OPEC countries, similar to that in the individual net spillover analysis. The better fit of return than volatility in the individual net spillover analysis also applies to the pairwise net spillover analysis.

In the cross-country study, distance, or region, is one important factor that could influence the spillover between countries. For example, Diebold and Yilmaz (2015a) found that the pairwise connectedness of the stock market is high if the markets are located in the same region. For example, Japan, Hong Kong and Australia in the East region have a high pairwise connectedness. US, UK, Germany and France in the North Atlantic region are also closely connected to each other. Therefore they propose to use region to explain the pairwise connectedness. H.-Y. Zhang et al. (2015)found that distance is the most significant factor impeding trade between countries, because it could effectively influence transportation costs and trade risks. Unfortunately, distance is a pure cross-section variable which cannot be included in fixed effects model. In order to study whether the distance or region could have any impact, the pairwise sample is split into two categories: "same region" or "different regions". If the countries of a pair are located in the same region, this pair is classified as "same region". If they are located in different regions, the pair is classified as "different regions". The region of each country is displayed in Table A.1. Then a similar method to the above is followed to build up panel the regression models, to determine if there is any difference between the two groups.

Table 5.8 presents the diagnostic results of the test to to select the models. Similar to the above, the fixed effects model is appropriate. Wooldridge serial test results suggest applying autocorrelation-robust covariance estimators. Table 5.9 shows the regression results. The full sample result is also included as a reference.

First, among the international trade variables, pairwise spillover in the same region is

Table 5.7: Pairwise net spillover determinants models: OPEC and NonOPEC comparison

	Same membership: OPEC		Same membership: Non OPEC	
	NETRT	NETVT	NETRT	NETVT
1. International trade variables				
ES	0.0098	0.0446*	0.0145	0.0485***
	(0.7045)	(1.9383)	(1.1695)	(3.0956)
IS	0.0235	0.1230	0.0328***	0.0621***
	(1.0399)	(1.2719)	(3.7432)	(3.4918)
NI	-0.0007*	0.0026***	-0.0009***	0.0004
	(-1.9206)	(4.7034)	(-4.6434)	(1.3766)
2. Fundamental variables				
RS	0.0033	0.0001	0.1457***	0.2155***
	(1.2801)	(0.061)	(3.8752)	(3.6381)
CS	0.1508***	-0.2548***	-0.0132	-0.0593**
	(3.7728)	(-3.7121)	(-0.9488)	(-1.9632)
PS	-0.082***	0.0171	-0.2169***	-0.2251***
	(-3.0389)	(0.6554)	(-11.0636)	(-8.0982)
3. Country risk variables				
GR	0.0016*	0.0010	0.0014*	0.0001
	(1.8724)	(1.1101)	(1.9507)	(0.1094)
OG	0.0067	0.0443***	-0.0087	0.0106**
	(0.9351)	(3.7548)	(-1.3298)	(2.0634)
EX	0.0003	0.0001	-0.0022***	-0.0016
	(0.5319)	(0.193)	(-2.6072)	(-1.1417)
V	-0.2347	-0.3614***	0.0731*	0.4726***
	(-1.2012)	(-4.2029)	(1.8479)	(3.141)
4. Global risk variables				
VIX	-0.0003*	0.0001	-0.0001**	0.0006***
	(-1.9563)	(0.8179)	(-2.3103)	(2.9674)
GOLD	-0.0001	0.0004	-0.0006*	-0.0042***
	(-0.1606)	(0.5111)	(-1.7192)	(-4.1318)
OPECSC	-0.0001***	0.0000	0.0000	0.0001
	(-3.5571)	(0.8847)	(0.5629)	(1.3376)
OECDS	-0.0018	-0.0005	-0.005***	-0.0144***
	(-1.1037)	(-0.1898)	(-4.7945)	(-6.2445)
5. Other variables				
TD	0.0000	0.0000	0.0000	0.0002***
	(1.2398)	(-0.0916)	(0.6873)	(3.8402)
R square	0.1625	0.1426	0.3734	0.3129

Note: This table presents the results of the regression of pairwise net spillover determinants models using a fixed effects model. The left hand part shows the result of sub-samples in which the countries of a pair both belong to OPEC member countries. The right hand part shows the result of sub-samples in which the countries of a pair both belong to non-OPEC member countries. The dependent variables are return/volatility net spillovers from country i to country j, represented by NETRT and NETVT respectively in the table. The results are scaled by 1000 to make them more presentable. In parenthesis below the parameter estimates are the corresponding t-statistics, computed using robust standard errors. *** significant at 1% ; significant at 5%; * significant at 10%.

TABLE 5.8: Pairwise net spillover determinants panel diagnostic test results: same/different regions

Test	Same region		Different regions	
	Return	Volatility	Return	Volatility
Poolability (F test)	22.131***	13.682***	28.558***	11.752***
Tests for individual and time effects (Breusch and Pagan LM test)	3283.2***	670.54***	52284***	4480.3***
F test	15.596***	6.7494***	64.405***	15.41***
Hausman test	326.76***	210.12***	1412.6***	1427.8***
Selected model	Fixed Effects	Fixed Effects	Fixed Effects	Fixed Effects
Wooldridge test for serial correlation	2237.8***	1665.5***	8337.8***	6512.1***

Note: This table presents results of the pairwise net spillover determinants model diagnostic test for sub-samples separated by regions. The left hand part of the table shows the results for the same region sub-sample. The right hand part of the table shows the results of the different regions sub-sample. *** significant at 1% ; ** significant at 5%; * significant at 10%.

not sensitive to export share. In other words, one country with a greater export share in a pair does not have significant spillover effects to the other country if they are in the same region. In contrast, it gives significant spillover to the other country if it is in a different region. This contradicts to the findings of Diebold and Yilmaz (2015a) and H.-Y. Zhang et al. (2015). The other two trade variables, import share (IS) and net import (NI) have similar effects in the two groups.

Second, among the fundamental variables, pairwise spillover from a different region is more sensitive to reserves than that of spillover from the same region, i.e. if a country has more reserves, it is more likely to transmit shocks to a country in a different region than a country in the same region. This is, again, a surprising result, because we expect countries to have more spillovers to those in the same region. Consumption has the expected positive effect on pairwise return spillover in the same region, implying that demand shock is more likely to spread to nearby countries. The production variable has

TABLE 5.9: Pairwise net spillover determinants models: full sample and grouped by regions

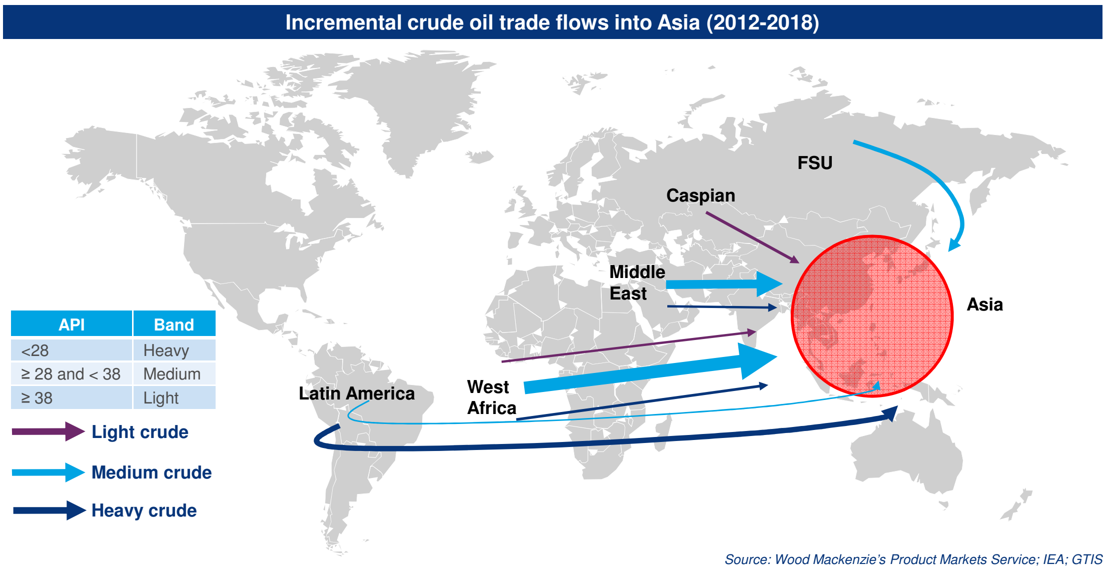
	Full sample		Same region		Different regions	
	NETRT	NETVT	NETRT	NETVT	NETRT	NETVT
1. International trade variables						
ES	0.0431***	0.0705***	-0.0078	0.0266	0.0512***	0.0783***
	(4.1277)	(5.3859)	(-0.8302)	(1.5242)	(4.7429)	(6.1271)
IS	0.0262***	0.0687***	0.0189**	0.0523***	0.0282***	0.0712***
	(3.4002)	(3.6148)	(1.9878)	(2.9062)	(3.5203)	(3.6817)
NI	-0.0014***	0.0008***	-0.0006***	0.0013***	-0.0015***	0.0007**
	(-9.3759)	(2.7921)	(-3.5674)	(4.0948)	(-9.2707)	(2.3866)
2. Fundamental variables						
RS	0.0046**	0.0065**	0.0022	0.0052*	0.0048**	0.0068***
	(2.4842)	(2.4278)	(1.0784)	(1.6551)	(2.4912)	(2.6068)
CS	0.0216*	-0.0506	0.0329***	-0.0472	0.0158	-0.0533
	(1.7112)	(-1.533)	(2.5872)	(-1.581)	(1.1341)	(-1.5799)
PS	-0.2212***	-0.1775***	-0.1331***	-0.0903***	-0.238***	-0.1948***
	(-12.4279)	(-7.1491)	(-7.9359)	(-4.4795)	(-12.67)	(-7.1766)
3. Country risk variables						
GR	0.002***	0.0013	0.002***	0.0032***	0.0019***	0.0007
	(4.5683)	(1.5463)	(3.9079)	(3.8518)	(3.5194)	(0.7725)
OG	0.0045	0.031***	0.018***	0.035***	0.0024	0.0307***
	(1.0415)	(4.5786)	(4.5159)	(3.1506)	(0.5321)	(4.7884)
EX	-0.0005	0.0003	0.0000	-0.0002	-0.0006*	0.0004
	(-1.4449)	(0.5776)	(-0.1357)	(-0.3877)	(-1.6802)	(0.9343)
V	0.0104	0.303*	-0.0923*	0.1853	0.0241	0.3216*
	(0.2503)	(1.8046)	(-1.8925)	(1.6438)	(0.5636)	(1.8104)
4. Global risk variables						
VIX	-0.0002**	0.0004***	-0.0001	0.0005***	-0.0001**	0.0004***
	(-2.2625)	(3.1092)	(-0.792)	(4.4459)	(-2.2865)	(2.8236)
GOLD	-0.0001	-0.002***	0.0011**	-0.0002	-0.0004	-0.0025***
	(-0.233)	(-3.2152)	(3.1333)	(-0.4961)	(-0.9885)	(-3.377)
OPECSC	-0.0001***	0.0000	-0.0001***	0.0000	-0.0001**	0
	(-2.8529)	(-0.996)	(-4.5513)	(-0.2678)	(-2.3284)	(-0.8899)
OECDS	-0.0031**	-0.007***	0.0022	0.0004	-0.0043***	-0.0087***
	(-2.3184)	(-4.1714)	(1.5075)	(0.2355)	(-3.0607)	(-4.4248)
5. Other variables						
TD	0.0000	0.00008***	-0.00004**	0.0000	0.0000	0.0001**
	(0.2936)	(2.9065)	(-2.4054)	(0.0745)	(0.7879)	(3.0214)
R square	0.2144	0.1326	0.1932	0.0999	0.2315	0.1467

Note: This table presents the results of the pairwise net spillover determinants model, for the full sample and sub-samples separated by same/different regions. The left hand part of the table shows the results for the full sample, while the right hand part presents the results for sub-samples. The dependent variables are return/volatility net spillovers from country i to country j, represented by NETRT and NETVT respectively. They are scaled by 1000 to make the results more presentable. In parenthesis below the parameter estimates are the corresponding t-statistics, computed using robust standard errors. *** significant at 1%; ** significant at 5%; * significant at 10%.

a similar effect on countries in the same region as it does on those in different regions.

The reason that export and reserves have a greater effect on spillover in different regions is the geographical mismatch between resource location and demand. According to Rempel (2011), approximately 70% of conventional global oil and natural gas reserves are concentrated inside a so called "Strategic Ellipse" stretching from Middle East to the North of West Siberia. The main consuming regions for oil in 2004 were North America, Australia-Asia, and Europe. Therefore countries do not trade intensively with their neighbors, but with oil producers that may be located far away. For example, it was predicted that Asia would need to import crude oil from the Middle East, West Africa, Europe and Latin America, as displayed in Figure 5.1 (Platts, 2013).

FIGURE 5.1: Trade flow to Asia



Source: Platts.

Third, for the country risk variables, spillover between countries in the same region seems to be more sensitive to GR (geopolitical risk) and OG (oil revenue in GDP) than spillover to countries in different regions. Only exchange rate has a negative but expected effect on return spillover between countries in different regions. Volatility has a negative impact on return spillover between countries in nearby regions.

Finally, for the global risk factors, spillover between countries in different regions is more sensitive to VIX than that between countries in the same region. This can be explained by similar reasoning as that which applies to OECD stock. Gold price has a positive effect as expected, but only for return spillover between countries in the same region.

Return spillovers between countries in the same region is decreasing over time, while volatility spillovers between countries in different regions is increasing.

R-squared shows that the models for spillovers between countries in different regions have a better fit than those between countries in the same region.

5.5 Conclusion

This study attempts to identify the driving forces of spillover effects in the international crude oil market. Why does a country spread shocks to other countries? What factors influence the amount of shocks transmitted between countries? This study uses five categories of variables to explain the spillover effects, including international trade variables, fundamental variables, country risk variables, global risk factors and time trends.

First, these explanatory variables are used to model individual net spillover of a country, i.e. the country's net spillover to all other countries. It measures the impact of a country in the international crude oil market. Using a balanced panel of 25 countries and 11 years of quarterly data, a fixed effects model is selected by diagnostic tests. The regression is first applied to the full sample, and then applied to sub-samples according to countries' OPEC/non OPEC membership.

International trade variables are important determinants of spillovers. Countries with a large market share in exports or imports will tend to transmit shocks to other countries.

Energy net import could enhance the volatility spillover of a country, but reduce its return spillover. This is attributed to the large influence of the supply side in the crude oil market. Net exporters (suppliers) have more power to influence price, while net importers can only receive shocks from them.

Fundamental variables such as production, consumption and reserve are also significant determinants for return spillover. Countries with more consumption will spread demand shocks to other countries, while greater production could reduce return spillover to others. Reserve, as potential supply, mainly has the effect of reducing spillovers from other countries, therefore having a positive net effect on spillovers to others. For volatility spillover, only production has a significant impact.

For the country risk variables, geopolitical risk has an unexpected negative effect on return spillover, implying that a safe country is more likely to transmit return shocks. This is attributed to the pricing mechanisms in the crude oil market. Two benchmark crudes which have significant return spillovers (WTI and Brent) are both produced in safe countries (the US and the UK), resulting in a different effect from that expected. This is different with the finding of H.-Y. Zhang et al. (2015). They found a positive effect of geopolitical risk. The reason is that their study object was trade flows, for which risky countries will spread more shocks and impede trade. In the case of volatility spillover, geopolitical risk does not show a significant effect.

Oil revenue in GDP and volatility are two important country risk factors for volatility spillover. If a country's GDP relies more on oil production, it is more likely to spread volatility shocks. This effect is attributed to the substantial influence of suppliers in the crude oil market. A country where oil revenues are a substantial part of GDP is likely to be a big supplier, and give volatility spillovers to other countries. Volatility is a driver of increased volatility spillovers to other markets. This hypothesis, proposed by Prasad et al. (2014), is also valid in the crude oil market.

OECD stock, as a cushion, has the effect of decreasing return and volatility spillovers. However, OPEC spare capacity, as an indicator of tightness in the crude oil market, does not have the expected impact in the full sample.

The comparison between OPEC and non OPEC groups shows that non-OPEC countries' spillover is more sensitive to market variables such as export, consumption, currency depreciation and volatility when compared with OPEC countries. The difference may arise from OPEC's special status. It is an influential supplier cartel. Logic which applies to a free trade market may not apply to OPEC countries. Non-OPEC countries, on the other hand, are more globalized and having more integrated economies makes them more sensitive to market movement.

The pairwise net spillover index was then modelled using the same explanatory variables, but in relative terms, except for the pure time series variables. Generally, factors such as international trade variables, fundamental variables and country risk variables have a similar effect as they do in individual spillover determinants models, with only global risk factors present slightly different effects.

Further examination shows that whether or not a pair of countries belongs to the same (OPEC) membership group does not have any impact on the pairwise spillover determinants results. However, regressions over OPEC pairs and non-OPEC pairs shows that expectation could be observed more in non OPEC pairs, but not in OPEC pairs. The R-squared also shows that the model fits better for non OPEC countries than OPEC countries.

Last, but by no means least, in order to explore whether the distance between countries impact their spillovers, the sample was split according to country pairs' in same/different locations. Generally the results do not support the argument that determinants' impact on spillovers would be enhanced if countries in a pair are close to each other, especially for export and reserve. This is attributed to the geographical mismatch of crude oil resource location and demand.

The selected determinants are found to explain the return spillover better than volatility spillover, this reflects the difference of return and volatility spillovers. The former reflects the integration of the market, while the latter reflects events or crises.

5.6 Discussion

The panel dataset here has time a dimension of 44 quarters, which composes a time series with greater dimensions than its cross-section (25). Eberhardt et al. (2011) advocates examining the time series properties of the panel with substantial T[11], and applying a macro panel ('long T') estimation technique if appropriate. The micro panel ('short T') estimators, including FE, may not be appropriate for a macro panel. One limitation is that the micro panel estimator assumes homogeneous slope coefficients across countries; all heterogeneity is assumed to pick up by the intercept. To overcome this limitation, three panel time-series estimators were used, allowing for heterogeneous slope coefficients across countries; these were the M. H. Pesaran and Smith (1995) mean group (MG) estimator, the M. H. Pesaran (2006) common correlated effects mean group (CCEMG) estimator, and the Eberhardt, Teal, et al. (2010) augmented mean group estimator (AMG) estimator.

[11]Typically a time series with greater than 20 periods is considered to be substantial (Eberhardt et al., 2011).

All the three mean group (MG) type estimators follow the same principle methodology:

1. Estimate N country-specific OLS regressions.
2. Average the estimated coefficients across countries.

The MG estimator follows the above standard method, whereas for the CCEMG and AMG estimators, each empirical equation is augmented using additional covariates.

Apart from the regressors (x_{it}) and an intercept, the equation of CCEMG includes the cross-section averages of the dependent and independent variables, $\overline{y_t}$ and $\overline{x_t}$, as additional regressors. The combination of $\overline{y_t}$ and $\overline{x_t}$ can account for the unobserved common factors. In practical terms, cross-section averages $\overline{y_t}$ and $\overline{x_t}$ for all observable variables in the model are computed (using the data for the entire panel) and then added as explanatory variables in each of the N regression equations. Subsequently, the estimated coefficients $\hat{\beta}_i$ are averaged across panel members, where different weights may be applied. The CCEMG estimator has the benefit of taking into account cross-section dependence, time-variant unobservables with heterogeneous impact across panel members, and problems of identification (Eberhardt et al., 2011).

The AMG estimator is similar to CCEMG but based on first difference models. It first applies a pooled regression model augmented with year dummies by first difference OLS. The coefficients on the (differenced) year dummies are collected. This represents the evolution of unobservable common dynamic process. Then a country-specific regression model is augmented with this estimated common dynamic process, and the country-specific model parameters are averaged across the panel.

Tables A.14 and A.15 show the estimation results when using these three estimators for individual return and volatility spillover indexes, with the same international trade variables, fundamental variables, country risk variables and global risk variables as Section **??**[12]. Trends and intercepts are also included. However, almost all of the variables lose significance with these panel time-series estimators. One possible reason is that some of the time variation of the explanatory variables are artificially created rather than real data. As discussed in Section 5.3, due to the low frequency of some explanatory variables, some technique are applied to convert annual series to quarterly series. If higher frequency data is available, these panel time-series estimators may perform better. Time-invariant estimators, including FE applied in this chapter, may not be the best estimator to study the determinants of spillovers. Future studies could explore more in this direction.

5.7 Further research

One deficit of this analysis is that the same determinants were applied for return spillovers and volatility spillovers. Events, which are more relevant for volatility spillovers, were not included as explanatory variables. Moreover, this study does not study the impact of quality on the spillovers, because the study at country level is not able to distinguish qualities. For example, if a country has two crudes, one light crude and the other heavy, it is not reasonable to aggregate their spillover indexes into a country level labelled as "medium". Further research could study the impact of events and quality on volatility spillovers.

Second, this analysis is based on data from public sources and limited by frequency. Some research institutions may have access to more detailed and higher frequent data about crude oil markets, such as monthly trade flows between countries and the energy

[12]The estimation of the CCEMG estimator does not include global risk variables because CCEMG constructs common factors with the combination of average dependent and independent variables. If common factors such as global risk variables are imposed, the CCEMG model cannot be developed.

consumption structure of each country. Detailed data of higher frequency could help to improve the explanatory power of the model, and therefore provide a better understanding of the functioning of the global crude oil market. For example, with detailed trade flow data from one country to another, one can study the impact of diversification of imports or exports on spillovers. Having various sources of import and/or export is supposed to mitigate shocks from other countries, just like a diversified portfolio can help to resist risks.

Third, mixed frequency is always a problem when modelling fast-changing variables using slow-changing macroeconomic variables. In this analysis I have had to convert low frequency data to high frequency. Econometric researchers have developed advanced methods for models with mixed frequency data. Ghysels, Santa-Clara, and Valkanov (2004) first introduced a mixed frequency data sampling (MIDAS) regression method, and this method has been developed to apply in VAR and factor models. However, it has not been developed to apply to panel data yet. An advanced econometric method would be expected to exploit more information in the data.

Finally, if high frequency data or a more advanced methodology become available, researchers could apply dynamic determinants models. For example, Syllignakis and Kouretas (2011) apply a rolling regression to estimate time-varying coefficients. It is not feasible in this study due to data limitations, but it would be interesting to investigate the dynamic impact of explanatory variables on spillovers. I leave this to future studies.

Chapter 6

Conclusion

Inspired by the debate over the effectiveness of benchmark crudes and the debate over the integration of the crude oil market, this thesis aims to contribute to the literature by providing a comprehensive analysis using a significant time span and large data set from various perspectives.

The first empirical chapter (Chapter 3) finds significant structural breaks in all of the tests of Wlazlowski et al. (2011), including the unit root test, the cointegration test and the Granger causality test. This chapter further examines the reason for and the impact of structural breaks on the price series', cointegration relationships and causality relationships. With respect to the unit root test, breaks detected by the abrupt change model relate to the breaking out events such as geo-political issues, but the breaks detected by the gradually shift model are more closely related to market fundamentals. The time-series properties of crudes do not change with the presence of structural breaks: the crude price series are always I(1).

From the cointegration test it was found that a long-run relationship among crudes exists despite the existence of the structural break. The detected structural break dates generally coincide with remarkable events. WTI's dislocation problem in 2011 was also found to lead to a break in its long-run relationship with crudes of same quality or the same region. This event shifts the level, trend and regime of the long-run relationship. In contrast, the Asian financial crisis only induces a shift in the level in the long-run relationship among crudes in Asia. The Libyan crisis in 2011 is also reflected in the test, although it does not show a great influence.

From the Granger causality test dynamic supremum Wald statistics show that the 2008 global financial crisis destroyed the stability of the coefficients in the equation of the Granger causality test, making the finding of Wlazlowski et al. (2011) that Russian Urals could serve as a potential benchmark invalid when considered over a longer time period.

The analysis in Chapter 3 illustrates the importance of structural breaks. Although structural breaks do not change the presence of cointegration, they change the form of the long-run relationship by shifting the level, trend or regime. The impact of structural breaks on Granger causality is more profound. In the case of Russian Urals, its price setting role diminishes when the sample period is extended to include the global financial crisis, which is demonstrated to be a structural break in the Supremum Wald test. Therefore, in the practice of time series modeling, it is critical to consider structural breaks and their influence on the conclusion.

The second empirical chapter (Chapter 4) investigates the relationship among crudes from the view of return and volatility spillover effects. An improved version of the methodology of Diebold and Yilmaz (2009b) is applied. The static analysis shows that the crude market has the largest spillover indexes in the literature (87.1% for return and 80.57% for volatility) even when compared to the global stock market (40% according to

Diebold and Yilmaz (2009b) for developed stock markets, and 68.1% according to Prasad et al. (2014) when emerging stock markets are taken into account). This indicates a high degree of integration, therefore supporting the integration hypothesis in the crude oil market. For returns, benchmark crudes play a key role, possibly due to the pricing formula mechanism in the spot crude oil markets; for volatility, WTI behaves as a dominant transmitter, and this can be attributed to the 2008 global financial crisis, which originated in the United States.

The dynamic analysis shows that return and volatility spillover indexes have different dynamic patterns. Return spillovers display gradually evolving trends but no bursts, whereas volatility spillovers display clear bursts that correspond closely to events like the 9/11 terrorist attack in 2001, the invasion of Iraq in 2003, China's increasing import and the 2008 financial crisis. It is noticed that the volatility spillover index was low and stable from early 2007 until the crude oil price reached peak in summer 2008, it then jumped and has remained high and stable stage since summer 2008. This implies that the 2008 financial crisis may have profoundly changed the spot crude oil market, making it more vulnerable to system risk.

Further dynamic analysis reveals spillover patterns at three different levels: individual directional spillover, pairwise directional spillover and trans-group directional spillover. First, the individual directional spillover study shows that WTI and Brent are dominant return spillover transmitters over the whole sample period; consistent with their benchmark roles in the crude oil market. Russian Urals used to have a large net return spillover effect to other crudes, but this effect disappeared in 2005. Although benchmark crudes like Brent and WTI also behave as transmitters in terms of volatility, the pattern is different with return spillover. Brent and Russian Urals only had volatility transmission effects before the middle of 2005, while WTI became a dominant volatility transmitter in 2007, and this effect was most remarkable when crude oil prices collapsed in 2008. The reason is possibly that the origin of the 2008 crisis was the United States, the location of production of WTI. Pairwise directional spillover provides similar but more detailed results than the individual directional spillovers.

At the group level, the non-OPEC group is a return transmitter to the OPEC group, but the OPEC group's influence on the non-OPEC group is increasing over time. However, there is no constant pattern for the volatility spillover between OPEC and non-OPEC groups.

With respect to the quality groups, the light sweet group is a return transmitter to all the other groups, and has the largest impact on the medium sour group. Although the low quality, medium sour crudes occupy a large share in the market, they fail to have large and stable influence over other crudes. The light sour and heavy sour are generally receivers. In terms of volatility, there is no constant receiver or transmitter, but the light sweet group has been a net volatility transmitter to other groups since 2007.

With respect to geographic regions, the Europe group is the net return transmitter to all the other groups, followed by the American group. The Asia and Africa region and the Sub-Saharan Africa regions are generally receivers, but had some transmission effects to the Middle East and North African groups during and after the 2008 financial crisis. In terms of volatility, the role of each group is time varying. Recently the America region became a net transmitter to other regions, possibly due to the dominant transmission of WTI.

The analysis in Chapter 4 supports the benchmark role of WTI and Brent in terms of transmitting return and volatility shocks, but their transmitting patterns reveals that Brent is more influential with respect to return, while WTI is more influential with respect to volatility, especially since 2007. In practice, market participants could treat them differently according to their objectives and strategies, as these two benchmarks may reveal different information.

The third empirical chapter (Chapter 5) explores the driving forces of return and volatility spillovers. Five categories of variables are selected to explain the spillover effect; international trade variables, fundamental variables, country risk variables, global risk factors and time trends. Regression over the whole sample shows that international trade variables such as export and import, are important determinants for both return and volatility spillovers. Fundamental variables such as production, consumption and reserve are more relevant for return spillover, while country risk and global risk variables are generally more relevant for volatility spillovers. Time trends which are applied to capture the globalization effect, reveal increases in volatility spillovers but not in return spillovers. These variables explain return spillover better than volatility spillover.

Regression over sub-samples divided by institution arrangement (OPEC or non-OPEC) show that these selected variables have better explanatory power for non-OPEC countries than OPEC countries. Non-OPEC countries are more sensitive to these variables and generally have the expected signs, possibly due to the fact that they are more globalized. More integrated economies make them respond quickly to market movement. In contrast, OPEC countries are less sensitive to these variables. As a member of a supplier-based organization, OPEC countries have to follow the decision of the group rather than respond to market signals individually.

Regression over sub-samples divided by regions does not provide much evidence to support the argument that determinants' impact on spillover would be enhanced if countries in a pair are close to each other. This may due to the fact that the oil trade does not happen intensively with neighbors, but with counter-parties located far at a geographical distance.

The analysis in Chapter 5 implies that policy makers need to distinguish the institution arrangement (OPEC or non-OPEC) of a specific country, if they want to take measures to mitigate the shocks from it, because OPEC countries and non-OPEC countries do not have the same sensitivity with respect to market variables. Researchers should be cautious to apply this conclusion to markets other than the crude oil market. For example, the geographical mismatch in the crude oil market makes the distance variable have different effect to that of the stock market.

Appendix A

Tables

Table A.1: Details of crudes analysed

Symbol	label	Region	Quality	Abbreviation	country
Non-OPEC					
x_1	WTI Cushing	American	light&sweet	WTI	US
x_2	Europe Brent	Europe	light&sweet	BRT	GB
x_3	Europe Norwegian Ekofisk	Europe	light&sweet	EFK	NO
x_4	Canadian Par	American	light&sweet	CPR	CA
x_5	Canada Lloyd Blend	American	heavy&sour	LYD	CA
x_6	Mexico Isthmus	American	medium&sour	IMS	MX
x_7	Mexico Maya	American	heavy&sour	MYA	MX
x_8	Colombia Cano Limon	American	medium&sweet	CLM	CO
x_9	Ecuador Oriente	American	medium&sour	ORT	EC
x_{10}	Angola Cabinda	Sub Sahara	medium&sweet	CBD	AO
x_{11}	Cameroon Kole	Sub Sahara	medium&sweet	KLE	CM
x_{12}	Egypt Suez Blend	North Africa	medium&sour	SUZ	EG
x_{13}	Oman Blend	Middle East	medium&sour	OMN	OM
x_{14}	Australia Gippsland	Asia&Austrilia	light&sweet	GPL	AU
x_{15}	Malaysia Tapis	Asia&Austrilia	light&sweet	TPS	MY
x_{16}	Mediterranean Russian Urals	Europe	medium&sour	URL	RU
x_{17}	China Daqing	Asia&Austrilia	medium&sweet	CDQ	CN
OPEC					
x_{18}	Saudi Arabia Saudi Light	Middle East	medium&sour	SSL	SA
x_{19}	Saudi Arabia Arab Medium	Middle East	medium&sour	SAM	SA
x_{20}	Saudi Arabia Saudi Heavy	Middle East	medium&sour	SSH	SA
x_{21}	Asia Murban	Middle East	light&sour	MBN	AE
x_{22}	Asia Dubai Fateh	Middle East	medium&sour	DBF	AE
x_{23}	Qatar Dukhan	Middle East	light&sour	DKN	QA
x_{24}	Mediterranean Seri K Iran Light	Middle East	medium&sour	IRL	IR
x_{25}	Mediterranean Seri K Iran Heavy	Middle East	medium&sour	IRH	IR
x_{26}	Kuwait Blend	Middle East	medium&sour	KWT	KW
x_{27}	Algeria Saharan Blend	North Africa	light&sweet	SHR	DZ
x_{28}	Europe Nigerian Bonny Light	Sub Sahara	light&sweet	BNL	NG
x_{29}	Europe Forcados	Sub Sahara	medium&sweet	FCD	NG
x_{30}	Europe Libyan Es Sider	North Africa	light&sweet	ESD	LY
x_{31}	Indonesia Minas	Asia&Austrilia	medium&sweet	MNS	ID
x_{32}	Venezuela Tia Juana	American	medium&sour	TJN	VE

TABLE A.2: Standard ADF test results

	price series										1st difference		
symbol	case1: constant		case 2: drift		case 3: trend		case 4: lags(4)		case5: lags(4) trend		variable	stat.	p
	stat.	p	stat.	p	stat.	p	stat.	p	stat.	p			
x_1	-0.71	0.84	-0.71	0.24	-2.56	0.3	-1.14	0.7	-3.22	0.08	D.x1	-23.2	0
x_2	-0.11	0.95	-0.11	0.46	-2.26	0.46	-0.6	0.87	-2.87	0.17	D.x2	-22.08	0
x_3	-0.08	0.95	-0.08	0.47	-2.22	0.48	-0.63	0.86	-2.9	0.16	D.x3	-21.63	0
x_4	-0.83	0.81	-0.83	0.2	-2.59	0.29	-1.34	0.61	-3.28	0.07	D.x4	-24.34	0
x_5	-1.05	0.73	-1.05	0.15	-3.04	0.12	-1.38	0.59	-3.54	0.03	D.x5	-25.46	0
x_6	-0.08	0.95	-0.08	0.47	-2.29	0.44	-0.71	0.84	-3.08	0.11	D.x6	-22.37	0
x_7	0.19	0.97	0.19	0.57	-2.1	0.55	-0.64	0.86	-3.11	0.1	D.x7	-21.84	0
x_8	-0.14	0.95	-0.14	0.44	-2.34	0.41	-0.7	0.85	-3.04	0.12	D.x8	-22.51	0
x_9	-0.13	0.95	-0.13	0.45	-2.29	0.44	-0.79	0.82	-3.1	0.11	D.x9	-22.48	0
x_{10}	-0.01	0.96	-0.01	0.5	-2.21	0.48	-0.58	0.87	-2.92	0.16	D.x10	-21.57	0
x_{11}	-0.18	0.94	-0.18	0.43	-2.35	0.41	-0.69	0.85	-3.01	0.13	D.x11	-21.96	0
x_{12}	-0.02	0.96	-0.02	0.49	-2.22	0.48	-0.53	0.89	-2.82	0.19	D.x12	-22.56	0
x_{13}	0.09	0.97	0.09	0.54	-2.09	0.55	-0.64	0.86	-2.97	0.14	D.x13	-21.42	0
x_{14}	-0.08	0.95	-0.08	0.47	-2.16	0.51	-0.73	0.84	-2.94	0.15	D.x14	-21.17	0
x_{15}	0.01	0.96	0.01	0.5	-2.08	0.56	-0.7	0.85	-2.97	0.14	D.x15	-21.45	0
x_{16}	-0.12	0.95	-0.12	0.45	-2.31	0.43	-0.54	0.88	-2.86	0.18	D.x16	-23.43	0
x_{17}	0.08	0.96	0.08	0.53	-2.09	0.55	-0.64	0.86	-2.96	0.15	D.x17	-20.45	0
x_{18}	0.04	0.96	0.04	0.52	-2.08	0.55	-0.59	0.87	-2.82	0.19	D.x18	-21.45	0
x_{19}	0.03	0.96	0.03	0.51	-2.1	0.55	-0.6	0.87	-2.83	0.19	D.x19	-21.56	0
x_{20}	-0.01	0.96	-0.01	0.5	-2.14	0.52	-0.63	0.87	-2.87	0.17	D.x20	-21.64	0
x_{21}	0.07	0.96	0.07	0.53	-2.07	0.57	-0.71	0.84	-3	0.13	D.x21	-21.21	0
x_{22}	0.08	0.96	0.08	0.53	-2.09	0.55	-0.64	0.86	-2.96	0.14	D.x22	-21.39	0
x_{23}	0.06	0.96	0.06	0.52	-2.05	0.57	-0.76	0.83	-3.05	0.12	D.x23	-21.12	0
x_{24}	0.02	0.96	0.02	0.51	-2.16	0.51	-0.54	0.88	-2.82	0.19	D.x24	-21.55	0
x_{25}	0	0.96	0	0.5	-2.19	0.5	-0.53	0.89	-2.82	0.19	D.x25	-21.66	0
x_{26}	0.16	0.97	0.16	0.56	-2.06	0.57	-0.59	0.87	-2.96	0.14	D.x26	-21.16	0
x_{27}	-0.07	0.95	-0.07	0.47	-2.2	0.49	-0.65	0.86	-2.92	0.16	D.x27	-21.6	0
x_{28}	-0.1	0.95	-0.1	0.46	-2.23	0.47	-0.7	0.85	-2.98	0.14	D.x28	-21.75	0
x_{29}	-0.03	0.96	-0.03	0.49	-2.18	0.5	-0.66	0.86	-2.95	0.15	D.x29	-21.34	0
x_{30}	-0.01	0.96	-0.01	0.49	-2.2	0.49	-0.55	0.88	-2.85	0.18	D.x30	-22.54	0
x_{31}	-0.14	0.95	-0.14	0.45	-2.43	0.37	-0.72	0.84	-3.22	0.08	D.x31	-21.6	0
x_{32}	-0.06	0.95	-0.06	0.48	-2.35	0.41	-0.74	0.84	-3.06	0.12	D.x32	-22.65	0

Note: This table provides standard ADF test result for price series and its 1st difference, including statistics and the corresponding p values.

TABLE A.3: Results of Clemente-Montanes-Reyes unit root tests for 1^{st} difference series: AO model

Symbol	label	t-statistic	Breakdate1	t-statistic of break1	Breakdate2	t-statistic of break2
x_1	WTI Cushing	-7.61^{**}	11/7/2008	-9.04^{***}	12/12/2008	8.9^{***}
x_2	Europe Brent	-7.1^{**}	11/7/2008	-9.54^{***}	12/12/2008	9.67^{***}
x_3	Europe Norwegian Ekofisk	-7.12^{**}	4/7/2008	-9.69^{***}	28/11/2008	9.69^{***}
x_4	Canadian Par	-7.36^{**}	4/7/2008	-9.05^{***}	12/12/2008	8.97^{***}
x_5	Canada Lloyd Blend	-8.4^{**}	4/7/2008	-7.09^{***}	12/12/2008	7.07^{***}
x_6	Mexico Isthmus	-6.66^{**}	4/7/2008	-9.56^{***}	12/12/2008	9.69^{***}
x_7	Mexico Maya	-6.34^{**}	4/7/2008	-9.82^{***}	28/11/2008	10.01^{***}
x_8	Colombia Cano Limon	-6.17^{**}	4/7/2008	-9.39^{***}	12/12/2008	9.4^{***}
x_9	Ecuador Oriente	-6.85^{**}	4/7/2008	$-9.1*^{***}$	12/12/2008	9.32^{***}
x_{10}	Angola Cabinda	-7.2^{**}	4/7/2008	-9.48^{***}	28/11/2008	9.55^{***}
x_{11}	Cameroon Kole	-6.75^{**}	27/06/2008	$-8.4*^{***}$	12/12/2008	8.59^{***}
x_{12}	Egypt Suez Blend	-7.19^{**}	4/7/2008	$-9.2*^{***}$	28/11/2008	9.27^{***}
x_{13}	Oman Blend	-7.01^{**}	25/07/2008	-10.5^{***}	28/11/2008	10.68^{***}
x_{14}	Australia Gippsland	-7.02^{**}	4/7/2008	-10.2^{***}	5/12/2008	10.31^{***}
x_{15}	Malaysia Tapis	-7.16^{**}	4/7/2008	-10.2^{***}	28/11/2008	10.29^{***}
x_{16}	Mediterranean Russian Urals	-7.65^{**}	4/7/2008	$-9.2*^{***}$	12/12/2008	9.32^{***}
x_{17}	China Daqing	-6.9^{**}	4/7/2008	-10.0^{***}	21/11/2008	10.14^{***}
x_{18}	Saudi Arabia Saudi Light	-7.48^{**}	4/7/2008	-9.79^{***}	28/11/2008	9.84^{***}
x_{19}	Saudi Arabia Arab Medium	-7.74^{**}	4/7/2008	-9.58^{***}	28/11/2008	9.66^{***}
x_{20}	Saudi Arabia Saudi Heavy	-7.95^{**}	4/7/2008	-9.39^{***}	28/11/2008	9.48^{***}
x_{21}	Asia Murban	-6.03^{**}	4/7/2008	-11.1^{***}	28/11/2008	11.21^{***}
x_{22}	Asia Dubai Fateh	-6.08^{**}	4/7/2008	-10.7^{***}	28/11/2008	10.83^{***}
x_{23}	Qatar Dukhan	-5.9^{**}	4/7/2008	-11.3^{***}	28/11/2008	11.36^{***}
x_{24}	Mediterranean Seri K Iran Light	-7.28^{**}	4/7/2008	-9.98^{***}	12/12/2008	10.1^{***}
x_{25}	Mediterranean Seri K Iran Heavy	-7.39^{**}	4/7/2008	-9.81^{***}	12/12/2008	9.95^{***}
x_{26}	Kuwait Blend	-6.31^{**}	4/7/2008	-10.6^{***}	28/11/2008	10.73^{***}
x_{27}	Algeria Saharan Blend	-7.38^{**}	4/7/2008	-9.71^{***}	28/11/2008	9.72^{***}
x_{28}	Europe Nigerian Bonny Light	-7.24^{**}	4/7/2008	-9.74^{***}	28/11/2008	9.71^{***}
x_{29}	Europe Forcados	-7.26^{**}	4/7/2008	-9.81^{***}	28/11/2008	9.79^{***}
x_{30}	Europe Libyan Es Sider	-6.59^{**}	4/7/2008	-9.73^{***}	12/12/2008	9.86^{***}
x_{31}	Indonesia Minas	-6.7^{**}	4/7/2008	-8.07^{***}	30/01/2009	8.25^{***}
x_{32}	Venezuela Tia Juana	-6.63^{**}	4/7/2008	-9.52^{***}	12/12/2008	9.66^{***}

Note: This table presents the results of Clemente-Montanes-Reyes unit root tests for 1st difference of price series with AO model. The date in the table is in format "dd/mm/yyyy". *** significant at 1%; ** significant at 5%. No deterministic terms included.

Table A.4: Results of Clemente-Montanes-Reyes unit root tests for 1^{st} difference series: IO model

Symbol	label	t-statistic	Breakdate1	t-statistic of break1	Breakdate2	t-statistic of break2
x_1	WTI Cushing	-11.15**	27/06/2008	-8.34***	19/12/2008	8.37***
x_2	Europe Brent	-17.6**	27/06/2008	-8.46***	19/12/2008	8.62***
x_3	Europe Norwegian Ekofisk	-16.21**	11/7/2008	-9.23***	5/12/2008	9.33***
x_4	Canadian Par	-11.07**	11/7/2008	-8.58***	19/12/2008	8.59***
x_5	Canada Lloyd Blend	-10.98**	11/7/2008	-7.41***	19/12/2008	7.43***
x_6	Mexico Isthmus	-10.21**	11/7/2008	-8.2****	19/12/2008	8.38***
x_7	Mexico Maya	-9.49**	11/7/2008	-8.95***	14/11/2008	9.12***
x_8	Colombia Cano Limon	-9**	11/7/2008	-7.97***	5/12/2008	8.02***
x_9	Ecuador Oriente	-9.62**	11/7/2008	-8.06***	28/11/2008	8.23***
x_{10}	Angola Cabinda	-15.9**	11/7/2008	-8.87***	5/12/2008	9******
x_{11}	Cameroon Kole	-16.22**	11/7/2008	-9.1****	5/12/2008	9.19***
x_{12}	Egypt Suez Blend	-16.3**	11/7/2008	-9.23***	5/12/2008	9.37***
x_{13}	Oman Blend	-11.36**	11/7/2008	-9.16***	21/11/2008	9.23***
x_{14}	Australia Gippsland	-11.65**	11/7/2008	-9******	14/11/2008	9.08***
x_{15}	Malaysia Tapis	-11.43**	11/7/2008	-8.72***	5/12/2008	8.79***
x_{16}	Mediterranean Russian Urals	-20.71**	11/7/2008	-8.74***	26/12/2008	8.9****
x_{17}	China Daqing	-11.28**	11/7/2008	-8.36***	28/11/2008	8.46***
x_{18}	Saudi Arabia Saudi Light	-15.97**	11/7/2008	-8.99***	5/12/2008	9.12***
x_{19}	Saudi Arabia Arab Medium	-15.95**	11/7/2008	-8.88***	5/12/2008	9.02***
x_{20}	Saudi Arabia Saudi Heavy	-15.91**	11/7/2008	-8.74***	5/12/2008	8.89***
x_{21}	Asia Murban	-11.14**	11/7/2008	-9.14***	21/11/2008	9.2****
x_{22}	Asia Dubai Fateh	-11.55**	11/7/2008	-8.67***	5/12/2008	8.76***
x_{23}	Qatar Dukhan	-20.95**	11/7/2008	-10.3***	5/12/2008	10.4***
x_{24}	Mediterranean Seri K Iran Light	-20.49**	27/06/2008	-8.73***	26/12/2008	8.89***
x_{25}	Mediterranean Seri K Iran Heavy	-16.24**	11/7/2008	-9.03***	5/12/2008	9.16***
x_{26}	Kuwait Blend	-11.63**	11/7/2008	-8.67***	5/12/2008	8.8****
x_{27}	Algeria Saharan Blend	-15.86**	11/7/2008	-8.96***	5/12/2008	9.05***
x_{28}	Europe Nigerian Bonny Light	-15.59**	11/7/2008	-8.82***	5/12/2008	8.88***
x_{29}	Europe Forcados	-20.13**	11/7/2008	-8.75***	5/12/2008	8.83***
x_{30}	Europe Libyan Es Sider	-20.94**	11/7/2008	-9.08***	5/12/2008	9.21***
x_{31}	Indonesia Minas	-9.85**	27/06/2008	-7.02***	6/2/2009	6.75***
x_{32}	Venezuela Tia Juana	-10.19**	11/7/2008	-8.21***	19/12/2008	8.38***

Note: This table presents the results of Clemente-Montanes-Reyes unit root tests for 1st difference of price series with IO model. The date in the table is in format "dd/mm/yyyy".*** significant at 1%; ** significant at 5%.No deterministic terms included.

TABLE A.5: Descriptive Statistics of Wednesday Return and Volatility

Panel A: Wednesday return																
	WTI	BRT	EFK	CPR	LYD	IMS	MYA	CLM	ORT	CBD	KLE	SUZ	OMN	GPL	TPS	URL
Min	-0.6225	-0.3685	-0.3384	-0.5116	-0.5436	-0.5156	-0.4960	-0.3826	-0.4954	-0.4004	-0.3960	-0.4024	-0.3693	-0.3244	-0.3076	-0.3831
Median	0.0048	0.0060	0.0047	0.0018	0.0015	0.0033	0.0049	0.0022	0.0033	0.0040	0.0050	0.0049	0.0044	0.0031	0.0000	0.0026
Mean	0.0017	0.0020	0.0022	0.0018	0.0021	0.0023	0.0024	0.0023	0.0022	0.0023	0.0023	0.0023	0.0023	0.0023	0.0024	0.0022
Max	0.4776	0.3994	0.3543	0.5384	0.5162	0.4597	0.4438	0.3583	0.4962	0.4278	0.4277	0.4516	0.4326	0.3676	0.3923	0.4190
Std. Dev.	0.0533	0.0493	0.0506	0.0578	0.0845	0.0546	0.0576	0.0529	0.0626	0.0524	0.0546	0.0571	0.0451	0.0435	0.0469	0.0578
skewness	-1.3757	-0.1640	-0.0529	-0.1574	-0.5530	-0.5219	-0.3867	-0.2589	-0.2325	0.0387	0.0349	-0.0393	0.4516	0.2169	0.5798	-0.0051
Kurtosis	32.3360	10.0477	6.9092	18.4365	6.9469	17.0121	12.0312	7.2119	11.0695	10.7755	9.1833	8.8939	17.8724	12.0958	15.8597	6.9587
	CDQ	SSL	SAM	SSH	MBN	DBF	DKN	IRL	IRH	KWT	SHR	BNL	FCD	ESD	MNS	TJN
Min	-0.3821	-0.4618	-0.4889	-0.5138	-0.3659	-0.3722	-0.3621	-0.4166	-0.4358	-0.3987	-0.3480	-0.3190	-0.3012	-0.3759	-0.2580	-0.5145
Median	0.0034	0.0040	0.0044	0.0050	0.0050	0.0048	0.0046	0.0033	0.0037	0.0040	0.0041	0.0046	0.0048	0.0048	0.0025	0.0004
Mean	0.0022	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023	0.0023	0.0022	0.0022	0.0022	0.0023	0.0023	0.0023
Max	0.4693	0.4673	0.5024	0.5414	0.4092	0.4318	0.4221	0.4464	0.4724	0.4935	0.3832	0.3470	0.3247	0.4146	0.5324	0.4587
Std. Dev.	0.0478	0.0499	0.0525	0.0551	0.0445	0.0464	0.0441	0.0489	0.0508	0.0484	0.0498	0.0505	0.0488	0.0507	0.0469	0.0556
skewness	0.2381	-0.1390	-0.0540	0.0294	0.2964	0.3360	0.4915	0.1377	0.1257	0.6920	0.0730	-0.1321	-0.0034	0.0787	1.3479	-0.4158
Kurtosis	18.3010	19.5172	20.4929	21.7553	16.7382	16.1937	18.2849	16.1994	16.8639	20.9793	8.3276	6.8776	5.7052	10.2987	23.1381	17.4908
Panel B: Volatility																
	WTI	BRT	EFK	CPR	LYD	IMS	MYA	CLM	ORT	CBD	KLE	SUZ	OMN	GPL	TPS	URL
Minimum	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Maximum	0.1931	0.0857	0.0650	0.2007	0.1825	0.1347	0.1250	0.0748	0.1253	0.0917	0.0908	0.1005	0.0855	0.0750	0.0649	0.0899
Mean	0.0005	0.0004	0.0003	0.0005	0.0010	0.0004	0.0005	0.0004	0.0005	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003	0.0004
Median	0.0001	0.0001	0.0001	0.0001	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001
Stdev	0.0069	0.0033	0.0024	0.0072	0.0069	0.0049	0.0045	0.0027	0.0046	0.0033	0.0033	0.0036	0.0031	0.0027	0.0025	0.0033
Skewness	27.5680	23.9897	25.8645	27.4122	24.1717	27.2890	27.0430	26.1789	26.6199	26.7633	26.5447	26.6229	27.0034	26.8559	23.4611	26.1838
Kurtosis	762.2509	610.9874	697.8653	756.3914	631.3395	751.7578	742.5947	709.7619	726.6370	731.9241	723.7197	726.7662	740.7756	735.0775	599.5994	710.1495
	CDQ	SSL	SAM	SSH	MBN	DBF	DKN	IRL	IRH	KWT	SHR	BNL	FCD	ESD	MNS	TJN
Minimum	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Maximum	0.0892	0.1185	0.1327	0.1464	0.0841	0.0834	0.0831	0.1040	0.1162	0.0972	0.0725	0.0591	0.0526	0.0882	0.0309	0.1341
Mean	0.0003	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003	0.0003	0.0004	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0004
Median	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Stdev	0.0032	0.0043	0.0048	0.0053	0.0030	0.0030	0.0030	0.0038	0.0042	0.0035	0.0026	0.0022	0.0019	0.0032	0.0012	0.0049
Skewness	26.9131	27.3433	27.3506	27.3558	26.9383	26.8868	26.9538	27.1938	27.2698	26.9631	26.4669	25.1464	25.2892	26.8419	21.6741	26.9184
Kurtosis	737.4094	753.8109	754.0942	754.3015	738.2798	736.3921	738.8121	748.1040	751.0351	739.1801	720.7773	670.1731	676.0518	734.9382	536.0022	737.3668

Note: For each crude we have 775 observations. No missing values.

TABLE A.6: Maximal spillover table SOT_{max} for weekly return

	WTI	BRT	EFK	CPR	LYD	IMS	MYA	CLM	ORT	CBD	KLE	SUZ	OMN	GPL	TPS	URL	CDQ	SSL	SAM	SSH	MBN	DBF	DKN	IRL	IRH	KWT	SHR	BNL	FCD	ESD	MNS	TJN
WTI	82.88	62.58	53.93	48.12	37.84	71.45	59.81	65.72	61.92	56.17	52.40	54.55	50.61	45.98	20.31	43.76	44.97	54.28	53.80	52.91	47.72	48.27	50.19	55.56	55.20	49.49	54.83	51.57	52.94	54.92	36.74	61.03
BRT	63.98	84.98	71.60	41.35	33.52	66.72	59.22	57.06	52.66	71.45	69.27	69.42	55.19	48.89	18.62	60.23	43.29	60.30	59.67	58.57	53.92	54.19	54.55	62.96	62.66	55.02	71.45	69.10	71.48	70.68	34.72	56.58
EFK	51.91	70.20	74.38	36.68	30.61	60.43	52.13	51.94	46.80	71.13	68.72	69.04	52.25	46.60	16.34	57.81	40.70	56.74	55.62	54.28	52.32	52.54	51.94	59.34	59.10	52.06	71.29	69.87	72.73	69.67	31.82	50.50
CPR	46.78	43.17	40.37	73.11	38.76	46.40	39.93	41.36	37.46	41.64	38.39	40.30	38.86	32.84	15.10	37.16	32.12	38.85	38.43	37.71	36.95	37.42	38.98	39.49	39.41	38.00	40.51	39.15	39.70	40.82	26.52	38.15
LYD	40.65	36.42	33.11	40.28	78.72	38.65	39.48	34.06	32.53	32.95	31.26	32.44	28.73	25.19	9.73	35.16	23.14	29.45	29.90	29.53	27.06	27.82	28.01	30.42	30.73	28.47	32.45	32.63	31.83	32.28	18.70	30.27
IMS	67.24	64.46	62.29	44.00	35.58	75.28	63.29	66.34	62.02	63.60	60.34	61.62	53.81	50.96	20.80	49.23	47.06	58.18	57.89	56.86	51.73	52.23	53.36	59.45	59.21	53.07	62.60	60.69	61.81	62.24	37.26	62.82
MYA	60.04	60.58	55.76	39.09	37.63	66.17	80.08	59.52	56.07	58.26	56.12	55.83	51.29	48.54	15.90	46.35	44.09	53.52	53.82	53.19	48.45	48.63	50.33	55.55	55.49	49.58	56.31	55.60	55.88	56.22	33.47	55.51
CLM	63.54	57.43	55.46	40.11	32.74	66.98	58.05	75.18	61.87	56.05	52.70	54.79	50.06	45.59	18.40	44.57	42.60	52.61	52.05	50.88	47.68	48.19	49.42	54.14	53.47	48.02	55.51	54.32	55.60	54.84	35.47	56.63
ORT	62.08	54.96	52.48	37.95	31.28	66.11	57.32	66.16	77.41	54.01	50.58	52.02	48.39	46.01	18.13	39.95	43.13	51.86	51.91	51.35	46.92	47.64	48.13	53.42	53.24	47.73	53.23	52.24	52.58	52.61	34.61	56.53
CBD	53.11	69.17	70.83	37.63	30.43	61.78	54.48	52.88	48.48	72.98	68.55	67.47	54.19	48.20	17.80	55.00	43.28	57.82	57.10	55.95	53.96	54.40	53.81	61.06	60.94	54.15	70.21	68.88	71.70	68.89	33.63	52.26
KLE	49.72	67.19	68.95	34.62	28.82	59.03	52.56	49.97	45.61	68.87	72.53	64.61	50.09	45.86	17.12	52.89	40.20	54.66	54.30	53.39	49.73	49.96	49.63	57.20	57.03	50.11	67.66	66.20	68.10	65.80	31.45	50.27
SUZ	52.06	68.21	70.28	37.26	30.29	60.80	53.00	52.62	47.71	69.13	65.64	73.40	52.78	46.39	16.07	57.13	41.33	57.68	57.03	55.95	52.70	52.94	52.51	59.35	59.30	53.03	68.91	68.05	70.32	69.46	32.23	50.37
OMN	50.17	57.83	56.45	37.24	29.36	55.98	51.20	51.98	47.93	58.11	53.45	55.23	68.43	53.52	20.91	44.69	47.86	60.27	59.03	57.77	65.35	65.85	67.27	62.56	62.31	65.60	56.42	54.59	57.42	56.25	35.77	47.36
GPL	47.95	53.35	50.27	30.95	26.67	53.13	49.45	48.70	45.07	51.25	48.82	48.08	51.21	68.04	23.23	38.65	52.01	52.24	51.67	50.68	48.76	49.37	50.85	52.86	52.60	49.07	50.87	50.19	50.94	49.88	39.84	46.45
TPS	24.66	24.20	21.12	15.60	10.58	25.98	20.01	23.53	23.18	22.59	21.69	19.65	24.13	29.28	79.61	18.14	25.58	26.94	26.71	26.24	21.74	22.24	24.12	26.82	26.42	22.92	21.62	20.88	21.09	21.55	18.26	26.00
URL	46.98	61.27	58.27	36.11	34.00	50.97	46.02	42.37	38.01	56.61	54.91	57.19	43.49	35.94	16.48	85.74	31.55	45.26	44.86	43.95	42.80	43.40	42.48	47.96	48.34	43.58	57.41	54.95	57.12	56.69	23.89	43.24
CDQ	46.35	49.17	46.73	32.17	25.67	51.23	47.21	47.86	44.44	48.32	44.93	45.44	48.92	55.82	21.50	35.60	70.55	50.41	49.65	48.66	46.16	46.89	48.27	50.03	49.72	47.73	47.49	47.19	46.56	46.07	56.63	44.94
SSL	52.17	60.20	59.55	36.87	28.07	58.79	52.01	52.91	49.40	60.50	56.71	59.03	60.03	53.70	22.47	43.63	48.77	71.40	70.35	68.96	59.48	59.45	59.71	65.36	64.92	60.59	59.91	57.88	59.50	59.32	38.00	50.53
SAM	51.86	59.67	58.71	36.64	28.56	58.82	52.37	52.73	49.81	60.03	56.54	58.67	59.25	53.46	22.43	43.31	48.30	70.69	71.31	70.70	58.83	58.93	58.98	65.14	64.76	60.60	59.12	57.30	58.58	58.74	37.27	50.38
SSH	51.21	58.82	57.86	36.35	28.53	58.35	52.31	52.11	49.83	59.41	56.10	58.14	58.82	53.20	22.31	42.59	47.99	70.10	71.53	71.71	58.46	58.66	58.64	64.79	64.53	60.51	58.36	56.63	57.70	58.05	37.03	49.87
MBN	47.74	55.67	54.89	35.14	27.87	53.18	48.07	48.84	45.52	56.37	51.62	53.57	64.30	50.35	18.63	43.80	44.61	58.59	57.49	56.32	68.45	67.22	64.17	60.63	60.73	64.80	55.12	53.52	56.25	54.93	33.13	44.64
DBF	48.31	56.30	55.53	35.57	28.72	53.95	48.57	49.65	46.40	57.17	52.21	54.23	64.90	51.04	19.06	44.78	45.53	58.80	57.83	56.76	67.31	68.34	64.32	61.13	61.39	65.29	55.77	54.17	56.84	55.56	34.33	45.28
DKN	49.88	57.08	55.87	37.19	28.68	55.44	50.20	51.28	47.66	57.43	52.74	54.71	67.02	52.88	20.81	43.54	46.97	59.68	58.46	57.28	64.95	65.00	68.17	61.99	61.71	64.75	56.13	54.33	57.06	55.93	35.12	47.06
IRL	54.24	63.64	63.06	37.63	29.43	61.10	54.51	55.46	51.81	64.82	60.26	61.51	63.19	54.62	22.07	47.10	48.66	66.50	65.95	64.87	62.31	62.69	62.93	73.86	73.00	63.10	63.25	60.86	63.41	62.94	37.36	52.39
IRH	53.71	63.20	62.60	37.37	29.64	60.80	54.43	54.88	51.67	64.55	60.00	61.28	62.91	54.47	21.92	47.16	48.62	66.06	65.65	64.72	62.40	62.91	62.61	73.01	73.78	63.47	62.88	60.69	62.87	62.55	37.33	51.47
KWT	49.25	57.60	56.11	36.84	29.69	55.64	50.00	50.33	47.66	58.08	53.35	55.43	66.24	51.96	19.98	44.81	47.34	61.16	60.66	59.73	66.47	66.87	65.68	62.82	63.19	68.95	56.33	54.56	57.09	56.56	35.33	47.16
SHR	52.29	69.59	71.04	36.12	29.60	60.70	52.51	52.24	47.69	70.21	67.30	67.34	52.40	47.45	16.85	55.84	41.74	57.08	56.05	54.78	52.72	53.01	52.39	59.50	59.28	52.36	72.72	68.72	71.53	69.34	33.15	51.95
BNL	49.71	67.68	69.72	35.02	29.30	58.54	51.50	51.03	46.18	68.94	65.38	66.35	50.13	45.89	15.98	54.13	40.64	54.86	54.01	52.86	50.70	50.90	50.15	57.46	57.38	50.21	68.67	73.11	71.41	67.42	32.53	48.99
FCD	51.10	70.03	72.06	35.58	29.52	59.52	51.75	51.63	46.36	71.30	67.40	68.23	52.31	46.32	15.78	56.78	39.99	56.01	54.83	53.48	52.92	53.13	52.24	59.09	58.82	52.15	70.98	71.05	74.42	69.40	31.69	49.56
ESD	52.29	69.19	70.60	37.75	30.06	61.22	53.09	52.75	47.85	70.20	66.38	69.07	53.68	48.01	17.31	55.51	41.91	57.87	57.04	55.84	53.90	54.18	53.70	60.39	60.13	53.98	70.79	68.64	71.20	72.77	32.68	51.43
MNS	43.80	47.29	42.66	31.58	24.26	46.60	41.90	45.44	41.18	44.06	41.10	41.66	41.70	48.31	17.04	33.72	63.46	45.48	44.52	43.71	39.35	40.34	41.37	44.71	44.40	40.89	44.06	43.89	42.84	42.11	77.27	40.95
TJN	59.54	56.79	53.95	37.93	29.04	65.46	55.24	58.61	54.94	55.70	53.25	52.95	47.26	47.06	21.60	42.63	43.04	51.80	51.34	50.30	44.94	45.45	47.09	52.92	52.11	46.69	55.64	52.78	53.58	53.97	34.02	76.24

Note: This table provides the variance decomposition matrix with maximal entries in the spillover tables.

Table A.7: Minimal spillover table SOT_{min} for weekly return

	WTI	BRT	EFK	CPR	LYD	IMS	MYA	CLM	ORT	CBD	KLE	SUZ	OMN	GPL	TPS	URL	CDQ	SSL	SAM	SSH	MBN	DBF	DKN	IRL	IRH	KWT	SHR	BNL	FCD	ESD	MNS	TJN
WTI	7.43	0.05	0.01	0.00	0.02	0.00	0.00	0.08	0.04	0.00	0.04	0.00	0.03	0.00	0.02	0.66	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.03	0.00	0.14	0.01
BRT	0.02	7.58	0.02	0.01	0.00	0.00	0.02	0.01	0.00	0.01	0.07	0.01	0.17	0.00	0.12	1.32	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.12	0.05	0.00
EFK	0.01	3.76	1.25	0.00	0.00	0.00	0.01	0.02	0.00	0.04	0.13	0.08	0.10	0.00	0.19	1.87	0.00	0.00	0.01	0.01	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.05	0.14	0.01	0.00
CPR	0.19	0.58	0.01	25.59	0.07	0.00	0.02	0.01	0.00	0.01	0.03	0.00	0.02	0.00	0.15	0.71	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.02	0.02	0.01	0.01	0.01	0.00	0.26	0.00
LYD	0.14	0.65	0.01	0.05	31.83	0.00	0.05	0.01	0.05	0.00	0.02	0.01	0.00	0.01	0.10	0.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.02	0.00	0.00	0.02	0.00
IMS	0.28	0.90	0.01	0.00	0.02	2.50	0.08	0.05	0.02	0.00	0.05	0.01	0.01	0.01	0.11	1.01	0.00	0.00	0.00	0.01	0.04	0.00	0.02	0.00	0.00	0.05	0.00	0.00	0.02	0.00	0.02	0.00
MYA	0.03	0.77	0.00	0.00	0.00	0.00	11.12	0.02	0.02	0.00	0.01	0.01	0.02	0.00	0.21	0.56	0.00	0.00	0.00	0.00	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.03	0.00
CLM	0.26	0.36	0.00	0.00	0.03	0.00	0.12	6.58	0.02	0.00	0.04	0.01	0.00	0.01	0.08	1.44	0.00	0.00	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.02	0.00	0.05	0.00
ORT	0.32	0.32	0.01	0.00	0.00	0.00	0.05	0.06	10.41	0.00	0.00	0.00	0.01	0.00	0.08	0.84	0.00	0.00	0.00	0.00	0.02	0.01	0.00	0.00	0.00	0.02	0.01	0.01	0.03	0.00	0.06	0.00
CBD	0.02	3.57	0.02	0.00	0.00	0.00	0.04	0.01	0.00	1.15	0.19	0.02	0.02	0.00	0.23	1.30	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.09	0.16	0.00	0.00
KLE	0.04	4.05	0.02	0.00	0.00	0.00	0.01	0.01	0.00	0.11	3.92	0.03	0.12	0.00	0.25	1.11	0.00	0.00	0.00	0.00	0.02	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.06	0.01	0.00	0.00
SUZ	0.02	3.13	0.00	0.00	0.00	0.00	0.04	0.01	0.00	0.01	0.07	2.75	0.08	0.00	0.20	2.35	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.01	0.00
OMN	0.14	2.61	0.02	0.00	0.01	0.00	0.03	0.01	0.04	0.01	0.04	0.02	0.95	0.01	0.22	0.62	0.00	0.00	0.00	0.00	0.04	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.03	0.00
GPL	0.10	2.56	0.01	0.00	0.02	0.00	0.06	0.05	0.02	0.00	0.04	0.01	0.02	9.01	0.17	0.21	0.01	0.00	0.01	0.01	0.00	0.00	0.04	0.00	0.01	0.06	0.00	0.00	0.03	0.00	0.00	0.00
TPS	0.07	0.64	0.03	0.05	0.00	0.00	0.00	0.00	0.15	0.00	0.01	0.04	0.01	0.01	45.09	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.00	0.00
URL	0.03	2.21	0.01	0.02	0.00	0.00	0.00	0.00	0.03	0.00	0.02	0.01	0.06	0.00	0.13	22.33	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.02	0.00	0.00	0.02	0.00	0.00	0.01	0.00
CDQ	0.11	1.99	0.02	0.00	0.03	0.00	0.07	0.12	0.01	0.00	0.03	0.01	0.01	0.01	0.22	0.28	6.47	0.00	0.00	0.01	0.01	0.00	0.03	0.02	0.02	0.03	0.00	0.00	0.02	0.00	0.01	0.00
SSL	0.11	2.95	0.03	0.00	0.01	0.00	0.01	0.01	0.02	0.01	0.03	0.01	0.01	0.00	0.19	0.33	0.00	0.38	0.01	0.06	0.04	0.00	0.02	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.09	0.00
SAM	0.14	2.77	0.03	0.00	0.02	0.00	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.00	0.17	0.33	0.00	0.00	0.11	0.21	0.01	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.10	0.00
SSH	0.15	2.61	0.03	0.00	0.02	0.00	0.01	0.01	0.02	0.01	0.02	0.01	0.00	0.00	0.16	0.31	0.00	0.00	0.03	0.41	0.01	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.10	0.00
MBN	0.14	2.68	0.02	0.00	0.01	0.00	0.02	0.00	0.02	0.00	0.02	0.02	0.02	0.00	0.22	0.75	0.00	0.00	0.01	0.01	1.07	0.00	0.02	0.00	0.00	0.09	0.00	0.00	0.01	0.01	0.03	0.00
DBF	0.14	2.72	0.02	0.00	0.01	0.00	0.02	0.00	0.02	0.01	0.01	0.02	0.03	0.00	0.22	0.84	0.00	0.00	0.01	0.00	0.03	0.85	0.02	0.00	0.01	0.08	0.01	0.00	0.01	0.00	0.03	0.00
DKN	0.15	2.69	0.02	0.00	0.01	0.00	0.03	0.01	0.05	0.00	0.04	0.02	0.01	0.00	0.20	0.56	0.00	0.00	0.01	0.01	0.07	0.00	1.04	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.02	0.00
IRL	0.10	3.00	0.05	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.07	0.01	0.04	0.00	0.18	0.37	0.00	0.00	0.01	0.05	0.00	0.00	0.02	0.68	0.00	0.01	0.01	0.00	0.01	0.01	0.05	0.00
IRH	0.11	3.30	0.05	0.00	0.01	0.00	0.01	0.02	0.00	0.00	0.06	0.01	0.03	0.00	0.16	0.40	0.00	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.71	0.00	0.00	0.00	0.00	0.01	0.05	0.00
KWT	0.16	2.83	0.02	0.00	0.02	0.00	0.02	0.00	0.04	0.00	0.01	0.02	0.00	0.00	0.22	0.66	0.00	0.00	0.01	0.01	0.06	0.00	0.01	0.00	0.01	1.79	0.00	0.00	0.01	0.01	0.03	0.00
SHR	0.02	3.97	0.01	0.00	0.00	0.00	0.01	0.03	0.00	0.03	0.06	0.02	0.04	0.00	0.21	1.45	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	1.45	0.00	0.38	0.20	0.00	0.00
BNL	0.02	3.49	0.01	0.00	0.00	0.00	0.01	0.03	0.01	0.01	0.07	0.02	0.03	0.01	0.21	1.49	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.00	0.00	0.00	2.98	0.10	0.02	0.01	0.00
FCD	0.02	3.73	0.01	0.00	0.00	0.00	0.01	0.02	0.00	0.02	0.09	0.05	0.05	0.00	0.21	1.68	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.03	0.00	1.22	0.22	0.00	0.00
ESD	0.02	4.04	0.01	0.00	0.00	0.00	0.02	0.02	0.01	0.01	0.08	0.01	0.02	0.00	0.18	1.43	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.35	2.02	0.02	0.00
MNS	0.06	2.38	0.01	0.00	0.01	0.00	0.05	0.04	0.00	0.00	0.01	0.01	0.03	0.00	0.15	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.01	0.01	0.00	0.01	0.00	0.00	12.66	0.00
TJN	0.24	0.99	0.01	0.00	0.00	0.00	0.01	0.05	0.02	0.00	0.04	0.01	0.01	0.01	0.09	0.50	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.02	0.00	0.02	11.46

Note: This table provides the variance decomposition matrix with minimal entries in the spillover tables. The number of each crude corresponds to number in Table A.1. For example, WTI represents Wednesday return of WTI; BRT represents Wednesday return of Brent,etc.

TABLE A.8: Maximal spillover table SOT_{max} for volatility

	WTI	BRT	EFK	CPR	LYD	IMS	MYA	CLM	ORT	CBD	KLE	SUZ	OMN	GPL	TPS	URL	CDQ	SSL	SAM	SSH	MBN	DBF	DKN	IRL	IRH	KWT	SHR	BNL	FCD	ESD	MNS	TJN
WTI	84.55	30.88	34.30	33.45	13.09	52.67	32.14	39.95	28.03	33.98	28.43	33.51	20.03	19.41	3.79	23.80	12.12	25.31	24.49	22.78	17.77	18.16	18.99	28.13	26.39	16.13	32.40	22.87	33.64	33.64	10.43	35.88
BRT	36.60	74.76	40.36	23.97	13.10	40.27	34.89	30.14	24.24	42.47	39.58	40.51	36.00	29.38	4.18	56.28	16.98	34.77	36.58	35.85	34.11	34.61	35.78	41.81	40.15	33.67	41.89	29.22	41.87	42.55	17.23	27.41
EFK	41.13	47.26	75.14	28.53	7.81	56.42	40.79	47.25	31.08	71.84	62.11	66.99	44.37	36.71	4.36	40.92	23.24	46.22	46.89	44.83	42.64	43.34	43.86	51.36	48.72	39.69	70.07	50.82	73.43	69.73	22.37	38.37
CPR	40.22	28.31	32.39	73.17	14.99	42.27	27.32	31.67	21.17	33.05	28.21	31.38	23.47	24.67	3.17	21.96	14.19	24.91	24.90	23.47	20.56	21.06	23.21	25.22	24.22	19.88	31.06	24.89	31.38	32.37	12.78	28.75
LYD	17.50	14.42	11.01	17.55	86.61	17.87	16.23	14.91	12.03	10.99	10.00	12.15	7.65	11.79	2.76	12.00	6.59	10.80	11.86	11.88	6.52	6.99	7.13	11.55	11.53	6.65	10.55	13.32	11.14	11.01	6.16	11.75
IMS	56.71	46.20	56.77	38.39	14.68	76.31	51.71	57.31	41.21	58.21	49.90	56.27	39.72	42.58	6.27	36.30	25.69	44.83	46.10	44.32	36.61	37.62	38.77	48.84	46.84	34.65	55.24	48.04	56.76	57.63	22.99	50.11
MYA	41.62	40.85	43.45	27.94	14.25	54.82	75.00	44.41	33.02	46.71	41.44	44.44	40.04	37.53	6.77	30.79	24.91	39.44	41.29	40.70	38.34	38.90	38.54	45.24	44.26	36.22	43.34	35.82	44.82	44.78	22.06	35.84
CLM	45.58	40.43	50.65	29.14	13.60	60.88	43.03	77.08	41.15	50.43	41.22	50.20	34.71	35.46	5.47	34.25	21.08	36.82	36.98	35.03	32.26	33.16	33.52	40.39	38.17	28.70	48.05	37.57	50.50	49.49	18.38	41.12
ORT	39.14	34.11	36.95	20.57	10.10	45.95	32.92	40.82	78.73	37.80	31.74	36.79	26.78	29.33	4.72	25.47	17.15	31.37	32.79	32.00	25.55	26.39	25.85	34.73	34.06	22.98	36.77	33.06	37.62	38.05	15.63	31.71
CBD	41.35	48.99	70.10	29.11	8.66	56.67	43.11	46.10	31.24	73.57	63.46	64.00	46.78	38.81	4.66	39.73	27.90	47.19	48.64	46.96	44.72	45.70	45.98	53.67	51.58	42.00	68.38	48.85	70.76	67.86	26.76	38.46
KLE	36.88	45.78	58.94	26.05	8.38	47.73	37.06	37.21	25.70	61.12	71.32	54.06	39.03	33.13	4.27	36.46	26.83	40.09	42.16	41.19	36.52	37.23	38.58	46.06	44.48	35.34	58.50	41.87	58.40	56.95	26.34	32.83
SUZ	41.41	47.15	69.82	28.51	8.42	58.64	43.26	49.75	32.73	68.70	58.47	77.39	45.80	35.08	5.39	42.61	20.74	46.94	48.54	46.82	43.55	44.26	45.35	51.69	49.74	41.53	67.07	50.86	70.25	70.14	20.14	36.72
OMN	39.27	38.42	42.53	25.00	8.25	41.32	35.53	33.78	25.10	45.86	39.71	41.24	63.65	40.99	5.29	26.15	21.05	47.60	48.52	46.89	59.73	60.13	62.67	55.97	54.82	58.42	43.97	29.51	44.35	44.18	21.19	28.02
GPL	38.14	33.95	36.02	25.67	12.05	44.21	35.03	32.75	27.23	38.88	34.16	32.81	40.64	64.91	7.20	21.91	34.41	40.87	41.61	40.02	37.52	38.16	41.05	42.10	41.54	36.17	37.54	37.69	37.29	39.05	31.31	30.64
TPS	8.99	5.47	7.27	4.50	2.32	9.02	7.08	6.86	7.74	7.53	6.86	7.79	6.80	10.20	86.82	3.64	5.85	7.29	7.55	7.37	6.25	6.35	6.90	7.96	7.47	5.92	7.32	7.99	7.72	7.56	5.44	6.48
URL	29.74	63.21	35.30	18.61	10.92	33.61	30.26	26.40	19.60	36.70	33.24	37.96	28.32	21.46	3.57	79.28	11.60	28.94	30.89	30.45	27.09	27.42	27.90	34.11	33.15	26.64	35.13	26.31	36.61	36.19	11.75	22.74
CDQ	22.73	24.70	26.88	15.87	9.57	30.94	25.70	24.19	18.62	30.22	31.28	23.63	23.65	39.22	4.58	16.25	73.57	31.21	32.80	32.45	21.15	21.65	22.55	28.64	28.33	20.31	27.81	29.21	26.74	27.45	65.80	21.95
SSL	39.42	40.99	48.53	25.28	10.05	50.79	39.37	40.84	31.68	50.45	43.90	46.75	54.04	45.55	5.89	29.22	29.19	78.01	75.56	72.03	54.06	53.48	53.24	66.03	64.70	49.02	51.16	40.55	50.18	50.68	27.75	35.46
SAM	39.21	40.68	47.00	24.47	10.18	49.87	39.15	38.53	31.55	49.37	43.75	46.34	52.42	43.82	5.97	29.44	28.01	71.88	74.81	73.62	52.23	52.15	51.78	63.98	63.28	49.85	49.12	39.98	48.10	49.22	27.74	34.87
SSH	37.37	39.52	45.04	23.20	10.11	47.99	38.10	36.51	30.95	47.61	42.61	44.95	50.93	42.08	5.86	28.85	26.97	68.73	73.85	74.56	50.87	51.00	50.36	62.03	61.75	49.66	47.01	39.09	45.97	47.22	27.27	33.54
MBN	37.83	38.09	41.68	23.16	8.23	39.96	35.12	32.87	24.79	44.76	38.42	39.89	61.84	39.34	5.01	26.36	19.63	48.81	49.48	47.90	64.93	63.48	61.23	56.30	55.73	59.68	43.11	28.66	43.77	43.25	19.49	27.57
DBF	37.57	38.82	42.56	23.19	8.49	40.66	35.64	33.71	25.71	45.96	39.33	40.94	62.41	40.02	5.12	26.94	20.22	48.76	49.86	48.44	63.70	64.50	61.50	56.84	55.96	59.99	44.11	29.57	44.65	44.23	20.38	27.95
DKN	39.22	36.97	40.92	24.49	7.77	39.76	33.46	31.69	23.68	43.93	38.19	39.72	60.44	40.12	5.19	24.90	19.49	45.35	46.32	44.77	57.11	57.20	61.36	53.19	52.07	55.79	42.50	28.86	42.54	42.73	19.91	26.98
IRL	40.67	44.30	49.91	24.37	9.82	50.49	41.98	40.37	31.57	53.33	47.06	47.41	57.98	43.03	5.89	31.11	25.59	60.64	61.57	59.47	56.68	56.86	56.73	73.09	71.06	53.37	51.97	35.98	51.52	52.15	25.06	34.88
IRH	39.07	42.74	48.06	23.57	9.99	49.20	41.73	38.49	31.27	52.04	46.21	46.12	57.21	43.02	6.12	30.47	26.26	60.19	61.86	60.27	56.48	56.44	55.95	71.77	72.84	53.86	50.28	36.26	49.87	50.33	25.87	34.00
KWT	36.40	35.20	37.50	22.25	8.04	36.52	31.88	28.41	21.93	40.51	35.51	36.91	57.47	36.26	4.65	24.40	18.00	42.89	45.60	45.04	56.71	56.87	56.83	50.96	50.89	60.30	38.58	25.70	38.69	38.97	19.16	25.36
SHR	41.13	48.56	70.76	28.04	8.31	56.03	41.75	45.91	31.64	70.82	62.04	64.62	47.06	39.60	4.77	38.03	25.42	49.02	49.37	47.13	45.25	46.05	46.68	54.41	51.87	41.90	74.41	50.23	71.67	69.97	24.43	40.16
BNL	30.43	37.07	54.99	25.29	12.93	54.20	37.31	37.82	33.07	55.18	49.13	53.38	34.84	48.38	6.44	31.26	30.54	44.26	46.64	46.18	32.87	34.11	35.11	41.31	40.97	30.85	54.47	81.04	58.83	56.43	27.39	36.00
FCD	40.55	49.95	74.53	28.17	8.29	57.35	42.99	47.86	32.12	74.14	62.86	68.15	48.10	39.66	4.74	41.26	24.40	49.11	49.33	47.03	46.56	47.25	47.41	54.49	51.99	42.60	72.15	54.40	77.39	72.26	22.66	38.38
ESD	42.16	49.17	70.73	29.31	8.19	58.30	42.54	47.05	32.99	70.80	60.74	68.24	46.34	40.21	4.77	38.52	23.57	48.38	49.10	46.89	44.55	45.28	46.12	54.12	51.58	41.49	70.57	52.24	72.16	75.46	22.24	38.27
MNS	23.92	23.37	24.84	14.36	8.94	27.78	22.42	20.61	16.98	27.62	29.43	21.87	22.55	34.71	4.32	15.55	64.61	28.13	30.70	30.97	19.95	20.77	21.66	27.27	27.17	20.59	25.73	25.00	23.77	24.68	68.35	20.31
TJN	42.04	33.59	42.86	27.01	10.03	54.85	36.96	42.12	30.17	43.99	37.74	40.21	30.18	32.45	5.40	28.12	19.72	33.84	34.90	33.60	28.20	29.01	29.26	37.22	35.81	26.73	43.78	35.37	42.65	42.54	17.84	75.89

Note: This table provides the variance decomposition matrix with maximal entries in the spillover tables. The number of each crude corresponds to number in Table A.1. For example, WTI represents volatility of WTI; BRT represents volatility of Brent,etc.

TABLE A.9: Minimal spillover table SOT_{min} for volatility

	WTI	BRT	EFK	CPR	LYD	IMS	MYA	CLM	ORT	CBD	KLE	SUZ	OMN	GPL	TPS	URL	CDQ	SSL	SAM	SSH	MBN	DBF	DKN	IRL	IRH	KWT	SHR	BNL	FCD	ESD	MNS	TJN
WTI	28.53	0.85	0.00	1.20	0.14	0.45	0.01	0.44	0.00	0.00	0.01	0.00	0.01	0.01	0.39	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.00	0.04	0.00	0.00	0.00	0.36
BRT	8.05	10.99	0.00	1.08	0.61	0.17	0.00	0.04	0.00	0.00	0.00	0.00	0.01	0.00	0.62	0.11	0.03	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.01	0.16
EFK	4.50	0.23	1.55	0.22	0.15	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.33	1.93	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.04	0.00	0.01	0.03	0.00	0.01	0.23
CPR	8.38	0.26	0.00	29.89	0.07	0.06	0.00	0.01	0.01	0.00	0.00	0.00	0.07	0.00	0.32	0.03	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.05	0.00	0.01	0.00	0.00	0.01	0.08
LYD	1.03	0.03	0.00	0.58	59.21	0.04	0.00	0.01	0.01	0.00	0.00	0.04	0.01	0.00	0.49	0.10	0.00	0.00	0.01	0.02	0.01	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
IMS	7.50	0.79	0.00	0.25	0.37	5.37	0.00	0.04	0.00	0.00	0.00	0.00	0.02	0.08	0.52	0.20	0.03	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.03	0.01	0.00	0.02	0.00	0.00	0.01	0.21
MYA	5.45	0.68	0.00	0.51	0.39	0.10	18.86	0.03	0.00	0.00	0.00	0.00	0.03	0.00	1.17	0.01	0.48	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.00	0.00	0.02	0.00	0.00	0.13	0.07
CLM	1.53	0.70	0.00	0.10	0.73	0.03	0.00	13.85	0.00	0.00	0.00	0.01	0.01	0.02	0.43	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.05
ORT	3.96	0.53	0.00	0.28	0.13	0.05	0.00	0.03	29.61	0.00	0.00	0.01	0.03	0.00	0.17	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.04
CBD	4.92	0.37	0.00	0.27	0.21	0.05	0.00	0.00	0.00	1.55	0.00	0.01	0.02	0.00	0.29	0.62	0.06	0.01	0.01	0.02	0.00	0.00	0.01	0.01	0.02	0.05	0.00	0.01	0.00	0.00	0.01	0.22
KLE	6.42	0.34	0.00	0.35	0.13	0.07	0.00	0.00	0.00	0.00	8.13	0.00	0.02	0.00	0.25	0.55	0.04	0.01	0.01	0.02	0.01	0.02	0.00	0.01	0.01	0.07	0.00	0.02	0.00	0.00	0.01	0.29
SUZ	4.51	0.22	0.00	0.20	0.18	0.05	0.00	0.01	0.00	0.00	0.00	4.84	0.01	0.00	0.41	1.84	0.01	0.02	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.01	0.02	0.00	0.01	0.25
OMN	13.52	0.58	0.00	0.78	0.20	0.33	0.00	0.10	0.00	0.00	0.00	0.01	0.76	0.01	0.35	0.15	0.01	0.00	0.00	0.00	0.04	0.01	0.06	0.01	0.00	0.24	0.00	0.01	0.00	0.00	0.01	0.16
GPL	11.71	0.72	0.00	0.80	0.37	0.24	0.00	0.00	0.00	0.00	0.00	0.02	0.02	11.05	0.33	0.20	0.09	0.01	0.00	0.00	0.01	0.01	0.01	0.02	0.01	0.10	0.00	0.01	0.01	0.00	0.01	0.11
TPS	1.96	0.10	0.00	0.24	0.07	0.03	0.00	0.00	0.05	0.00	0.00	0.01	0.01	0.00	77.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.03
URL	3.94	0.45	0.00	1.00	0.39	0.06	0.00	0.02	0.00	0.00	0.00	0.00	0.01	0.00	0.53	16.71	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.08
CDQ	2.11	0.40	0.01	0.09	0.43	0.03	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.18	0.02	6.49	0.04	0.01	0.09	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	1.41	0.04
SSL	6.25	0.64	0.00	0.14	0.31	0.10	0.00	0.07	0.00	0.00	0.00	0.01	0.02	0.00	0.47	0.09	0.02	1.19	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.07	0.00	0.02	0.00	0.00	0.01	0.13
SAM	8.64	0.57	0.00	0.29	0.28	0.17	0.00	0.11	0.00	0.00	0.00	0.01	0.02	0.00	0.50	0.12	0.02	0.03	0.25	0.02	0.01	0.01	0.01	0.01	0.01	0.09	0.00	0.02	0.00	0.00	0.01	0.15
SSH	8.99	0.47	0.00	0.37	0.28	0.20	0.00	0.12	0.00	0.00	0.00	0.01	0.02	0.00	0.51	0.12	0.01	0.02	0.02	0.43	0.01	0.00	0.00	0.01	0.01	0.08	0.00	0.01	0.00	0.00	0.01	0.14
MBN	12.90	0.72	0.00	0.64	0.30	0.36	0.00	0.18	0.00	0.00	0.00	0.01	0.03	0.01	0.46	0.12	0.01	0.01	0.00	0.00	1.38	0.23	0.00	0.01	0.00	0.22	0.00	0.01	0.00	0.00	0.01	0.16
DBF	12.33	0.71	0.00	0.65	0.32	0.31	0.00	0.15	0.00	0.00	0.00	0.01	0.02	0.00	0.45	0.13	0.01	0.01	0.00	0.00	0.37	1.08	0.01	0.01	0.00	0.20	0.00	0.01	0.00	0.00	0.01	0.17
DKN	15.11	0.54	0.01	0.97	0.17	0.43	0.00	0.10	0.00	0.00	0.00	0.01	0.10	0.01	0.31	0.14	0.01	0.00	0.00	0.00	0.04	0.01	0.88	0.00	0.00	0.26	0.00	0.01	0.00	0.00	0.01	0.16
IRL	8.71	0.70	0.00	0.45	0.36	0.15	0.00	0.10	0.00	0.00	0.00	0.01	0.04	0.00	0.50	0.10	0.04	0.03	0.02	0.01	0.02	0.02	0.00	1.20	0.00	0.11	0.00	0.01	0.00	0.00	0.01	0.14
IRH	8.48	0.55	0.00	0.48	0.36	0.14	0.00	0.11	0.00	0.00	0.00	0.02	0.04	0.00	0.62	0.10	0.04	0.04	0.04	0.03	0.02	0.02	0.01	0.02	1.30	0.12	0.00	0.01	0.00	0.00	0.01	0.13
KWT	15.57	0.54	0.01	0.89	0.23	0.43	0.00	0.16	0.00	0.00	0.00	0.01	0.04	0.00	0.36	0.17	0.01	0.01	0.01	0.01	0.25	0.05	0.00	0.01	0.02	2.56	0.00	0.02	0.00	0.00	0.01	0.18
SHR	5.57	0.39	0.00	0.41	0.20	0.03	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.38	0.58	0.04	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.01	0.02	2.78	0.02	0.04	0.00	0.01	0.21
BNL	2.03	0.21	0.00	0.13	0.23	0.04	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.03	0.33	0.71	0.01	0.01	0.01	0.06	0.00	0.00	0.01	0.03	0.06	0.03	0.00	11.86	0.00	0.00	0.00	0.11
FCD	3.67	0.35	0.00	0.14	0.18	0.04	0.00	0.01	0.00	0.00	0.00	0.01	0.02	0.00	0.37	0.99	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.04	0.01	0.01	1.24	0.01	0.01	0.22
ESD	5.61	0.58	0.00	0.29	0.16	0.04	0.00	0.00	0.01	0.00	0.00	0.00	0.02	0.00	0.34	0.51	0.02	0.01	0.00	0.00	0.00	0.00	0.01	0.03	0.03	0.04	0.00	0.01	0.01	2.48	0.01	0.22
MNS	4.90	0.17	0.01	0.34	0.41	0.05	0.00	0.00	0.00	0.00	0.01	0.01	0.03	0.00	0.19	0.02	0.56	0.01	0.02	0.19	0.01	0.00	0.01	0.01	0.00	0.03	0.00	0.03	0.00	0.00	5.20	0.07
TJN	5.25	0.19	0.00	0.25	0.23	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.45	1.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.00	23.25

Note: This table provides the variance decomposition matrix with minimal entries in the volatility spillover tables. The number of each crude corresponds to number in Table A.1. For example, WTI represents volatility of WTI; BRT represents volatility of Brent,etc.

TABLE A.10: Maximal spillover table SOT_{max} for Friday return

	WTI	BRT	EFK	CPR	LYD	IMS	MYA	CLM	ORT	CBD	KLE	SUZ	OMN	GPL	TPS	URL	CDQ	SSL	SAM	SSH	MBN	DBF	DKN	IRL	IRH	KWT	SHR	BNL	FCD	ESD	MNS	TJN
WTI	88.91	62.67	51.12	40.25	33.38	70.87	56.95	64.04	57.12	52.04	47.8	50.19	40.43	35.46	10.15	42.54	32.65	47.23	46.31	44.86	38.15	38.65	40.02	48.75	48.28	38.71	51.2	48.35	50.48	50.4	21.84	56.32
BRT	62.7	86.58	69.86	33.2	28.2	64.22	55.06	51.5	46.03	69.87	66.95	67.13	49.8	41.84	10.59	59.12	35.43	56.19	55.48	54.16	48.61	48.99	49	59.23	59	50.14	69.7	66.53	69.68	68.73	24.17	51.25
EFK	52.37	72.27	73.37	30.71	26.48	58.17	48.19	46.13	40.49	70.55	66.96	67.64	48.06	40.19	9.28	57.57	34.65	53.63	52.37	50.88	48.29	48.7	47.58	56.6	56.59	48.74	70.13	67.58	71.03	68.59	22.87	45.59
CPR	44.11	40.8	35.77	67.04	31.81	39.98	33.12	34.21	28.9	36.12	33.01	34.86	29.48	24	7.98	34.93	21.62	31.35	31.07	30.25	28.64	29.04	29.83	33.04	33.11	28.77	35.89	34.25	35.17	35.74	17.65	29.93
LYD	39.46	34.18	29.23	33.84	75.76	34.98	35.18	29.23	27.61	28.85	26.96	28.38	22.92	19.68	5.45	31.97	17.2	25.14	25.8	25.36	21.37	22.16	22.23	26.27	26.67	22.62	28.54	28.46	27.73	28.43	13.22	25.16
IMS	71.38	66.9	60.56	36.79	31.54	75.31	60.63	62.74	56.51	61.35	57.29	59.06	46.34	42.03	11.21	49.99	37.49	53.2	52.77	51.45	44.59	45.17	45.76	54.83	54.61	45.61	60.37	58.37	59.95	59.75	25.42	58.43
MYA	62.3	61.63	52.49	31.8	32.8	64.37	80.86	55.06	50.39	55.08	52.44	52.29	45.02	40.81	7.44	45.26	36.07	48.55	49.01	48.31	42.18	42.36	43.83	51.26	51.3	43.41	52.88	52.07	52.61	52.83	23.27	50.56
CLM	66.01	57.12	51.98	34.28	28.58	65.27	54.75	71.81	56.48	52.7	48.56	51.11	44.59	37.4	10.34	43.59	34.45	48.21	47.51	46.16	41.94	42.63	43.72	49.59	48.96	42.59	51.93	50.19	51.91	51.23	23.98	51.76
ORT	63.4	53.69	48.2	30.44	26.17	63.18	52.85	61.56	73.81	49.33	45.48	47.03	40.77	36.81	9.28	38.01	33.69	45.91	46.01	45.46	39.43	40.45	40.37	47.55	47.43	40.41	48.61	47.7	48.23	47.87	22.74	50.74
CBD	53.75	71.75	69.39	30.3	26.12	58.95	50.36	46.79	41.46	72.35	66.61	65.38	48.41	40.47	9.63	55.08	36.24	53.38	52.57	51.28	48.48	49.11	47.78	57.42	57.55	49.06	68.68	66.64	70.16	67.17	24.39	46.69
KLE	49.88	69.49	67.69	27.68	24.7	56.54	48.75	44.15	39.08	68.09	71.41	62.65	44.45	39.06	9.73	52.54	33.96	50.71	50.35	49.38	44.6	44.99	43.81	53.85	53.9	45.35	66.26	64.05	66.43	64.33	22.97	45.23
SUZ	51.83	69.75	68.34	30.14	25.73	57.6	48.46	46.31	40.67	67.51	62.84	72.35	47.26	38.65	8.46	57.15	33.95	53.49	52.75	51.55	47.67	48	46.83	55.4	55.65	48.4	66.87	65.38	68.18	67.75	22.74	44.42
OMN	54.66	62.03	55.41	29.98	25.87	54.37	48.16	47.97	43.02	56.81	50.97	53.61	66.18	47.07	12.1	45.36	41.24	57.69	56.13	54.62	62.73	63.56	64.56	61.17	61.12	63.57	54.96	52.74	56.32	55	27.89	42.87
GPL	54.6	57.92	49.11	26.22	24.61	52.7	48.04	45.46	40.78	50.07	47.16	46.48	47.42	66.51	14.74	39.36	48.38	50.16	49.61	48.58	44.48	45.28	46.97	51.33	51.19	45.35	49.81	48.44	49.43	48.99	34.08	43.13
TPS	24.76	22.67	17.12	8.99	7.23	21.48	15.82	18.59	18.78	17.88	17.26	15.01	17.28	22.76	76.07	14.49	19.4	21.79	21.64	21.28	15.15	15.65	17.33	22.52	22.02	16.71	17.46	16.66	17.14	17.36	13.25	20.96
URL	44.3	59.52	53.74	28.08	28.1	46.13	40.38	35.53	31.21	52.11	50	52.68	36.36	27.87	9.14	84.31	23.46	39.25	38.9	37.98	36.04	36.66	35.28	42.19	42.8	36.93	52.92	50.03	52.4	52.27	15.78	36.59
CDQ	51.1	52.99	45.24	25.56	23.16	49.94	45.22	44.75	39.81	46.11	42.27	43.29	43.01	50.29	12.1	36.21	70.5	46.68	45.91	44.9	39.76	40.87	42.19	46.98	46.58	42.23	45.75	45.2	44.71	44.09	47.79	41.14
SSL	55.91	64.53	59	29.94	24.56	57.05	48.91	48.91	43.98	59.33	54.55	57.73	55.79	47.95	13.53	43.75	42.7	71.77	70.42	68.61	55.73	55.67	55.29	64.51	64.13	56.93	58.9	56.67	58.84	58.09	29.71	45.93
SAM	55.66	63.83	57.92	29.68	25.05	57.04	49.14	48.65	44.48	58.57	54.18	57.16	54.58	47.33	13.4	43.33	41.73	70.59	71.38	70.58	54.71	54.82	54.16	63.99	63.73	56.72	57.81	55.93	57.71	57.16	28.72	45.67
SSH	54.71	62.66	56.89	29.14	24.96	56.42	49.09	47.98	44.54	57.7	53.55	56.42	53.87	46.89	13.21	42.4	41.18	69.72	71.56	71.8	54.05	54.33	53.56	63.4	63.28	56.43	56.81	55.15	56.66	56.17	28.23	45
MBN	52.27	59.62	53.71	28.9	24.88	51.48	45.24	44.81	40.5	54.91	49.06	51.82	61.97	44.31	10.48	44.87	38.04	56.12	54.7	53.22	67.31	65.96	61.62	59.35	59.72	63.34	53.54	51.61	55.03	53.56	26.02	40.35
DBF	52.58	59.99	54.08	28.88	25.61	52.14	45.61	45.47	41.32	55.46	49.42	52.23	62.13	44.44	10.61	45.65	38.92	55.87	54.66	53.37	65.24	66.71	61.16	59.35	59.95	63.48	53.87	51.97	55.28	53.83	26.24	40.75
DKN	54.86	61.6	55.17	30.38	25.48	54.23	47.44	47.6	43.16	56.4	50.57	53.44	64.98	46.86	12.23	44.42	40.61	57.44	55.88	54.42	62.73	62.92	66.26	60.94	60.85	62.89	55.02	52.79	56.28	55.01	27.89	42.9
IRL	56.23	66.55	61.59	29.86	25.46	58.39	50.42	50.65	45.74	63.11	57.42	58.96	59.28	48.12	12.94	46.41	41.71	64.25	63.59	62.24	58.46	59.08	58.84	73.7	72.87	59.86	61.32	58.5	61.8	60.95	28.44	46.92
IRH	55.53	66.08	60.96	29.38	25.66	57.92	50.27	50.05	45.55	62.66	57.08	58.56	58.66	47.81	12.85	46.42	41.52	63.57	63.19	62.07	58.36	59.16	58.16	72.56	73.75	60.1	60.76	58.2	61.08	60.35	28.45	45.7
KWT	53.12	61.39	54.38	29	26.14	53.38	46.4	45.73	42.33	55.89	50.09	53.05	62.51	44.28	10.91	45.26	39.89	57.58	56.9	55.81	63.06	63.92	61.57	60.51	61.24	66.81	54.04	52.14	55.38	54.44	26.6	42.03
SHR	53.56	72.62	70.21	30	25.64	58.81	48.92	46.81	41.62	69.95	65.86	66.15	48.07	41.19	9.65	56.07	35.79	54.09	52.94	51.54	48.72	49.18	47.9	56.94	56.95	48.81	72.25	66.95	70.4	68.6	24.59	47.28
BNL	50.74	70.05	68.97	29.76	25.32	57.12	48.36	46.12	40.75	69.18	64	65.5	46.85	40.47	9.45	54	35.5	52.81	51.9	50.67	47.66	47.95	46.73	55.87	55.98	47.79	68.11	71.74	70.41	67.06	24.08	44.94
FCD	52.5	72.71	71.17	30.67	25.89	58.15	48.54	46.46	40.84	71.58	66.16	67.36	49.33	40.8	9.18	56.75	35.08	53.98	52.7	51.25	50.08	50.45	49.07	57.36	57.34	50.09	70.36	69.36	73.31	68.97	23.54	45.42
ESD	52.75	71.86	69.49	31.1	25.85	58.53	48.92	47.01	40.96	69.38	64.31	67.73	48.67	40.95	9.52	55.8	34.79	54.08	53.1	51.72	49.36	49.73	48.56	57.13	57.03	49.72	69.78	66.74	69.96	72.3	23.77	46.11
MNS	34.87	39.99	35.11	22.52	17.98	36.59	32.33	34.74	30.6	36.12	33.03	34.28	34.96	41.64	9.77	27.78	58.29	37.78	36.97	36.34	32.3	33.25	34.72	37.17	37.01	34.64	36.56	35.92	35.07	34.99	75.24	30.37
TJN	62.26	57.85	51.08	30.71	24.57	63.77	51.49	54.29	48.58	52.23	49.25	49.27	39.74	38.73	11.79	41.7	33.75	46.23	45.62	44.3	37.75	38.33	39.4	47.93	47.15	39.25	52.34	49.53	50.75	50.36	23.06	74.29

Note: This table provides the variance decomposition matrix with maximal entries in the spillover tables for returns generated by Friday prices. The number of each crude corresponds to number in Table A.1. For example, WTI represents Wednesday return of WTI; BRT represents Wednesday return of Brent,etc.

TABLE A.11: Minimal spillover table SOT_{min} for Friday return

	WTI	BRT	EFK	CPR	LYD	IMS	MYA	CLM	ORT	CBD	KLE	SUZ	OMN	GPL	TPS	URL	CDQ	SSL	SAM	SSH	MBN	DBF	DKN	IRL	IRH	KWT	SHR	BNL	FCD	ESD	MNS	TJN
WTI	12.14	0.02	0.01	0.01	0	0.05	0	0.14	0.14	0	0	0	0	0.01	0.07	1.28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.02	0.02
BRT	0.65	8.13	0	0.04	0.01	0	0	0.03	0	0.01	0.01	0.03	0.07	0.01	0.21	2.03	0	0.01	0.01	0	0	0	0.01	0.01	0	0	0	0	0	0	0.05	0
EFK	0.23	3.62	1.42	0	0	0	0.02	0.02	0	0.01	0.04	0.02	0.09	0.01	0.21	2.21	0	0.01	0	0	0	0	0.02	0.01	0	0	0	0.01	0.02	0	0.03	0
CPR	2.97	0.26	0.01	30.44	0	0.03	0	0.04	0.01	0	0.01	0.02	0.08	0.01	0.21	1.41	0	0	0	0	0	0.02	0.01	0	0.02	0	0.01	0.01	0	0	0.06	0
LYD	1.79	0.25	0	0.19	36.28	0.02	0.03	0	0.01	0	0.01	0	0.05	0.01	0.14	0.67	0	0	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0
IMS	4.29	0.86	0	0.03	0	3.52	0.04	0.05	0.03	0.01	0	0	0.02	0.01	0.16	1.74	0	0	0	0	0	0	0	0	0	0	0.01	0.01	0	0	0.03	0
MYA	1.33	0.66	0	0.02	0	0	12.88	0.01	0.01	0	0	0	0.01	0.01	0.34	1.06	0	0.01	0	0	0	0	0.01	0	0	0	0	0.01	0	0	0.01	0
CLM	4.12	0.28	0	0.03	0	0.01	0.1	7.5	0.01	0	0.01	0	0.01	0.01	0.11	2.12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.06	0
ORT	4.48	0.25	0	0.05	0	0.01	0.03	0.04	12.49	0	0	0	0.02	0.01	0.13	1.39	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0	0.02	0
CBD	0.45	3.31	0.01	0	0	0	0.02	0.01	0	1.21	0.08	0.03	0.08	0	0.26	1.66	0.02	0.01	0	0	0	0	0.02	0	0	0	0.02	0	0	0.02	0.06	0
KLE	0.25	3.73	0.01	0.01	0	0	0.03	0.01	0	0.09	4.36	0.03	0.08	0.01	0.31	1.32	0.01	0	0	0	0	0	0.04	0	0	0	0	0.01	0	0	0.02	0
SUZ	0.34	2.83	0	0	0	0	0.03	0.02	0	0.01	0.03	3.15	0.07	0	0.23	2.91	0	0.01	0	0	0	0	0.01	0.01	0	0	0	0.01	0	0	0.04	0
OMN	2.17	1.8	0	0.02	0	0.01	0.01	0	0.02	0	0.01	0.02	1.29	0.01	0.3	0.71	0.03	0	0	0	0.05	0	0.02	0.01	0.01	0	0	0	0	0	0.03	0
GPL	2.76	1.78	0	0.02	0	0.01	0.01	0.01	0.01	0	0	0	0.05	10.56	0.27	0.3	0	0.01	0	0	0	0	0.02	0	0	0	0	0	0	0	0.04	0
TPS	1.89	0.28	0.02	0.16	0	0	0	0	0.03	0	0	0.02	0.01	0.02	51.31	0.01	0.02	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0.05	0
URL	0.72	1.94	0	0.01	0	0	0.01	0	0.02	0.02	0	0.02	0.14	0	0.14	25.14	0	0	0	0	0	0	0.01	0	0	0	0	0.01	0.01	0	0.02	0
CDQ	1.7	0.72	0.01	0.02	0	0	0.02	0.02	0	0.01	0	0.01	0.01	0.01	0.4	0.41	10.47	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0
SSL	1.51	2.24	0.01	0.01	0	0	0	0	0	0.01	0.02	0.01	0.12	0.01	0.24	0.35	0.04	0.5	0	0	0	0	0.04	0	0	0	0	0	0	0	0.02	0
SAM	1.79	2.07	0.01	0.01	0	0	0	0	0	0.01	0.01	0.01	0.11	0.01	0.22	0.36	0.02	0	0.12	0	0	0	0.04	0	0	0	0	0	0	0	0.01	0
SSH	1.87	1.91	0.01	0.01	0	0.01	0	0	0	0.01	0	0.01	0.11	0.01	0.21	0.34	0.01	0	0	0.27	0	0	0.04	0	0	0	0.01	0	0	0	0.01	0
MBN	2.24	1.47	0	0.02	0	0.01	0.01	0	0.01	0	0	0.01	0.09	0.01	0.29	0.92	0.01	0	0	0	1.37	0	0.03	0.01	0.01	0	0	0	0	0	0.01	0
DBF	2.11	1.6	0	0.02	0	0.01	0.01	0	0.01	0	0.01	0.01	0.11	0	0.29	0.99	0.01	0	0	0	0.03	1.05	0.02	0	0.01	0	0.01	0	0	0	0.02	0
DKN	2.32	1.81	0	0.02	0	0.01	0.01	0	0.02	0	0.01	0.02	0.09	0	0.27	0.63	0.01	0	0	0	0.08	0	1.31	0	0.01	0	0	0	0	0	0.03	0
IRL	1.25	1.95	0.01	0.02	0	0	0.01	0	0	0	0.02	0.01	0.07	0.01	0.24	0.46	0.01	0.01	0	0	0	0	0.04	0.87	0.01	0	0.01	0	0	0	0.02	0
IRH	1.17	2.06	0.01	0.02	0	0	0.01	0	0	0	0.02	0.01	0.09	0.01	0.23	0.44	0.01	0.01	0	0	0	0	0.03	0.01	0.9	0	0	0	0	0	0.01	0
KWT	2.07	1.73	0	0.02	0	0.01	0.01	0	0.02	0	0.01	0.01	0.06	0	0.3	0.71	0.01	0	0	0	0.03	0	0.02	0	0.01	1.94	0	0	0	0	0.02	0
SHR	0.41	3.81	0	0	0	0	0.01	0.03	0	0.01	0.02	0.01	0.09	0.01	0.24	1.73	0.01	0.01	0	0	0	0	0.02	0.01	0	0	1.61	0.01	0.01	0.02	0.04	0
BNL	0.3	3.3	0.01	0	0	0	0.01	0.03	0	0	0.07	0.01	0.06	0.01	0.25	1.82	0	0	0	0	0	0	0.03	0.02	0	0	0	3.43	0.04	0	0.03	0
FCD	0.24	3.56	0.02	0	0	0	0.02	0.02	0	0	0.03	0.01	0.08	0	0.22	1.95	0.01	0	0	0	0	0	0.02	0	0	0	0.04	0.01	0.84	0.03	0.04	0
ESD	0.36	3.78	0	0	0	0	0.03	0.02	0	0.01	0.02	0.01	0.03	0	0.22	1.83	0.01	0	0	0	0	0	0.02	0.01	0	0	0.01	0	0	2.01	0.03	0
MNS	0.37	0.58	0	0.01	0	0	0.04	0.01	0	0	0	0.01	0.03	0.01	0.34	0.62	0.41	0	0	0	0.01	0	0	0.01	0	0	0	0.01	0	0	19.52	0
TJN	3.8	0.72	0	0.02	0	0	0	0.02	0.01	0	0	0.01	0.01	0.01	0.21	0.75	0	0	0	0	0	0	0	0	0	0	0.01	0.01	0	0	0.02	14.31

Note: This table provides the variance decomposition matrix with minimal entries in the spillover tables for returns generated by Friday price. The number of each crude corresponds to number in Table A.1. For example, WTI represents Wednesday return of WTI; BRT represents Wednesday return of Brent,etc.

Table A.12: Minimal spillover table SOT_{min} for GARCH volatility

	WTI	BRT	EFK	CPR	LYD	IMS	MYA	CLM	ORT	CBD	KLE	SUZ	OMN	GPL	TPS	URL	CDQ	SSL	SAM	SSH	MBN	DBF	DKN	IRL	IRH	KWT	SHR	BNL	FCD	ESD	MNS	TJN
WTI	0.6	0.69	0.02	1.1	0.03	0.03	0.07	0.17	0.36	0.16	0	0.02	0.02	0.24	0.18	0.02	0.03	0.22	0.03	0.01	0.05	0.06	0.23	0.01	0	0.37	0.01	0.03	0.01	0	0.03	0.01
BRT	0.01	5.22	0	0.03	0.02	0.04	0.02	0.04	0.16	0.07	0	0.02	0.01	0.14	0.71	0.01	0.02	0.14	0.01	0.01	0.03	0.01	0.05	0	0	0.13	0.03	0.01	0	0.01	0.03	0
EFK	0.01	1.42	0.15	0.01	0.02	0.02	0.03	0.03	0.11	0.14	0	0.01	0.01	0.03	0.68	0.28	0.02	0.1	0.01	0	0.01	0.02	0.01	0.01	0	0.08	0.17	0.01	0.01	0	0.06	0
CPR	0.06	0.77	0.02	3.79	0.04	0.06	0.03	0.07	0.17	0.08	0	0.01	0.03	0.41	0.21	0.02	0.03	0.32	0.06	0.04	0.04	0.08	0.19	0.01	0.01	0.13	0.02	0.01	0	0	0.01	0.01
LYD	0	1.19	0.02	0	25.47	0.01	0.02	0.39	0.1	0.01	0	0.01	0.01	0.03	1.59	0.04	0	0.58	0.07	0	0	0	0.03	0.01	0	0.07	0.01	0	0	0.01	0.05	0
IMS	0.03	1.62	0.03	0.43	0.03	0.2	0.14	0.09	0.34	0.12	0	0.01	0.02	0.29	0.42	0.06	0.02	0.35	0.04	0.02	0.02	0.03	0.09	0.02	0	0.23	0.02	0.01	0	0	0.06	0.01
MYA	0.03	0.67	0.01	0.02	0.03	0.11	1.62	0.06	0.18	0.12	0	0.01	0.03	0.18	0.36	0.03	0.05	0.44	0.06	0.02	0.04	0.01	0.02	0.01	0.01	0.14	0.01	0.01	0.01	0	0.09	0.01
CLM	0.06	2.56	0	0.02	0.04	0.07	0	1.9	0.22	0.04	0	0.01	0.02	0.2	0.89	0.16	0.03	0.26	0.04	0.02	0.02	0.05	0.01	0.01	0	0.09	0.03	0.01	0.01	0	0.02	0.01
ORT	0.04	1.06	0.03	0.02	0.03	0.07	0.07	0.09	4.66	0.06	0	0.01	0	0.2	0.39	0.06	0.02	0.22	0.03	0	0.01	0.03	0.01	0.01	0.01	0.2	0.03	0.01	0	0	0.04	0.01
CBD	0.01	1.75	0.02	0.03	0.02	0.02	0.03	0.05	0.17	0.41	0.01	0.01	0.02	0.08	0.3	0.09	0.07	0.31	0.01	0.01	0.02	0.02	0.03	0	0	0.11	0.04	0.01	0	0	0.17	0.01
KLE	0.01	1.21	0.03	0.05	0.02	0.04	0.03	0.04	0.13	0.03	0.94	0.01	0.03	0.08	0.41	0.09	0.04	0.18	0.01	0.01	0.01	0.02	0.05	0.01	0.01	0.08	0.01	0.01	0	0	0.07	0.01
SUZ	0.02	1.28	0.01	0.01	0.02	0.03	0.02	0.04	0.13	0.04	0	0.32	0.01	0.03	0.22	0.33	0.01	0.21	0.02	0.01	0.06	0.02	0.01	0.01	0	0.12	0.15	0	0.01	0	0.03	0
OMN	0	1.05	0	0.17	0.04	0.03	0.06	0.06	0.12	0.05	0	0	0.08	0.26	0.2	0.01	0.01	0.19	0.01	0.01	0.09	0.02	0.25	0.02	0	0.17	0.02	0.01	0	0	0.02	0
GPL	0	1.26	0.02	0.04	0.02	0.01	0.01	0.03	0.15	0.05	0	0.01	0.02	2.14	0.42	0.02	0.02	0.43	0.08	0.03	0.01	0.02	0.08	0	0	0.12	0	0	0	0	0.14	0.01
TPS	0.02	0.36	0	0.08	0	0.02	0	0.01	0.01	0.04	0	0.01	0.02	0	34.65	0.03	0.02	0.01	0	0	0	0	0.06	0.02	0.01	0.17	0.01	0.01	0.03	0	0.02	0
URL	0.01	0.63	0.01	0.01	0.04	0.02	0.01	0.03	0.14	0.03	0	0.01	0	0.04	0.35	4.56	0	0.19	0.02	0	0	0.02	0.01	0.02	0.01	0.07	0.03	0.01	0	0.01	0.02	0
CDQ	0.01	0.73	0.03	0.02	0.02	0.04	0.04	0.06	0.12	0.05	0	0.01	0.03	0.3	0.23	0.01	1.79	0.61	0.02	0.01	0	0.03	0.05	0.01	0	0.05	0.01	0	0	0	0.89	0
SSL	0.06	0.89	0	0.23	0.03	0.06	0.1	0.06	0.23	0.06	0	0.01	0.02	0.21	0.23	0.01	0.01	0.29	0.06	0.02	0.04	0.06	0.23	0.01	0	0.18	0.02	0.01	0	0	0.07	0.01
SAM	0.04	0.79	0.03	0.21	0.04	0.06	0.09	0.07	0.22	0.06	0	0.01	0.02	0.21	0.21	0.01	0.02	0.4	0.19	0.18	0.03	0.04	0.23	0.01	0	0.21	0.02	0.01	0	0	0.08	0
SSH	0.04	0.7	0.03	0.21	0.04	0.06	0.09	0.07	0.23	0.06	0	0.01	0.01	0.19	0.19	0.01	0.03	0.54	0.29	0.34	0.01	0.04	0.21	0.01	0	0.22	0.02	0.01	0	0	0.08	0
MBN	0.02	1.1	0	0.13	0.04	0.03	0.08	0.06	0.13	0.04	0	0.01	0.01	0.28	0.16	0.01	0.01	0.16	0.01	0	0.04	0.1	0.12	0	0	0.28	0.01	0.01	0	0	0.02	0
DBF	0.01	1.21	0	0.11	0.03	0.04	0.07	0.04	0.15	0.05	0	0	0.01	0.25	0.21	0.01	0.01	0.2	0.01	0	0.08	0.15	0.09	0.01	0	0.25	0.01	0.01	0	0	0.02	0
DKN	0.02	0.98	0	0.16	0.03	0.02	0.06	0.07	0.11	0.04	0	0.01	0.02	0.28	0.15	0.01	0.01	0.14	0.01	0	0.07	0.02	0.37	0.01	0	0.15	0.01	0.01	0	0	0.02	0
IRL	0.01	1.47	0	0.08	0.03	0.03	0.08	0.05	0.2	0.07	0	0.01	0.02	0.23	0.31	0.02	0.02	0.39	0.07	0.02	0.01	0.03	0.22	0.18	0.09	0.2	0.01	0.01	0	0	0.06	0
IRH	0.01	1.26	0.02	0.07	0.03	0.04	0.09	0.05	0.2	0.08	0	0.01	0.02	0.19	0.34	0.02	0.02	0.53	0.05	0.02	0.02	0.03	0.21	0.16	0.18	0.23	0.01	0.01	0	0	0.06	0
KWT	0.01	0.82	0.01	0.19	0.04	0.02	0.05	0.07	0.12	0.06	0	0.01	0.01	0.25	0.16	0.01	0.01	0.22	0.02	0	0.05	0.04	0.21	0.01	0.01	0.57	0.01	0.01	0	0	0.01	0
SHR	0	1.89	0.01	0.02	0.02	0.03	0.03	0.03	0.12	0.01	0	0.01	0.01	0.05	0.43	0.07	0.03	0.18	0.03	0	0.03	0.02	0.04	0.01	0	0.09	0.74	0	0	0	0.08	0
BNL	0	0.4	0.01	0	0.01	0.02	0.01	0.01	0.11	0.07	0	0.01	0	0.08	0.69	0.08	0.06	0.11	0	0.01	0	0.02	0.01	0.02	0	0.1	0.04	2.45	0.01	0	0.48	0
FCD	0.01	0.86	0.01	0.01	0.01	0.02	0.02	0.02	0.08	0.14	0	0.01	0.01	0.01	0.6	0.26	0.03	0.06	0.01	0	0.01	0.03	0	0.01	0	0.06	0.12	0.01	0.28	0	0.06	0
ESD	0.01	1.88	0	0.04	0.02	0.04	0.03	0.03	0.18	0.06	0	0.01	0.01	0.05	0.35	0.05	0.01	0.21	0.03	0.01	0.05	0.03	0.03	0.01	0	0.15	0.11	0.01	0	0.16	0.04	0.01
MNS	0	0.62	0.02	0.04	0.01	0	0.01	0.01	0.03	0.02	0	0.02	0.01	0	0.44	0.01	0.11	0.56	0	0	0	0	0.01	0.01	0	0.02	0.01	0	0	0	5.41	0
TJN	0.03	1.55	0.03	0.38	0.03	0.01	0.14	0.04	0.23	0.05	0	0.01	0.01	0.22	0.36	0.04	0.02	0.32	0.07	0.01	0.02	0.02	0.13	0.01	0.01	0.24	0.02	0.01	0	0	0.09	0.87

Note: This table provides the variance decomposition matrix with minimal entries in the spillover tables for volatility measure based on univariate GARCH. The number of each crude corresponds to number in Table A.1. For example, gWTI represents Wednesday return of WTI; gBRT represents Wednesday return of Brent,etc.

TABLE A.13: Maximal spillover table SOT_{max} for GARCH volatility

	WTI	BRT	EFK	CPR	LYD	IMS	MYA	CLM	ORT	CBD	KLE	SUZ	OMN	GPL	TPS	URL	CDQ	SSL	SAM	SSH	MBN	DBF	DKN	IRL	IRH	KWT	SHR	BNL	FCD	ESD	MNS	TJN
WTI	35.99	41.95	32.87	43.83	17.92	39.55	37.17	33.21	39.19	40.49	39.14	38.45	45.2	44.86	14.12	33.68	40.99	40.52	41.68	42.41	42.38	43.72	45.12	42.06	42.27	46.12	38.68	29.49	30.57	39.38	40.59	37.17
BRT	33.34	49.86	39.44	40.44	17.21	39.2	40.36	35.73	38.83	42.94	42.82	41.44	43.35	44.84	17.33	36.9	38.27	37.71	38.79	39.32	41.43	42.71	43.33	40.84	40.8	43.23	42.55	35.4	38.02	42.3	37.06	36.56
EFK	31.32	48	48.09	36.52	16.37	37.56	39.16	35.98	36.94	45.99	46.03	44.48	39.54	41.22	16.54	40.8	34.34	35.02	35.72	36	38.39	39.44	39.63	37.9	37.73	38.86	47.29	42.65	47.51	45.29	32.34	34.34
CPR	33.57	41.75	33.38	47.39	18.33	38.7	36.67	33.4	38.32	39.77	38.57	37.8	42.97	44.07	14.42	32.86	39.59	38.5	39.56	40.2	40.22	41.48	42.92	39.81	40.01	43.29	38.11	31.34	31.36	38.82	38.16	36.43
LYD	22.32	29.23	22.61	29.09	62.34	27.32	29.31	28.33	28.31	25.63	26.62	25.44	26.81	31.53	15.87	26.4	26.46	23.41	24.7	25.38	25.13	25.88	26.73	25.97	26.44	26.96	25.59	23.96	21.45	24.7	24.76	25.19
IMS	37.08	47.51	38.25	45.47	20.39	43.68	42.44	37.92	42.95	44.9	44.2	42.87	47.94	49.59	17.83	38.25	44.46	42.68	43.99	44.73	45.18	46.66	47.84	44.98	45.09	48.49	43.49	35.78	36.12	43.95	43.06	40.98
MYA	35.16	46.81	37.42	42.39	20.12	41.69	48.07	37.46	42.03	43.73	43.6	42.27	48.09	49.3	17.04	37.75	44.15	41.51	42.87	43.68	45.85	47.11	47.89	44.59	44.85	48.42	42.34	35.11	35.81	42.74	42.22	39.05
CLM	33.96	45.92	37.26	38.58	22.48	39.6	39.97	44.08	41.7	40.28	39.58	39.49	40.03	43.11	17.33	38.66	36.56	35.38	36.3	36.73	38.33	39.49	39.85	37.92	37.89	39.5	39.82	34.7	36.23	39.78	33.83	36.69
ORT	32.02	42.3	33.74	38.23	18.92	37.73	37.49	34.82	48.59	39.09	38.81	37.83	41.13	43.97	15.92	34.16	38.88	36.76	37.89	38.54	39.27	40.72	40.99	39.26	39.41	41.51	38.36	32.7	32.25	38.79	37.95	35.18
CBD	36.13	51.03	46.43	43.3	18.45	42.96	43.76	38.34	42.28	50	49.36	47.15	47.55	48.87	16.43	41.93	43.76	42.03	43.19	43.79	45.45	46.79	47.52	45.02	45.03	47.48	49.36	42.01	45.1	48.47	42.32	40.07
KLE	33.01	47.86	44.78	40.18	17.79	39.83	40.71	34.99	38.94	46.84	49.64	44.62	43.78	45.4	16.59	40.16	41.26	38.79	39.96	40.54	41.58	42.73	43.78	41.67	41.69	43.52	46.86	41.04	43.28	45.66	38.94	36.86
SUZ	34.72	49.24	46.15	40.53	17.74	40.92	42.5	38.08	40.54	47.58	46.92	48.09	45.24	45.26	14.83	42.21	38.78	39.58	40.66	41.17	43.69	44.9	45.34	42.46	42.62	45.14	48.01	41.53	45.12	47.23	36.92	37.67
OMN	34.6	45.03	36.17	42.33	17.52	40.25	41.11	34.27	40.18	43.06	42.46	41.07	49.78	48.98	14.85	35.63	42.44	42.44	43.64	44.27	47.44	48.69	49.78	45.28	45.61	49.98	41.73	32.75	34.47	42.23	41.06	37.89
GPL	32.25	44.81	34.61	41.1	19.39	38.99	40.39	33.6	39.81	40.8	40.83	38.06	44.96	52.07	17.25	34	44.09	38.83	40.18	40.82	42.34	43.75	45.02	41.55	41.73	44.91	39.48	34.05	32.81	39.98	43.32	36.57
TPS	7.91	22	14.5	9.16	6.42	11.03	10.16	10.93	10.4	17.06	11.61	20.89	22.09	11.25	49.68	10.33	10.53	16.73	18.17	17.8	17.19	20.12	23.07	14.68	16.38	22.56	13.13	9.48	13.63	11.12	7.68	10.13
URL	30.66	41.74	38.69	33.01	19.67	34.84	37.58	34.39	35.07	38.8	39.14	39.66	36.11	37.47	14.05	45.62	31.24	31.58	32.64	33.06	34.74	35.63	36.24	34.27	34.46	35.92	38.92	35.97	37.65	38.14	28.58	31.65
CDQ	34.63	47.06	36.25	45.17	19.32	42.07	41.86	35.65	42.68	44.8	45.6	41.33	48.71	53.35	15.43	35.75	59.12	43.84	45.49	46.6	45.19	46.82	48.23	45.9	46.27	49.43	43.03	35.99	33.6	43.54	58.28	40.71
SSL	38.84	48.93	39.05	47.33	18.75	44.73	44.21	38.04	45.21	47.03	46.35	44.87	53.33	53.24	16.87	38.33	48.7	48.87	49.97	50.72	50.59	52.02	53.22	50.22	50.53	53.95	45.86	36.28	36.89	46.3	48.18	42.57
SAM	37.95	47.73	37.9	46.34	18.81	43.96	43.46	36.94	44.31	46	45.46	44.03	52.38	52.38	16.51	37.75	48.28	47.85	49.29	50.2	49.66	51.1	52.29	49.34	49.71	53.29	44.72	35.4	35.63	45.29	47.74	41.86
SSH	37.6	47.18	37.46	46.06	18.91	43.7	43.2	36.53	44.14	45.67	45.17	43.77	52.12	52.15	16.35	37.41	48.44	47.63	49.22	50.26	49.41	50.85	52.03	49.11	49.53	53.19	44.34	35.15	35.12	44.96	48.02	41.67
MBN	33.95	44.37	35.48	41.06	17.21	39.32	40.89	33.8	39.52	42.08	41.63	40.32	48.96	48.05	13.79	35.29	41.12	41.7	42.81	43.42	47.61	48.57	49.03	44.51	44.91	49.36	40.91	32.07	33.99	41.42	39.46	37.09
DBF	34.26	44.92	36.05	41.42	17.68	39.94	41.31	34.46	40.26	42.75	42.29	40.97	49.48	48.64	14.58	35.8	41.92	42.3	43.47	44.1	47.89	49.12	49.48	45.17	45.51	49.88	41.57	32.68	34.51	42.11	40.31	37.73
DKN	33.37	43.67	34.97	40.94	16.89	38.61	39.72	32.73	38.67	41.41	40.87	39.65	47.86	47.43	13.88	34.33	40.32	40.45	41.66	42.25	45.63	46.82	48.1	43.27	43.62	48	40.24	31.81	33.29	40.65	39.09	36.3
IRL	37.44	49.1	39.2	45.23	19.01	43.78	44.23	37.39	44.11	46.46	46.1	44.41	52.2	52.12	17.45	38.72	46.54	46.23	47.57	48.3	49.67	51.09	52.15	49.65	49.88	52.67	45.43	35.84	37.16	45.74	45.76	41.54
IRH	37.27	48.59	38.88	45.18	19.18	43.71	44.25	37.06	44.07	46.37	46.04	44.29	52.35	52.16	17.52	38.6	47.19	46.52	47.93	48.73	49.84	51.23	52.28	49.76	50.26	52.99	45.23	35.87	36.78	45.61	46.46	41.6
KWT	33.62	43.44	34.78	41.21	17.47	39.35	40.07	33.02	39.29	41.92	41.3	40.15	48.99	48.01	13.92	34.64	42.17	42.07	43.44	44.2	46.96	48.16	49	44.73	45.17	50.05	40.51	31.63	32.93	41.21	40.94	37.26
SHR	33.67	49.86	47.18	39.95	17.51	40.32	41.83	37.31	40.16	48.04	47.91	46.09	44.44	45.76	16.28	40.61	39.23	39.1	39.93	40.31	42.84	44.1	44.54	42.28	42.16	43.93	49.53	42.5	46.45	47.4	37.75	37.67
BNL	27.23	43.19	42.35	33.94	17.82	34.83	36.99	32.27	35.43	41.63	43.1	40.4	35.78	41.24	15.47	35.82	38.47	32.65	33.68	34.29	34.3	35.48	35.78	34.38	34.53	35.35	43.06	48.73	42.27	41.46	36.84	32.39
FCD	28.42	45.71	47.34	32.72	15.05	34.38	37.47	34.23	34.02	43.88	43.88	42.14	36.19	37.62	15.42	39.28	30.58	31.7	32.18	32.31	35.6	36.45	36.24	34.68	34.45	35.12	45.58	42.1	48.48	43.21	28.46	31.15
ESD	34.14	49.06	44.77	41.3	17.09	40.41	41.53	36.45	40.84	47.2	46.71	45.26	45.37	46.42	16.22	39.74	39.81	39.56	40.58	41.06	43.52	44.9	45.46	42.6	42.62	45.21	47.44	40.27	43.73	47.16	38.6	37.67
MNS	26.42	40.64	30.57	37.14	16.59	33.22	34.7	28.55	35.73	36.9	38.22	33.94	38.7	45.16	14.09	29.17	52.44	34.37	35.99	37.17	35.08	36.92	38.19	36.58	37.06	39.19	36.01	31.33	28.05	36.08	60.89	33.38
TJN	35.25	45.93	36.68	43.84	19.86	41.56	40.83	36.19	40.98	42.97	42.3	41.2	45.96	47.91	17.04	36.41	42.71	40.34	41.66	42.41	43.24	44.83	45.93	42.8	43.03	46.54	41.85	34.28	34.45	42.08	42.29	42.6

Note: This table provides the variance decomposition matrix with maximal entries in the spillover tables for volatility measure based on univariate GARCH. The number of each crude corresponds to number in Table A.1. For example, gWTI represents Wednesday return of WTI; gBRT represents Wednesday return of Brent,etc.

Table A.14: Estimation of individual return spillover with MG, CCEMG and AMG estimators

	MG		CCEMG		AMG	
	Coef.	P¿—z—	Coef.	P¿—z—	Coef.	P¿—z—
ES	0.270	0.807	10.597	0.453	-0.223	0.823
IS	-0.077	0.930	3.139	0.636	0.042	0.971
NI	0.024	0.726	-0.598	0.557	-0.029	0.645
RS	1.125	0.331	39.953	0.216	0.139	0.933
CS	4.111	0.727	40.809	0.833	16.710	0.078
PS	-0.611	0.364	-0.331	0.417	-0.629	0.227
GR	0.032	0.513	-1.193	0.119	0.024	0.578
OG	-0.745	0.008	2.145	0.697	-0.564	0.066
EX	-0.009	0.260	-0.005	0.557	-0.008	0.168
V	-0.446	0.262	4.232	0.432	0.576	0.704
Intercept	-0.224	0.259	-5.817	0.628	-0.263	0.228
TREND	0.000	0.319	-0.027	0.227	0.000	0.704
VIX	0.000	0.964			0.000	0.911
GOLD	0.005	0.625			-0.005	0.651
OPECSC	0.001	0.516			0.001	0.445
OECDS	0.020	0.268			0.007	0.714
cross section averaged regressor						
average return spillover			991317.500	0.095		
average ES			49.659	0.268		
average IS			-29.053	0.274		
average NI			2.365	0.493		
average RS			38.054	0.61		
average CS			458.356	0.238		
average PS			-0.928	0.251		
average GR			-0.291	0.918		
average OG			-3.389	0.84		
average EX			-0.010	0.471		
average V			-4.467	0.385		
common dynamic process					0.711	0.681

Note: This table presents the estimation results for individual return spillover with MG, CCEMG and AMG estimators. Global risk factors, i.e. VIX, GOLD, OPECSC and OECDS are not included in the equation for CCEMG estimator because the common factors are constructed with average dependent and independent variables. Intercept and trend are included in all estimations.

TABLE A.15: Estimation of individual volatility spillover with MG, CCEMG and AMG estimators

	MG		CCEMG		AMG	
	Coef.	P¿—z—	Coef.	P¿—z—	Coef.	P¿—z—
ES	4.115	0.016	-3.902	0.901	2.695	0.214
IS	1.110	0.672	-0.217	0.986	1.806	0.441
NI	-0.078	0.596	-1.324	0.356	0.034	0.818
RS	2.292	0.595	-32.929	0.315	-0.141	0.968
CS	2.586	0.856	-124.756	0.494	15.271	0.229
PS	-0.825	0.484	-0.029	0.966	0.091	0.908
GR	-0.143	0.077	-1.060	0.183	-0.099	0.331
OG	0.291	0.443	-13.216	0.572	-0.028	0.949
EX	-0.013	0.214	-0.007	0.616	-0.006	0.625
V	-0.192	0.772	30.179	0.000	2.381	0.757
Intercept	-0.922	0.002	1.817	0.741	-0.708	0.038
Trend	0.000	0.763	0.015	0.496	-0.001	0.549
VIX	-0.002	0.413			-0.002	0.724
GOLD	0.015	0.395			0.006	0.715
OPECSC	-0.001	0.361			0.000	0.865
OECDS	0.053	0.096			0.027	0.379
cross section averaged regressor						
average volatility spillover			202927.700	0.822		
average ES			-53.025	0.160		
average IS			38.867	0.255		
average NI			-3.576	0.568		
average RS			136.332	0.318		
average CS			-293.462	0.525		
average PS			-0.102	0.940		
average GR			4.187	0.082		
average OG			9.790	0.540		
average EX			-0.033	0.310		
average V			-28.457	0.000		
common dynamic process					0.278	0.866

Note: This table presents the estimation results for individual volatility spillover with MG, CCEMG and AMG estimators. Global risk factors, i.e. VIX, GOLD, OPECSC and OECDS are not included in the equation for CCEMG estimator because the common factors are constructed with average dependent and independent variables. Intercept and trend are included in all estimations.

Appendix B

Figures

FIGURE B.1: Wednesday return of crude oil series

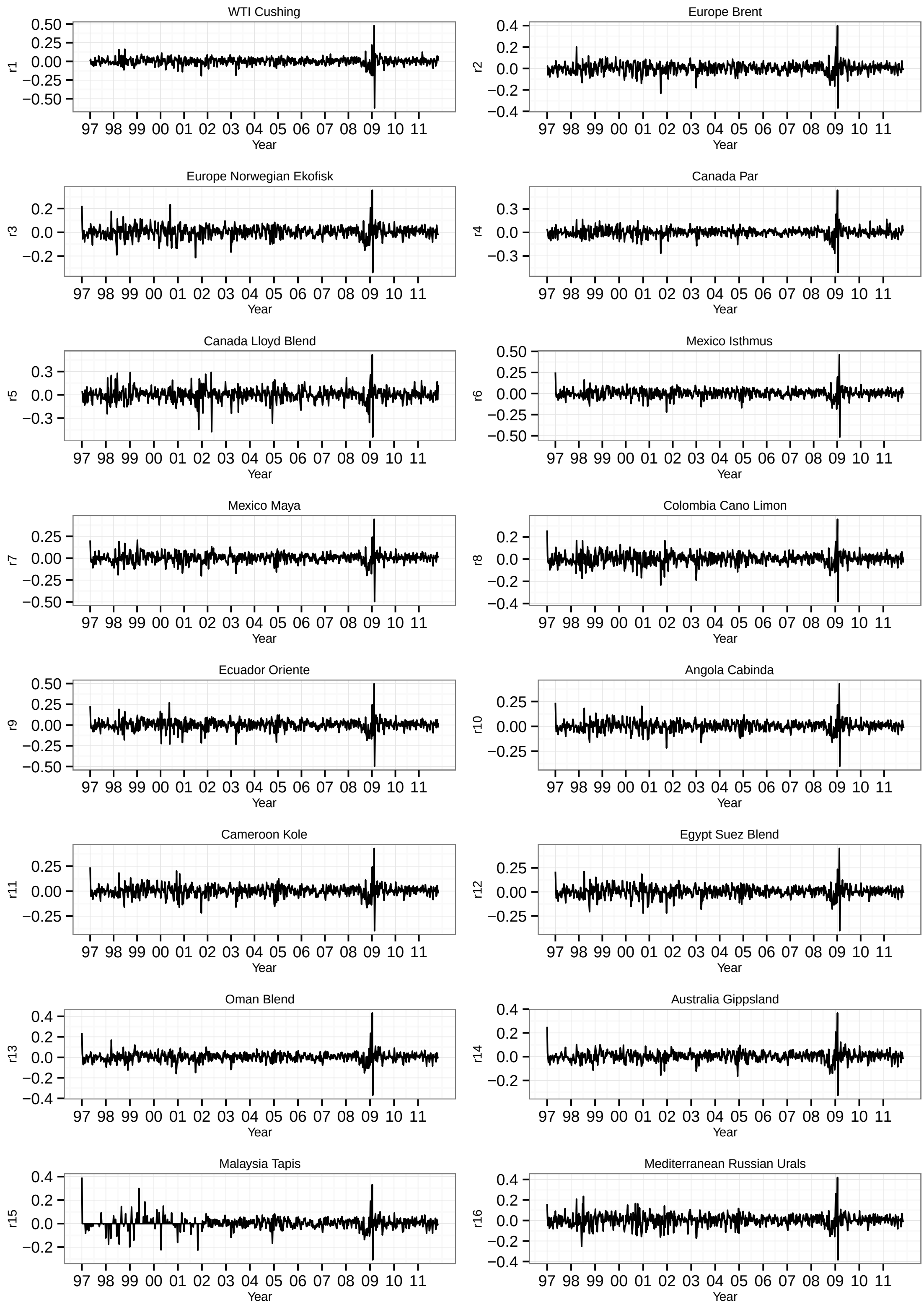


Figure B.1 (cont.): Wednesday return of crude oil series(Cont.)

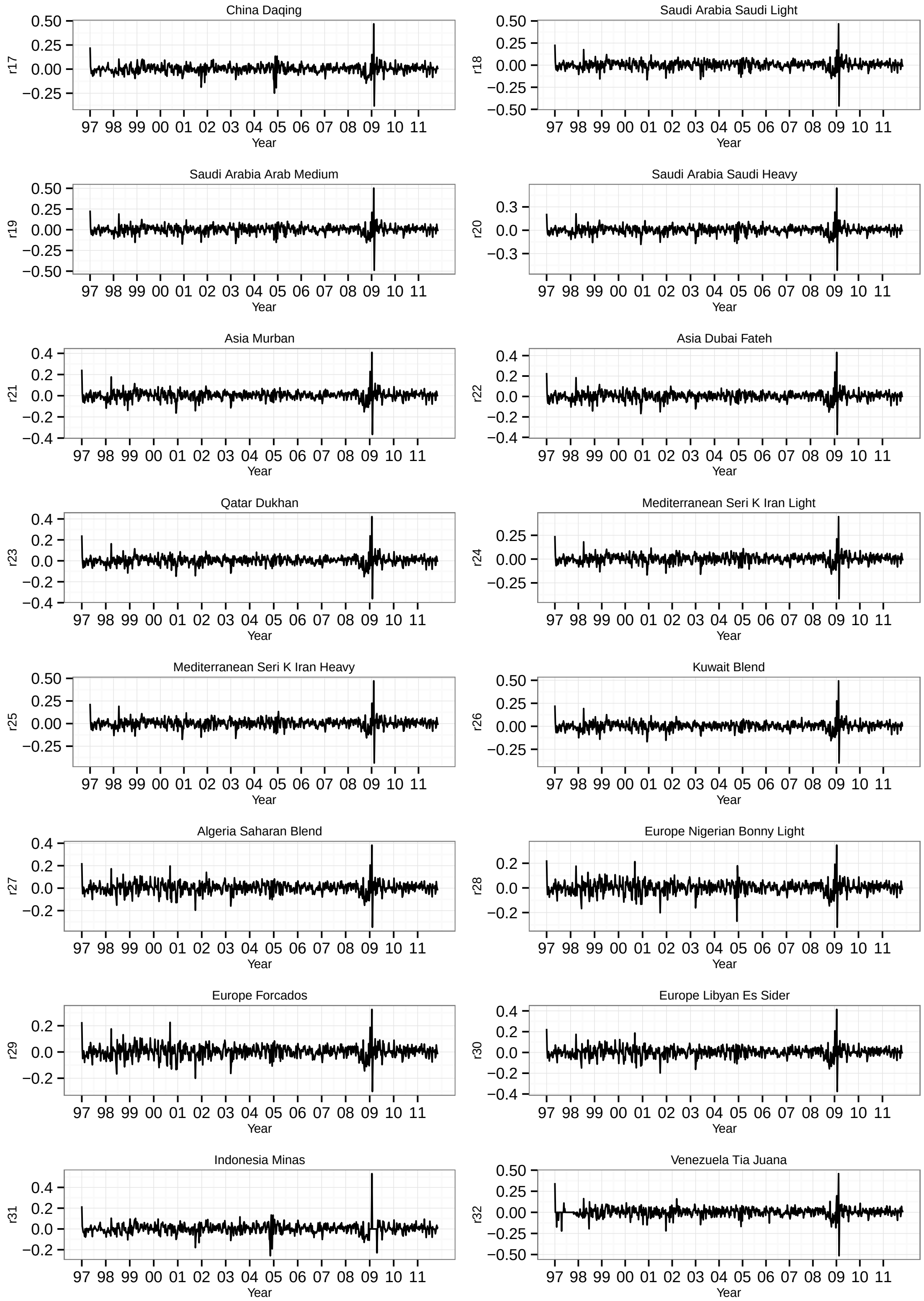


Figure B.2: Volatility of crude oil series

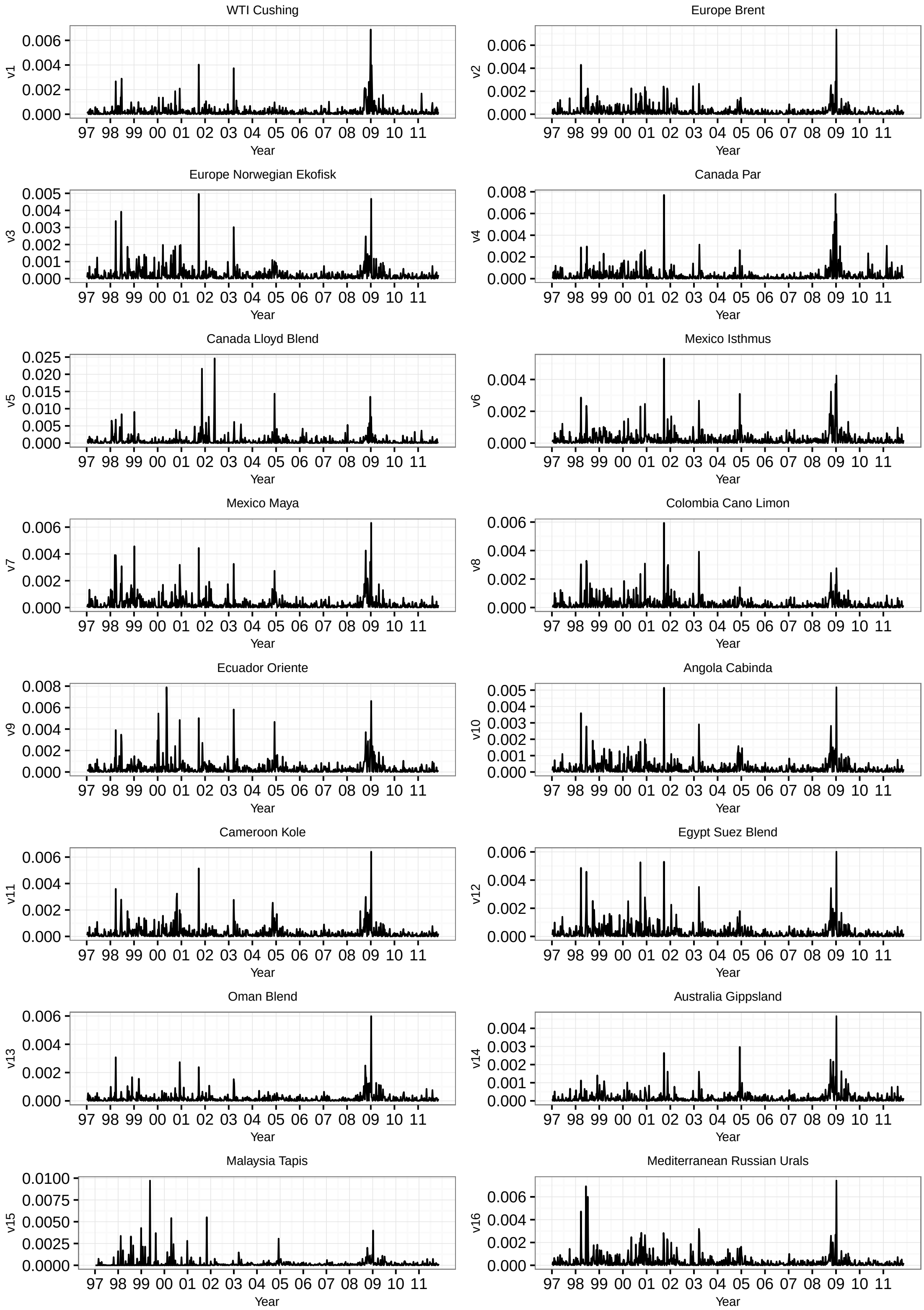


Figure B.2 (cont.): Volatility of crude oil series(Cont.)

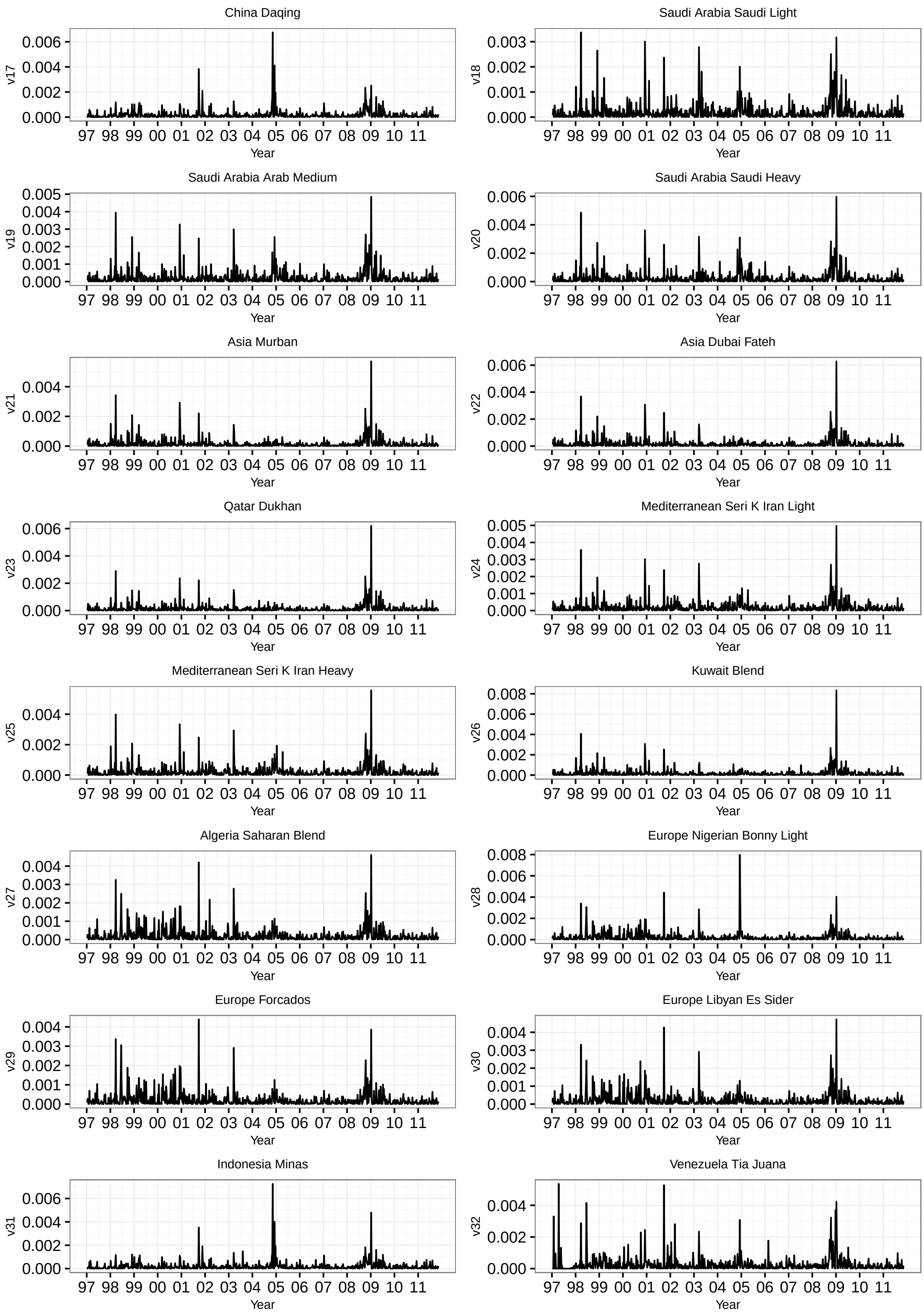


FIGURE B.3: Price of crude oil series

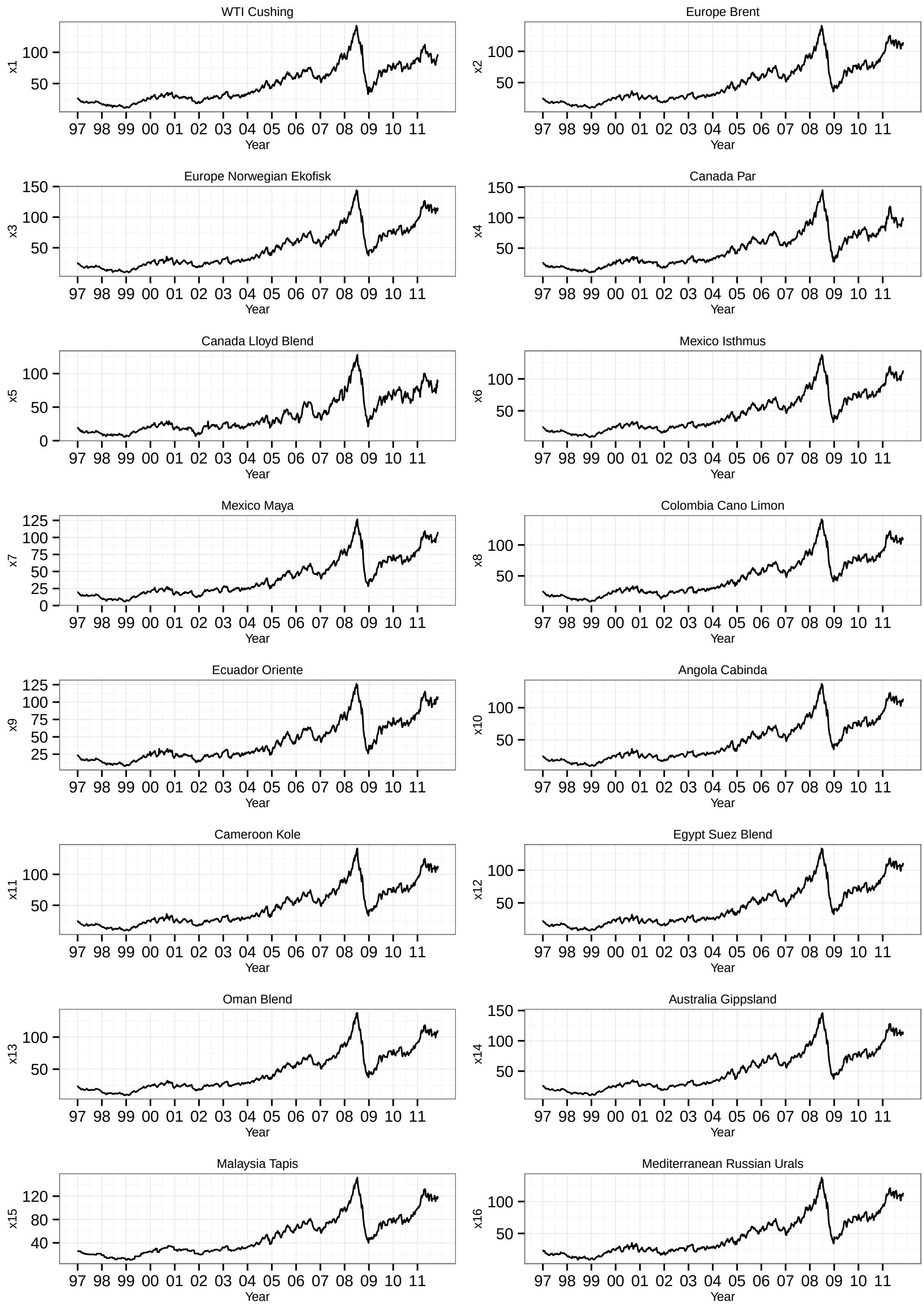


FIGURE B.3 (cont.): Price of crude oil series(Cont.)

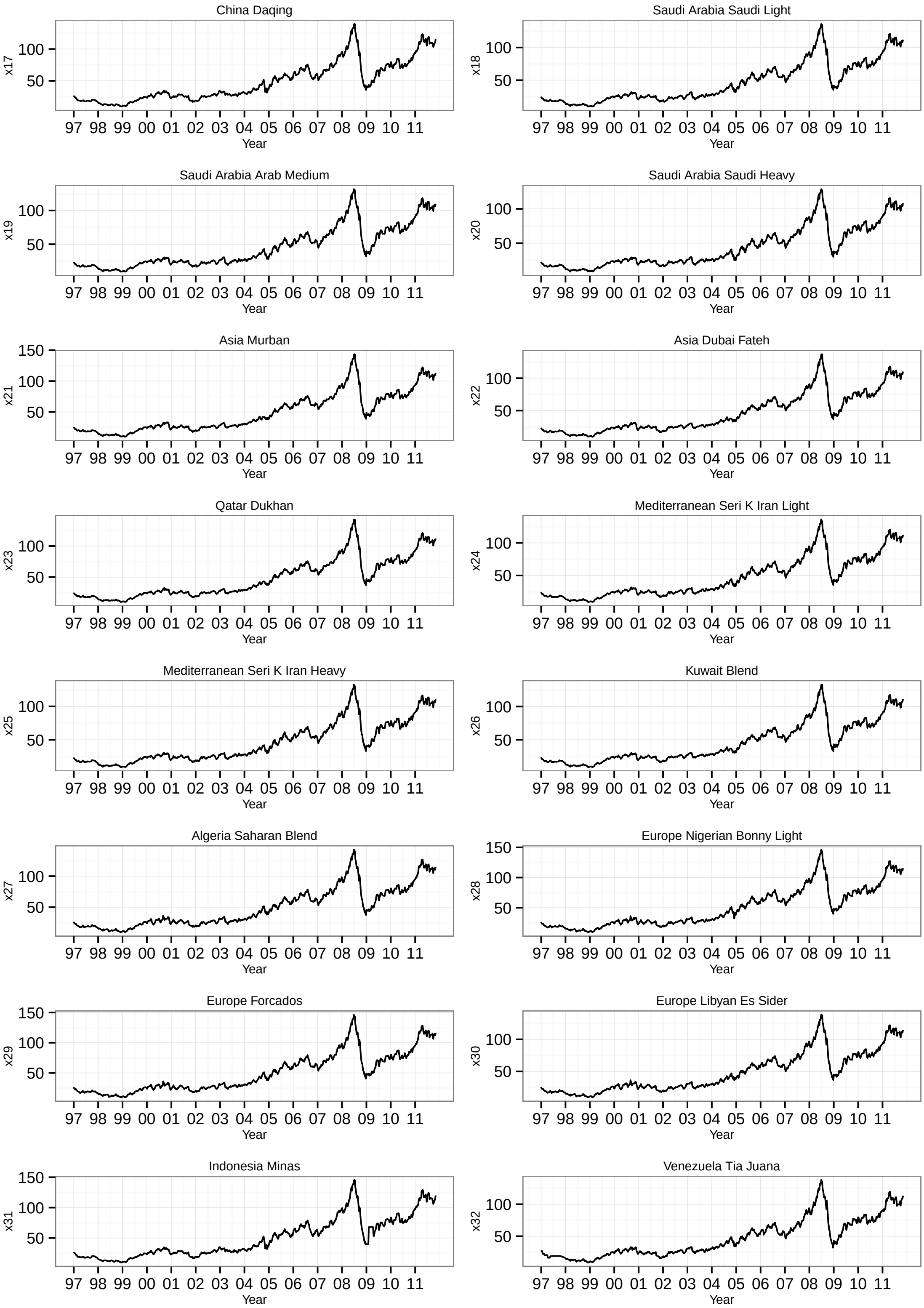
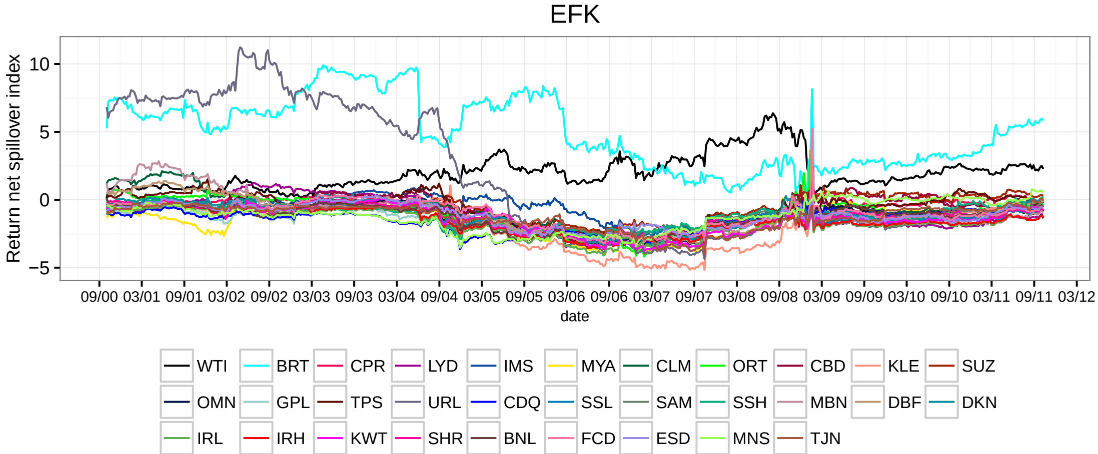
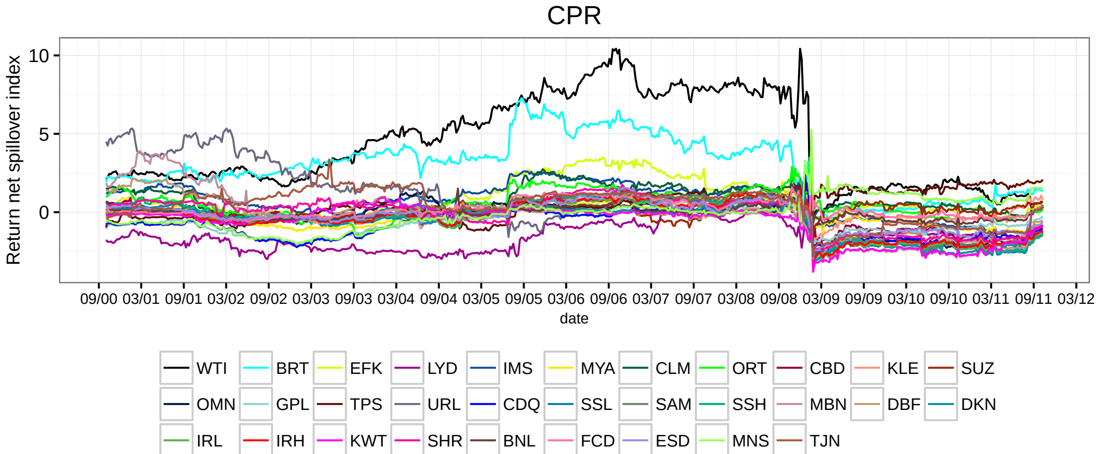


FIGURE B.4: Pairwise net return spillover: the rest crudes





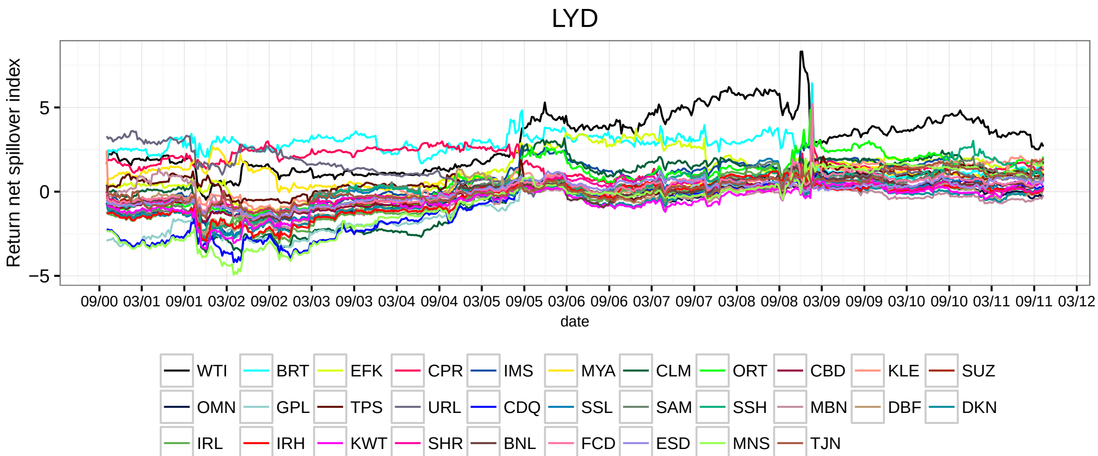
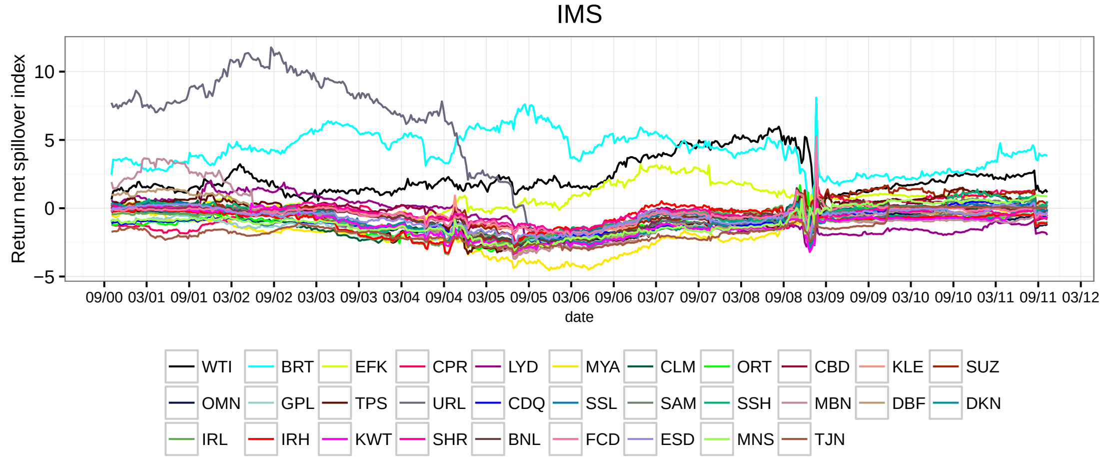
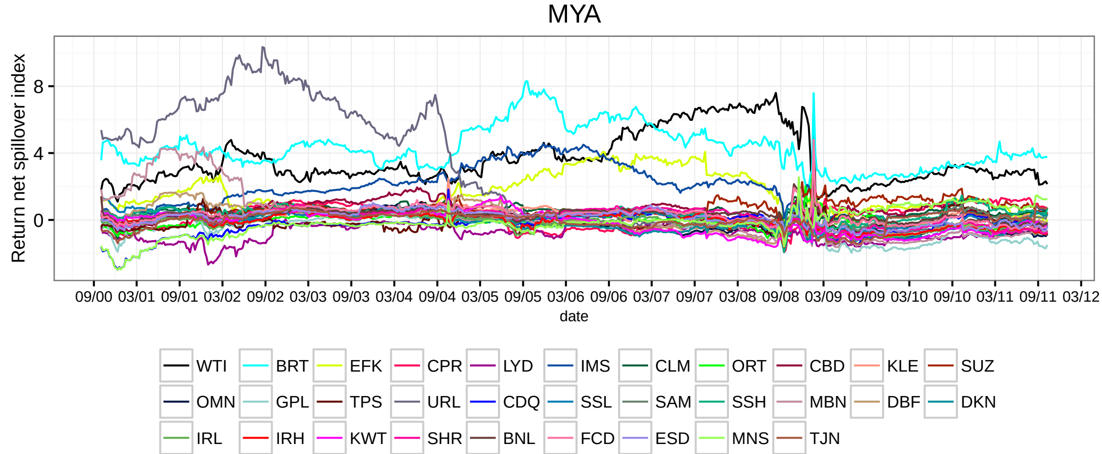


FIGURE B.4 (cont.): Pairwise net return spillover: the rest crudes(Cont.)





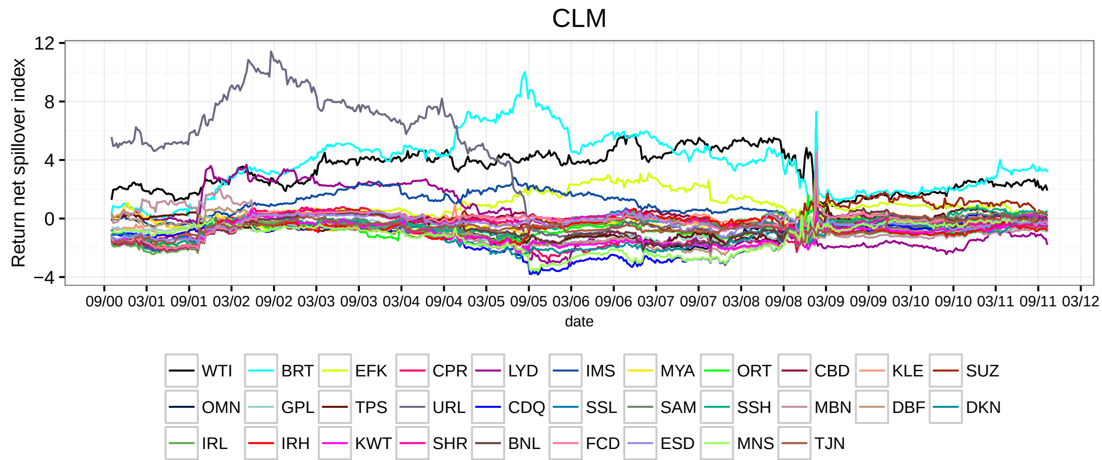
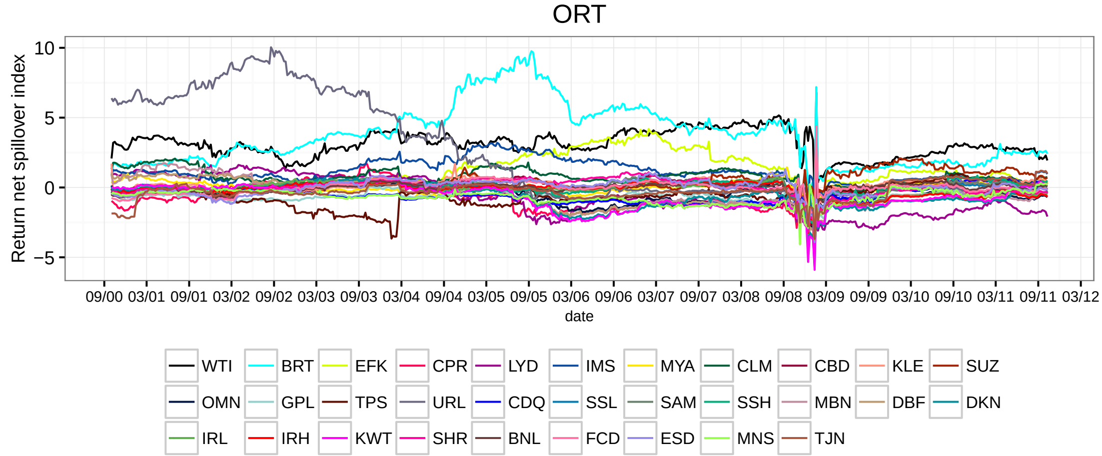
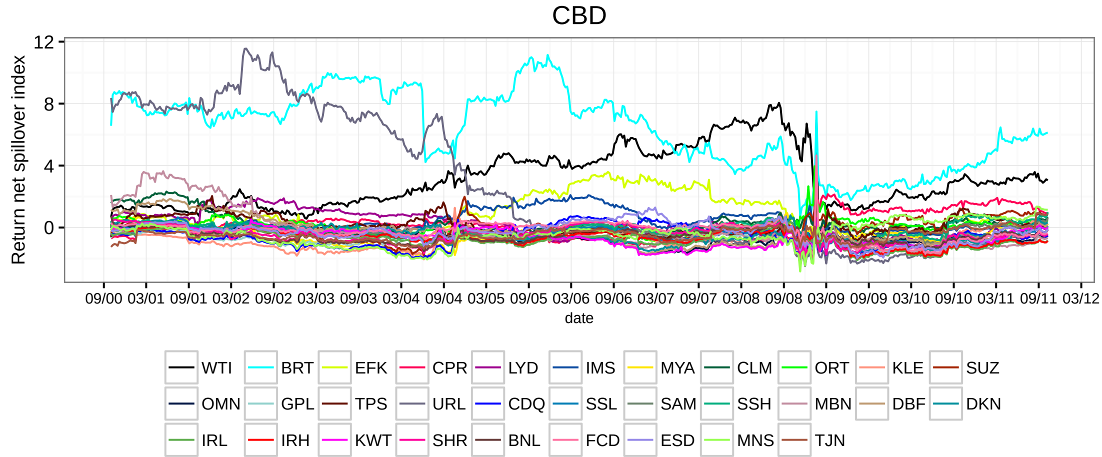


FIGURE B.4 (cont.): Pairwise net return spillover: the rest crudes(Cont.)





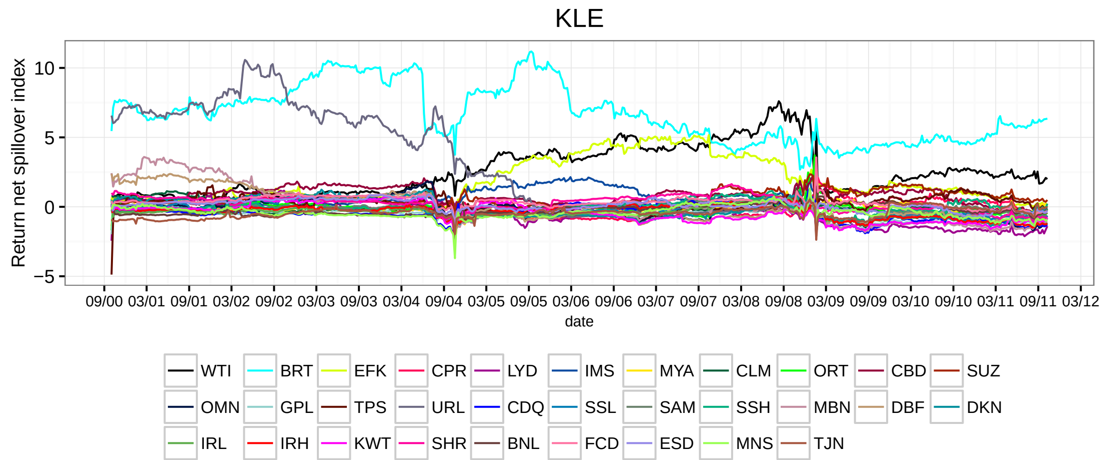
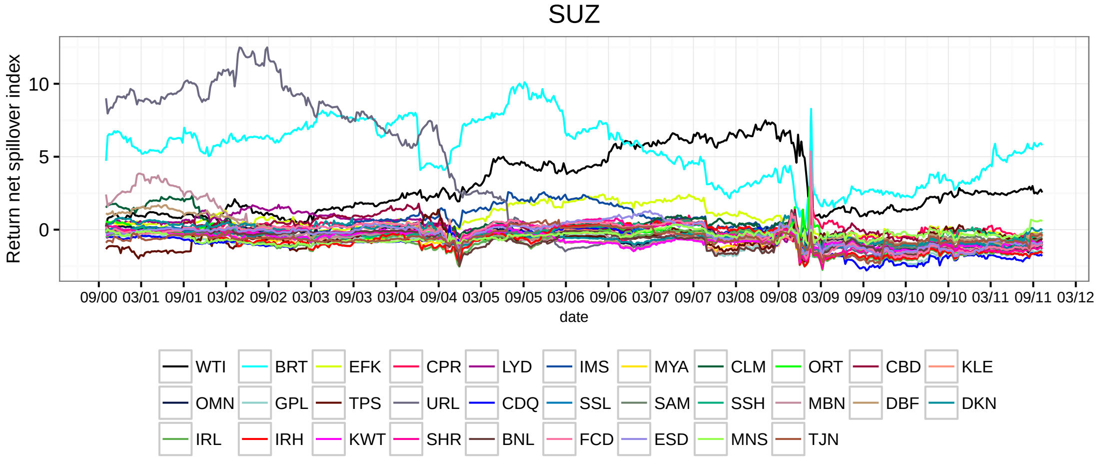
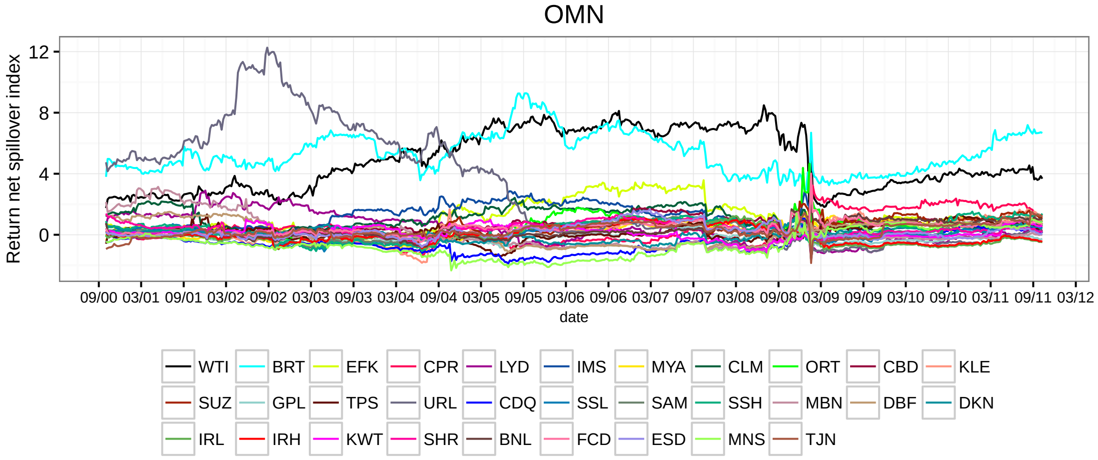


FIGURE B.4 (cont.): Pairwise net return spillover: the rest crudes(Cont.)





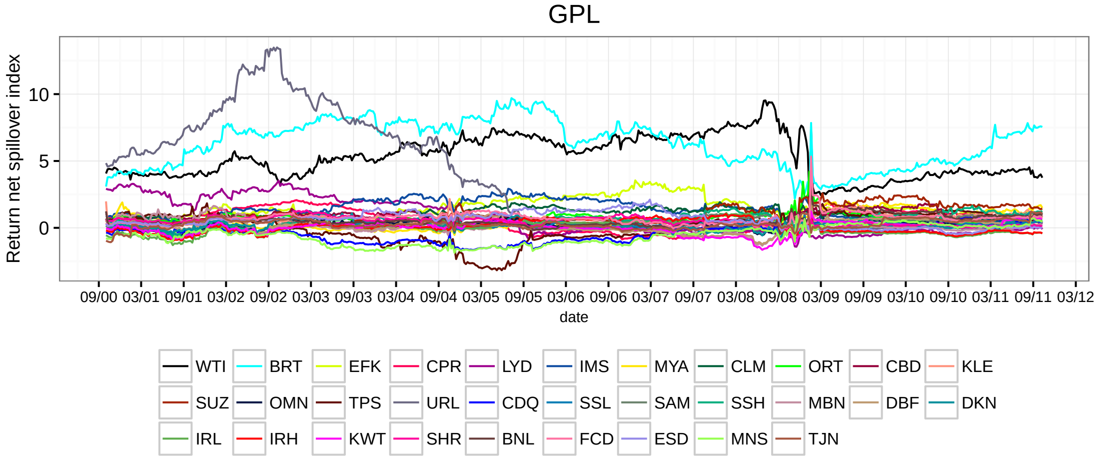
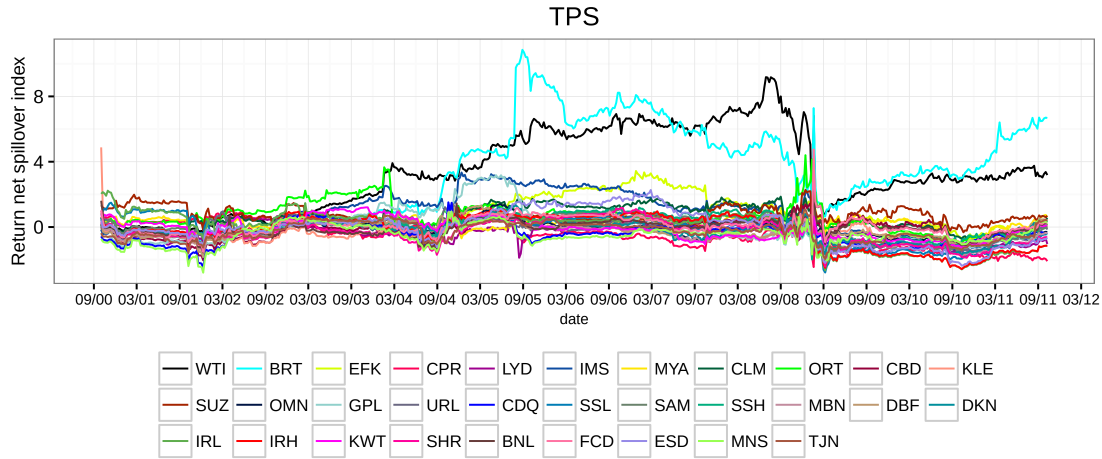
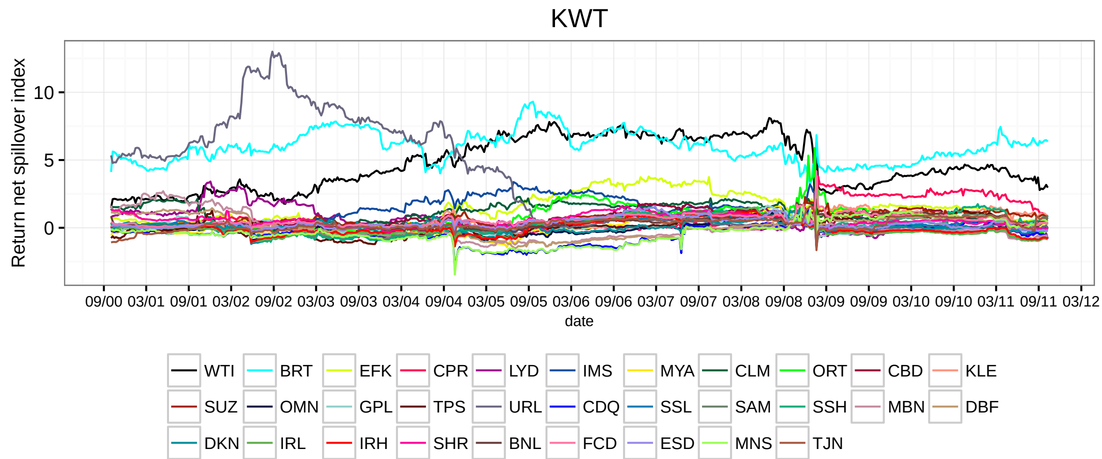


FIGURE B.4 (cont.): Pairwise net return spillover: the rest crudes(Cont.)





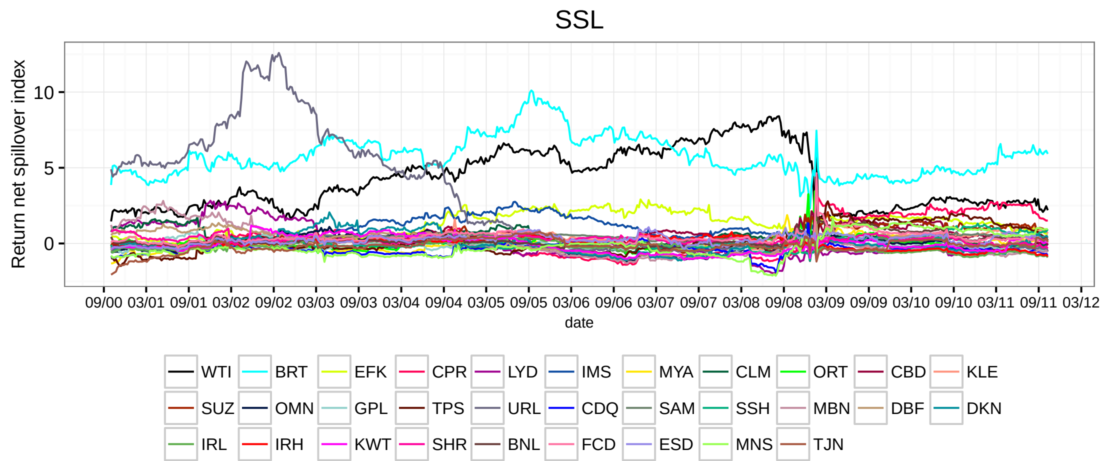


FIGURE B.4 (cont.): Pairwise net return spillover: the rest crudes(Cont.)

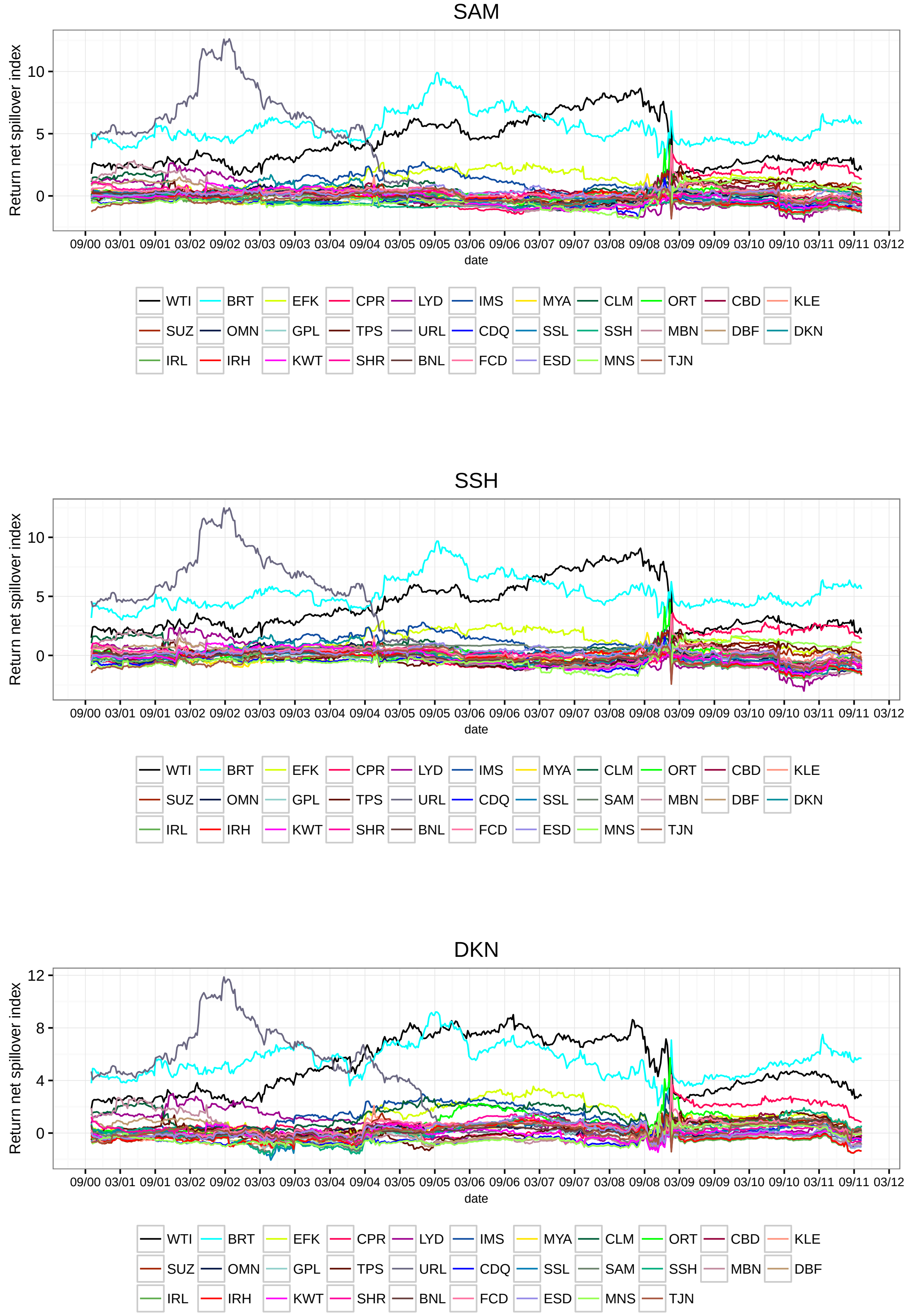


FIGURE B.4 (cont.): Pairwise net return spillover: the rest crudes(Cont.)

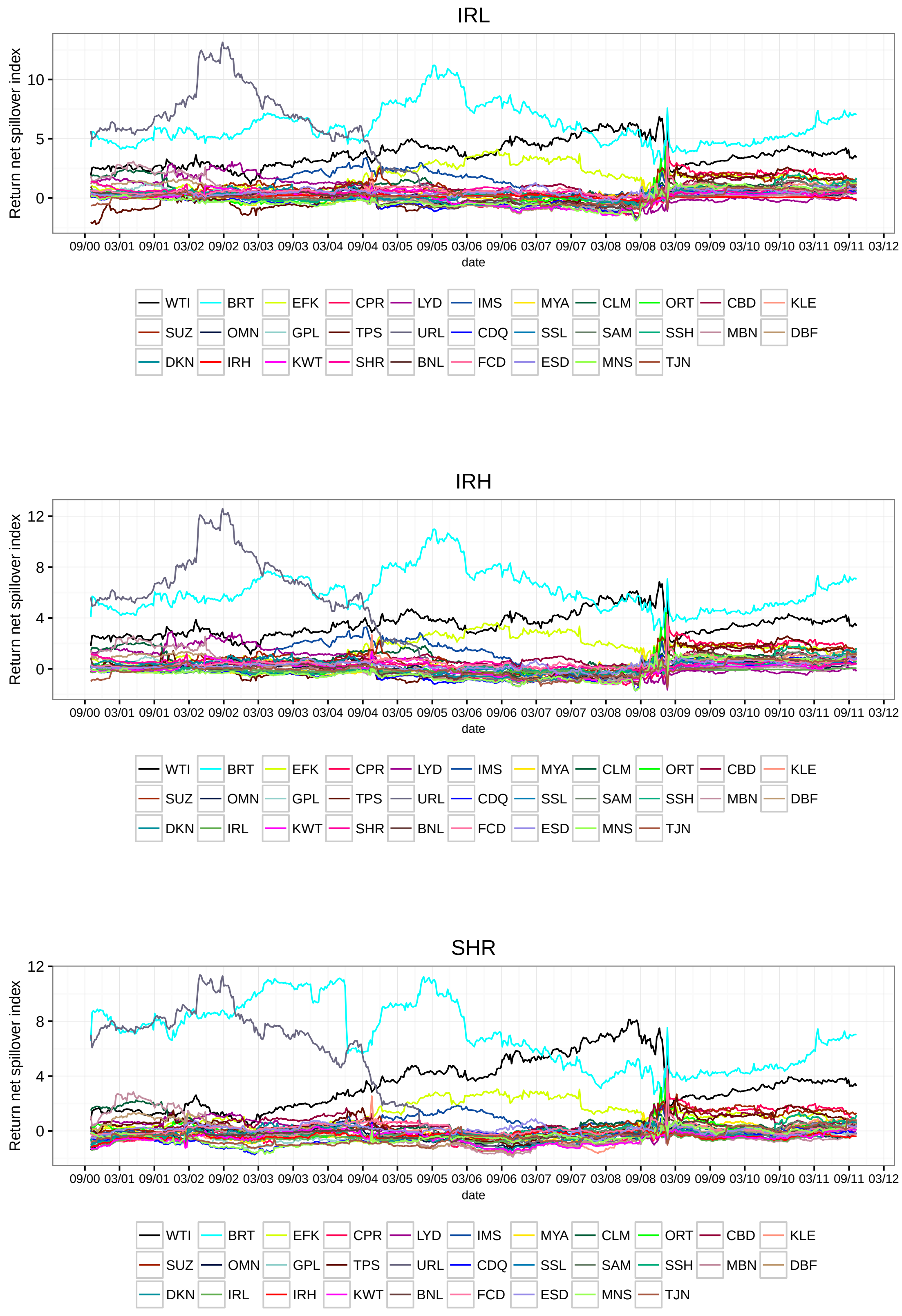
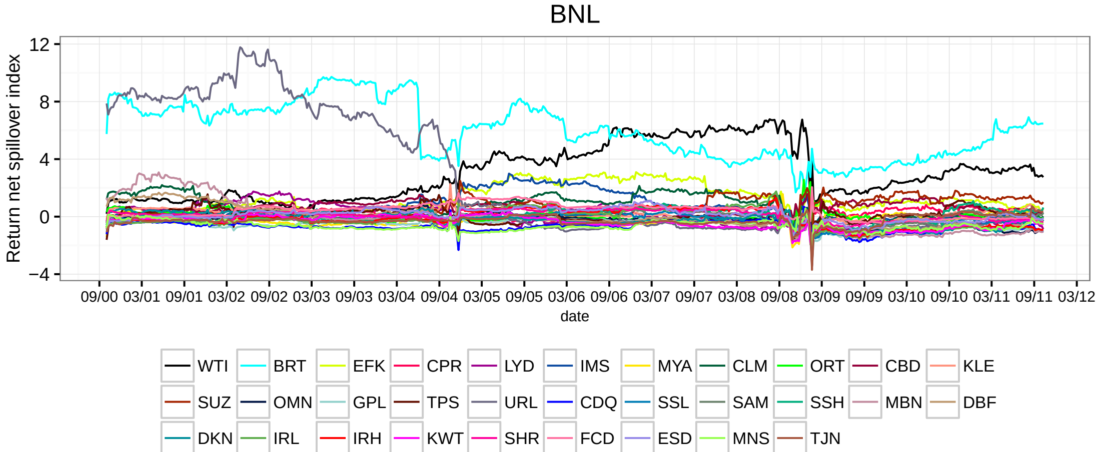
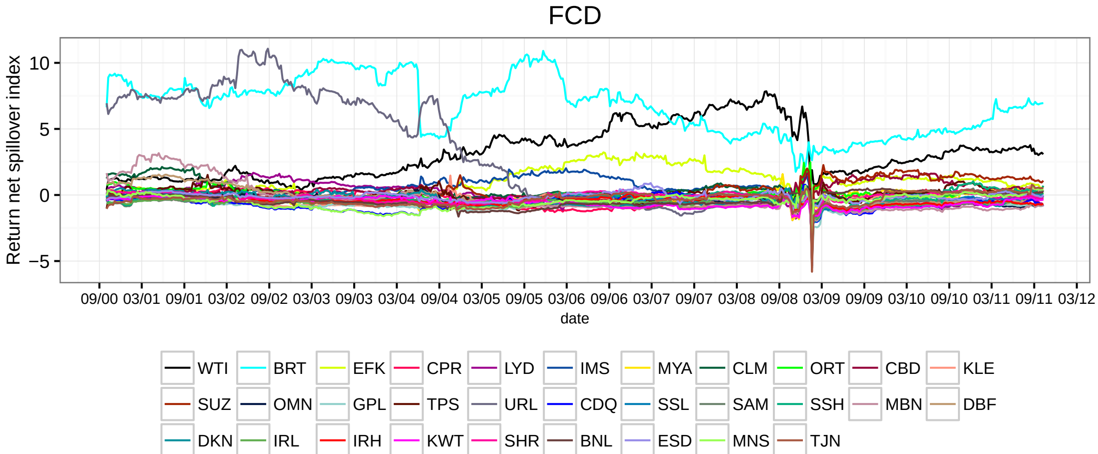


FIGURE B.4 (cont.): Pairwise net return spillover: the rest crudes(Cont.)





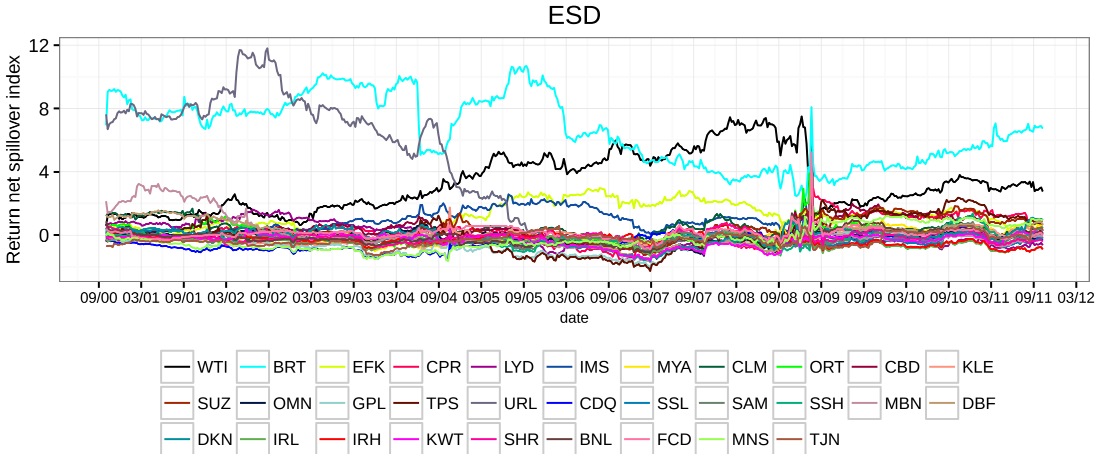
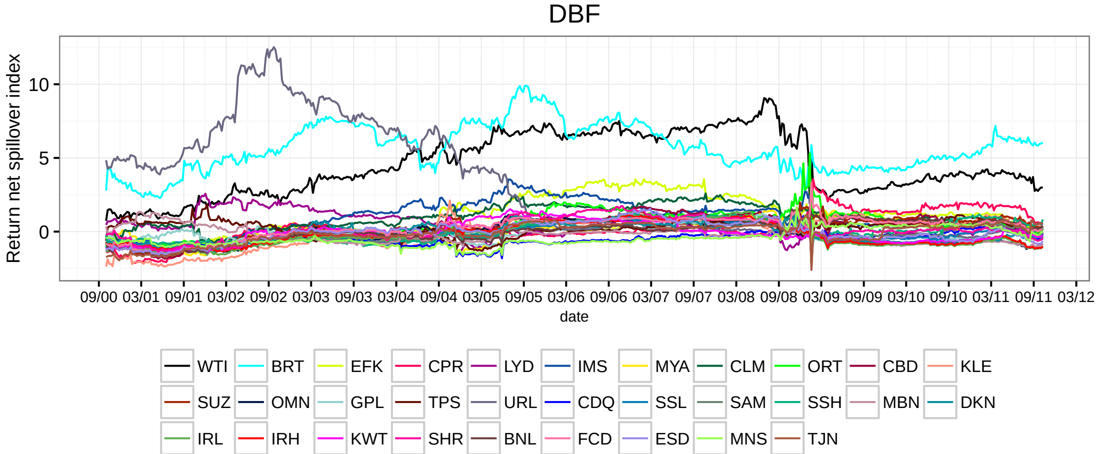
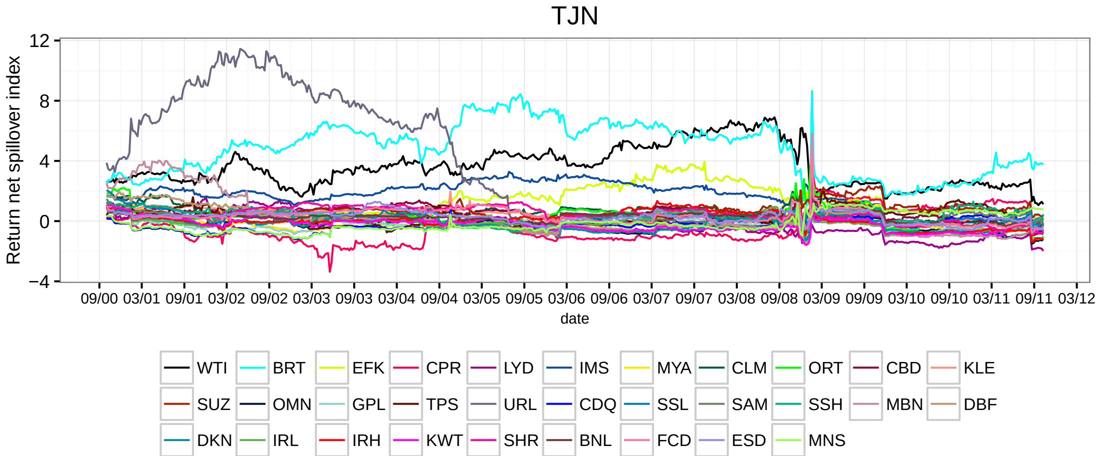


FIGURE B.4 (cont.): Pairwise net return spillover: the rest crudes(Cont.)





Notes: This picture shows the pairwise net return spillover of the rest crudes in sample except WTI, Brent(BRT), Dubai Fateh(DBF), Russian Urals(URL) and Kuwait Blend(KWT), whose plots are in Figure 4.5. If the line stay above zero, it means the crude represented by the color of the line transmits shocks to the crude investigated, and vice versa.

FIGURE B.5: Pairwise net volatility spillover: the rest crudes

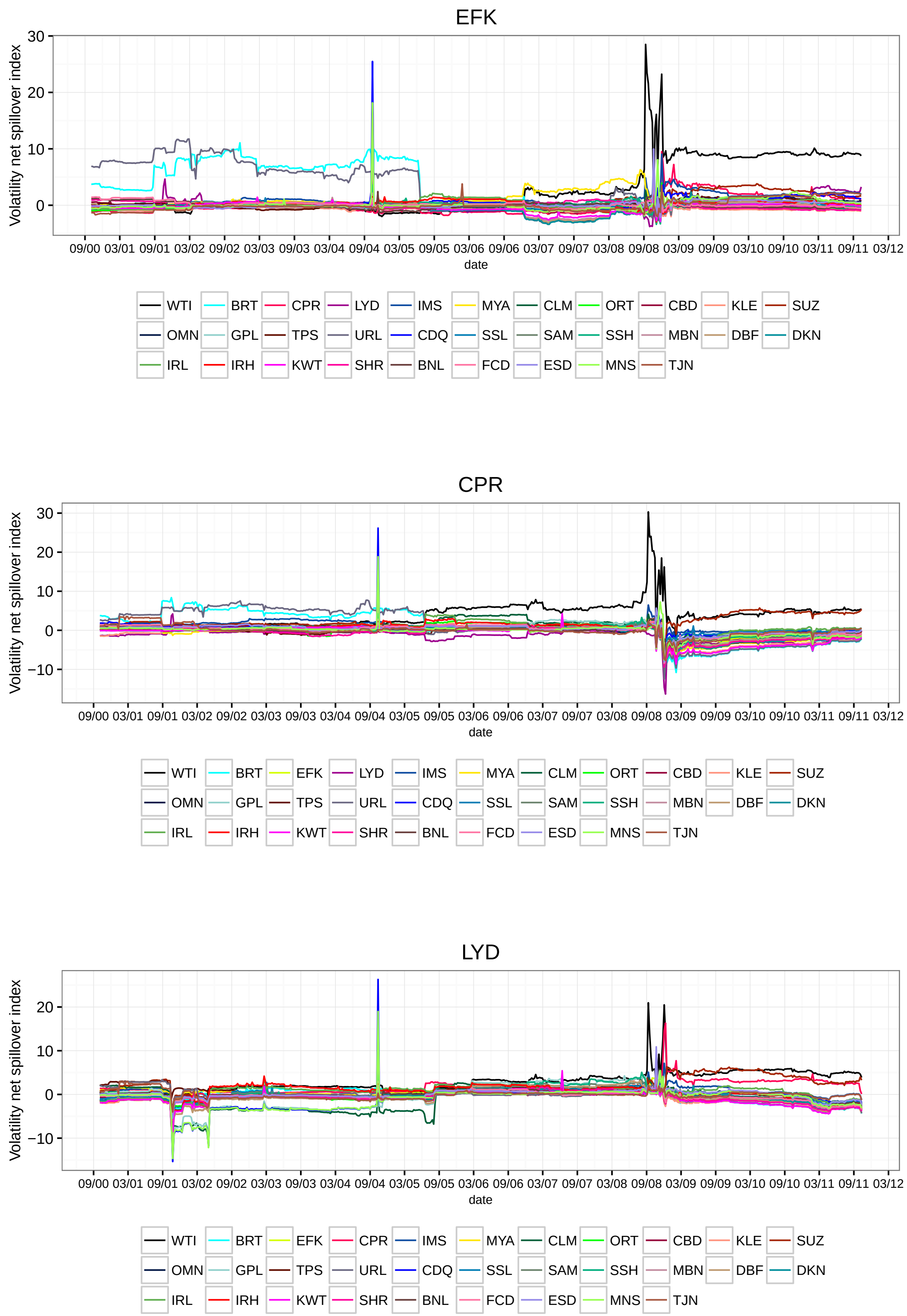
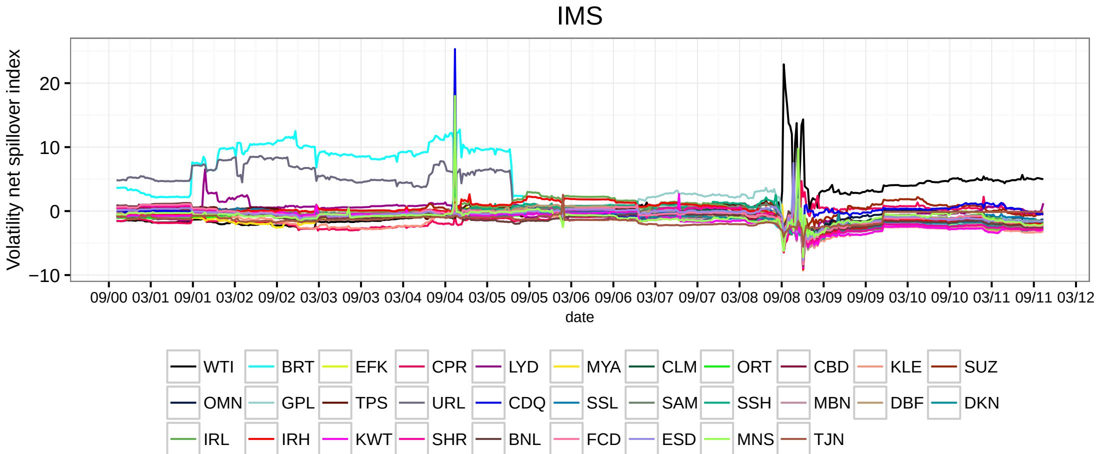
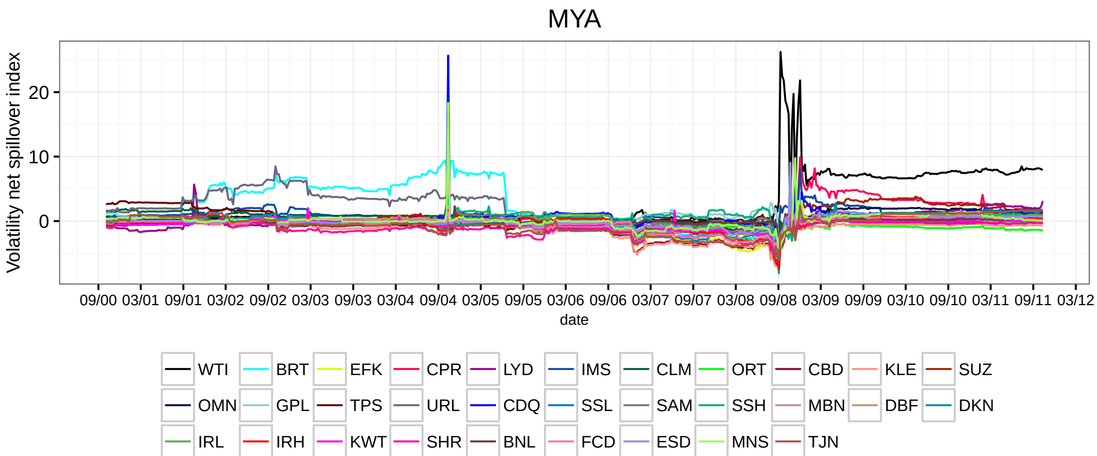


FIGURE B.5 (cont.): Pairwise net volatility spillover: the rest crudes(Cont.)





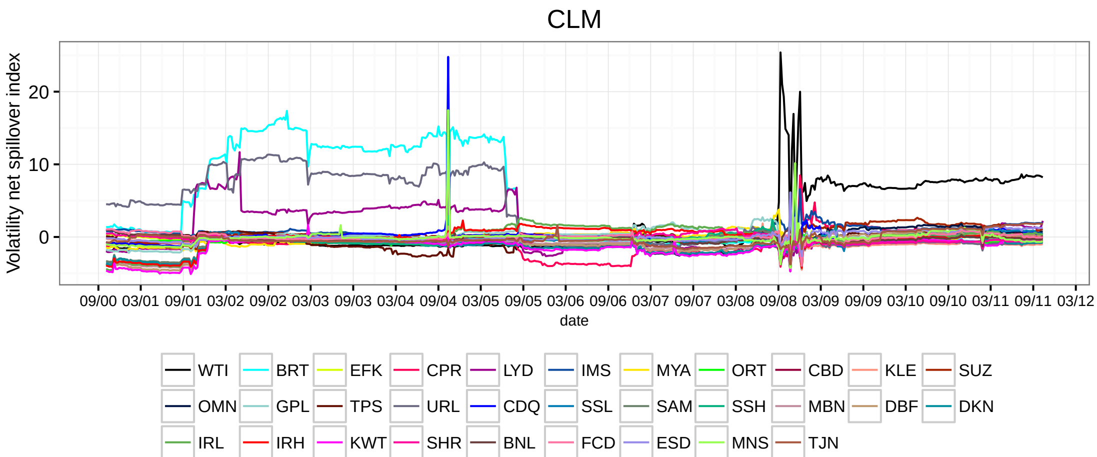
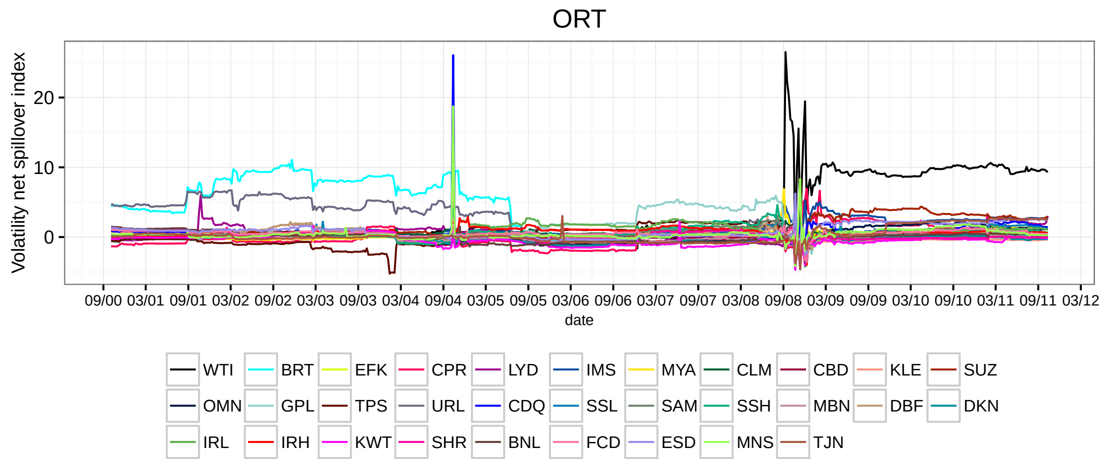
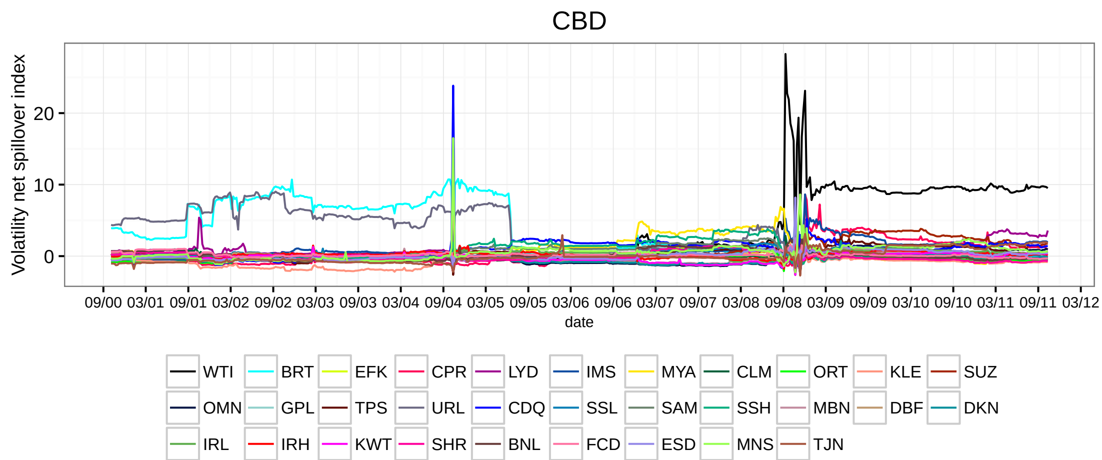


FIGURE B.5 (cont.): Pairwise net volatility spillover: the rest crudes(Cont.)





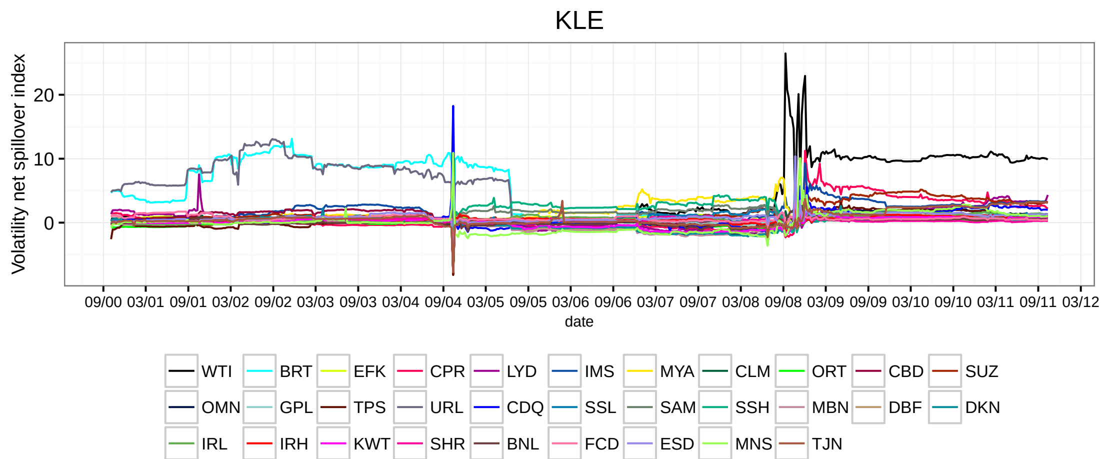
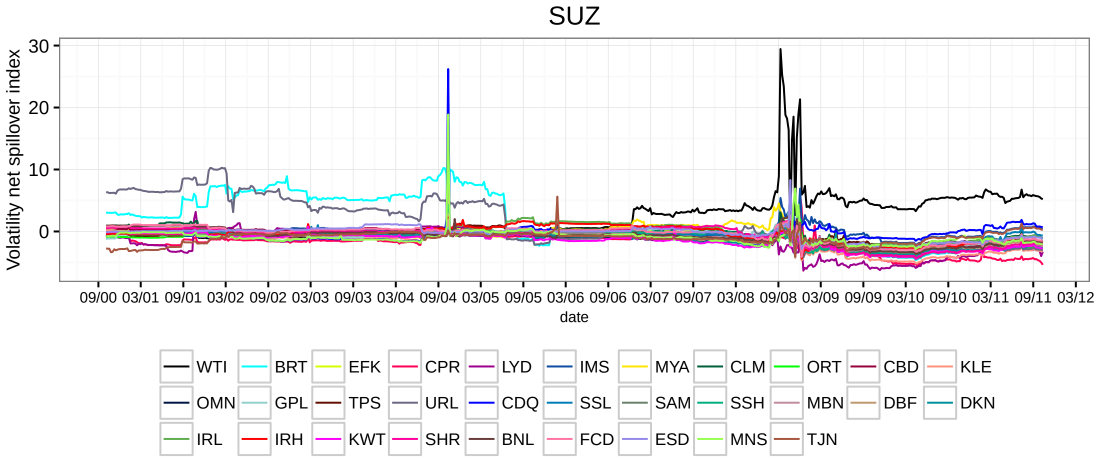
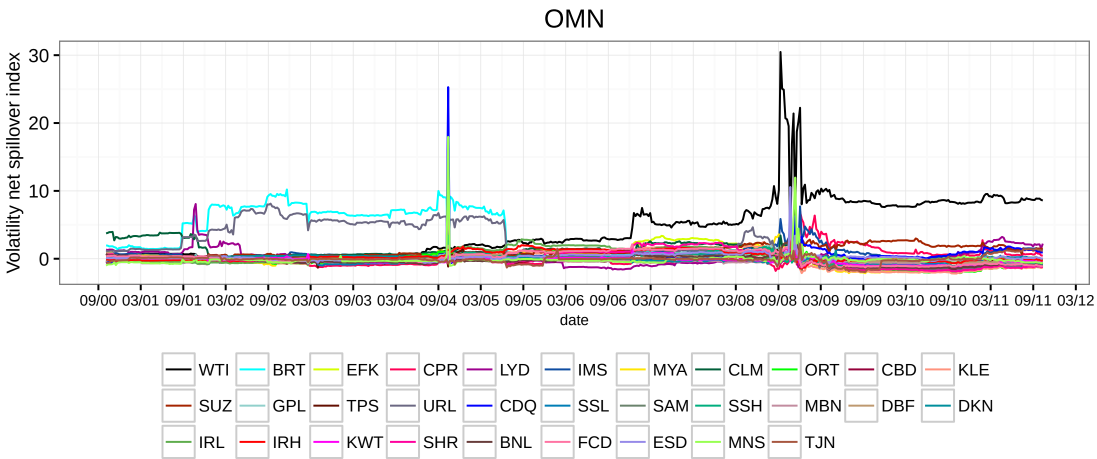


FIGURE B.5 (cont.): Pairwise net volatility spillover: the rest crudes(Cont.)





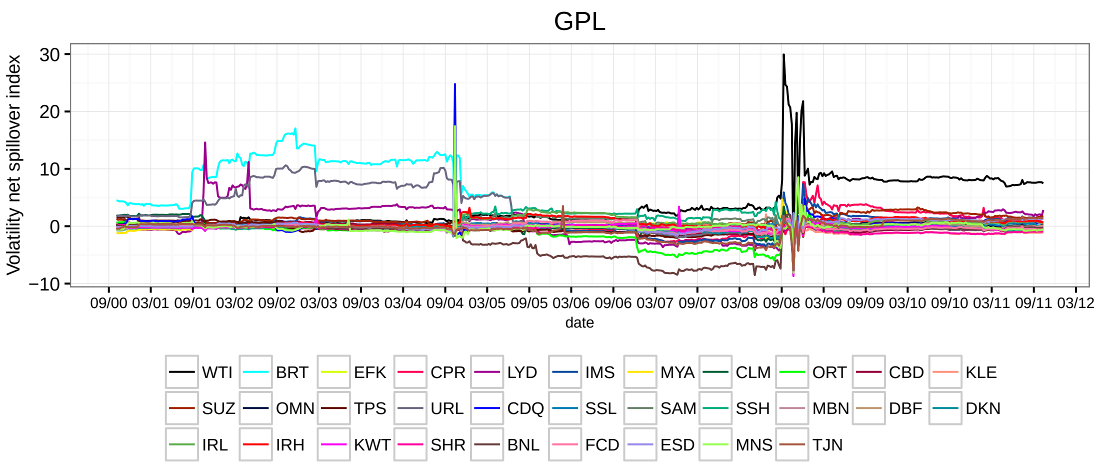


FIGURE B.5 (cont.): Pairwise net volatility spillover: the rest crudes(Cont.)

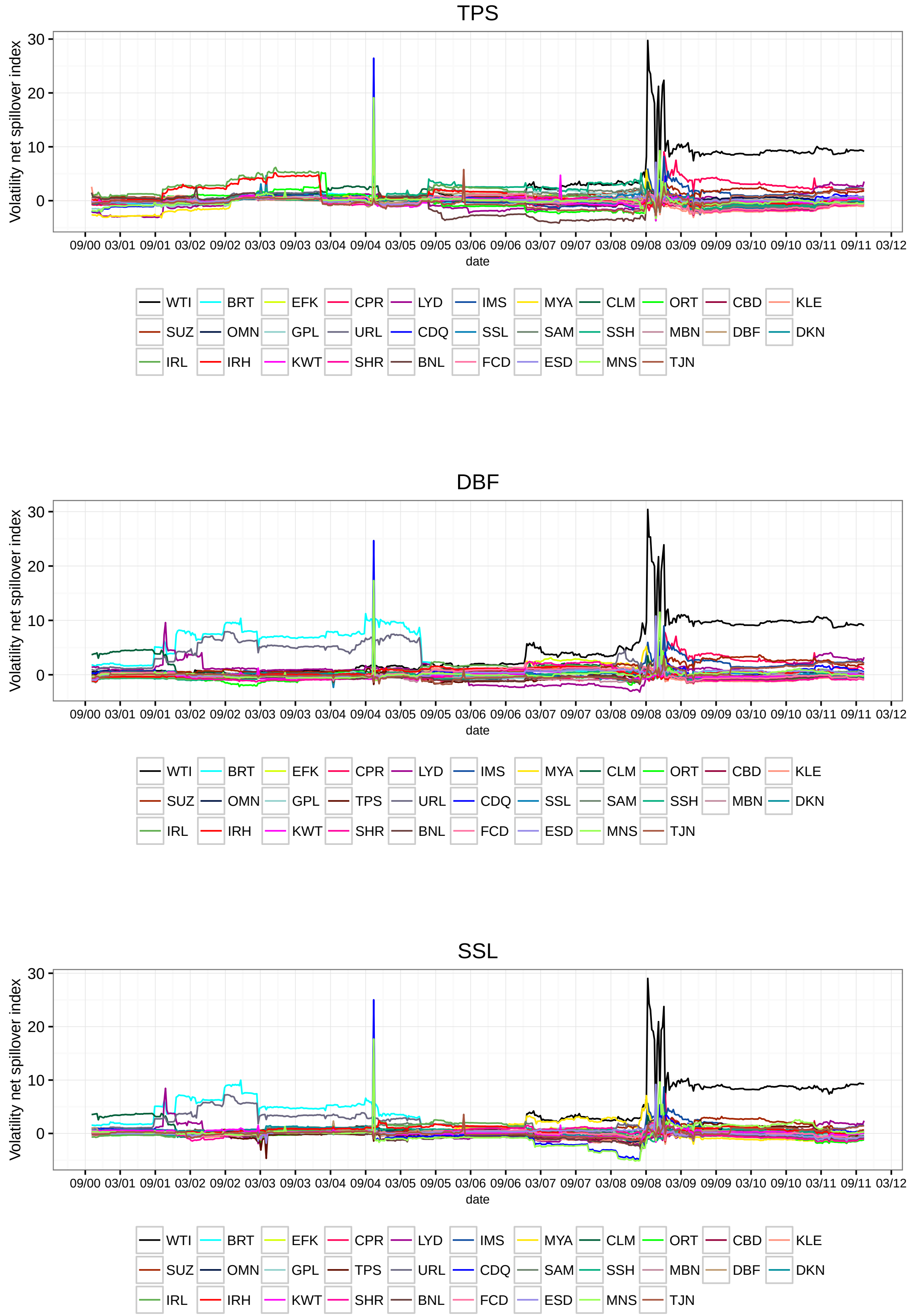
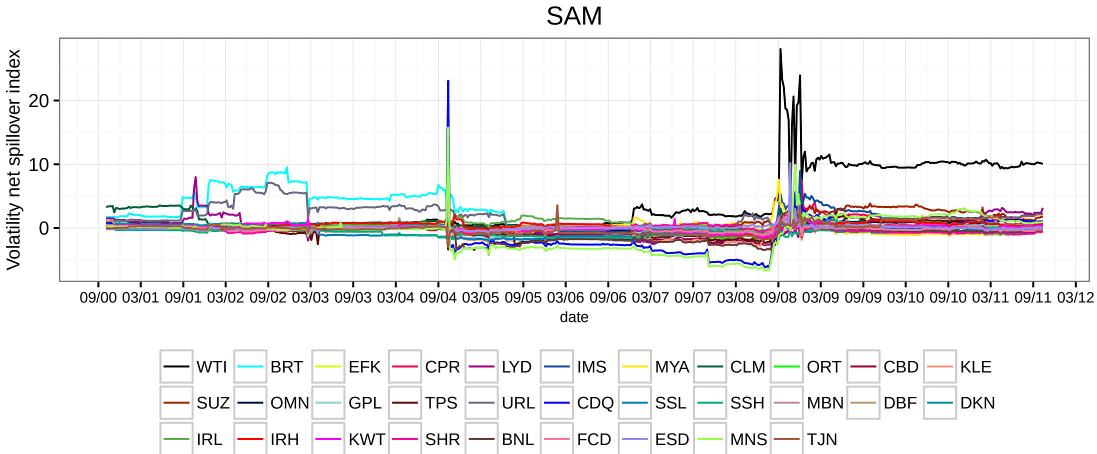
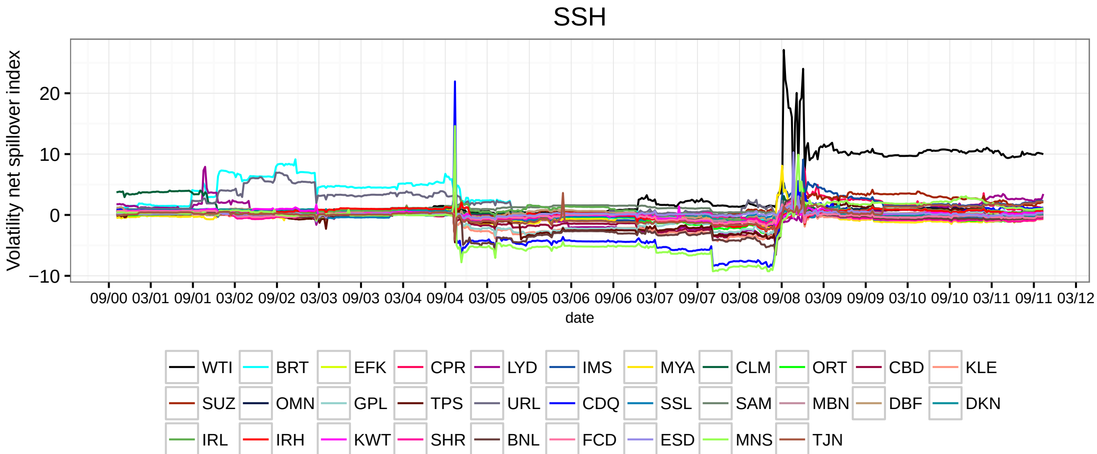


FIGURE B.5 (cont.): Pairwise net volatility spillover: the rest crudes(Cont.)





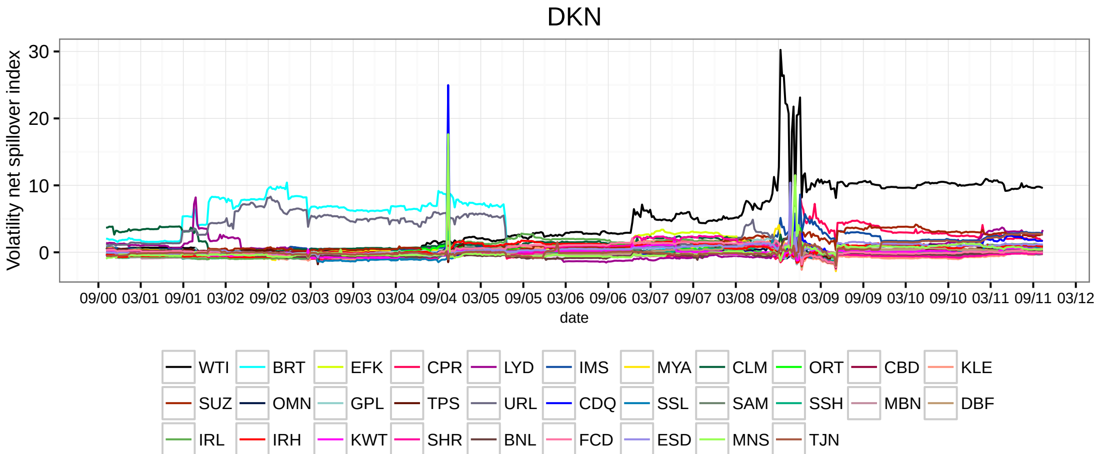
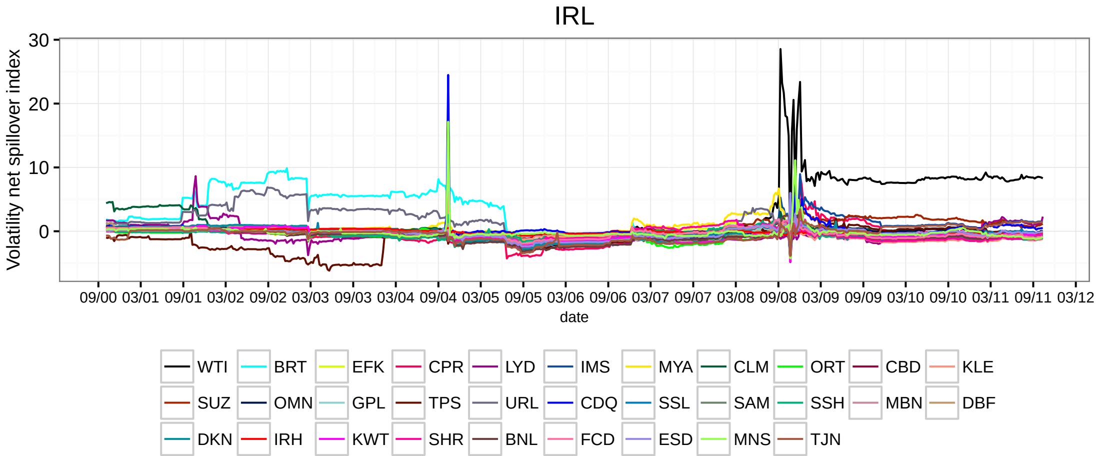
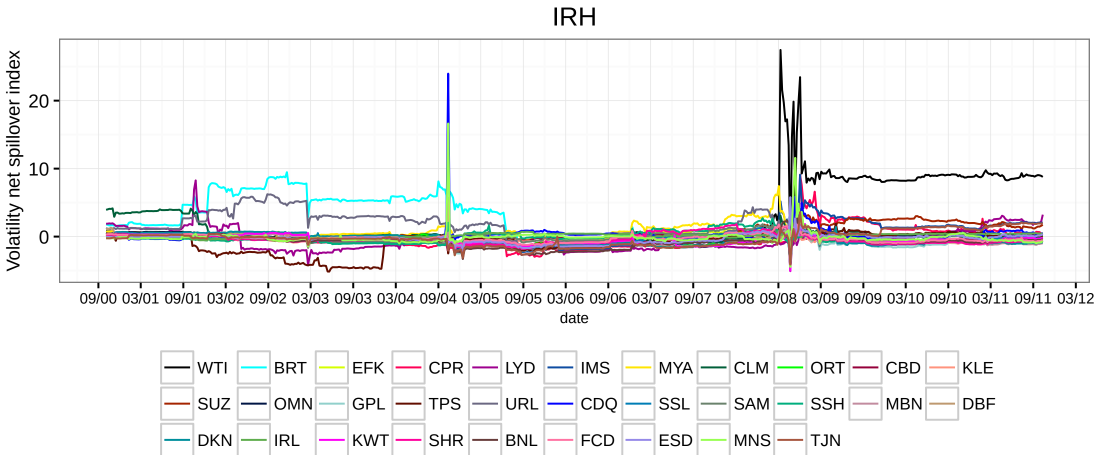


FIGURE B.5 (cont.): Pairwise net volatility spillover: the rest crudes(Cont.)





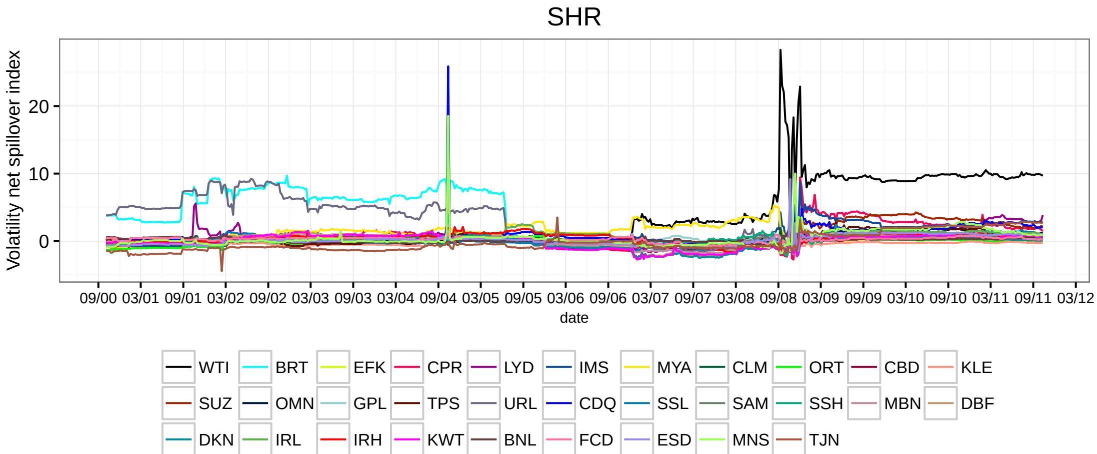
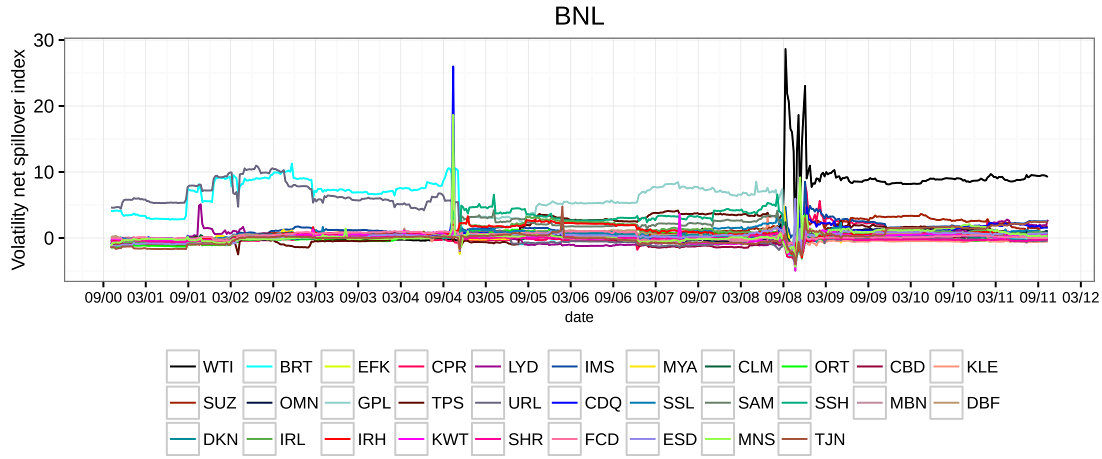
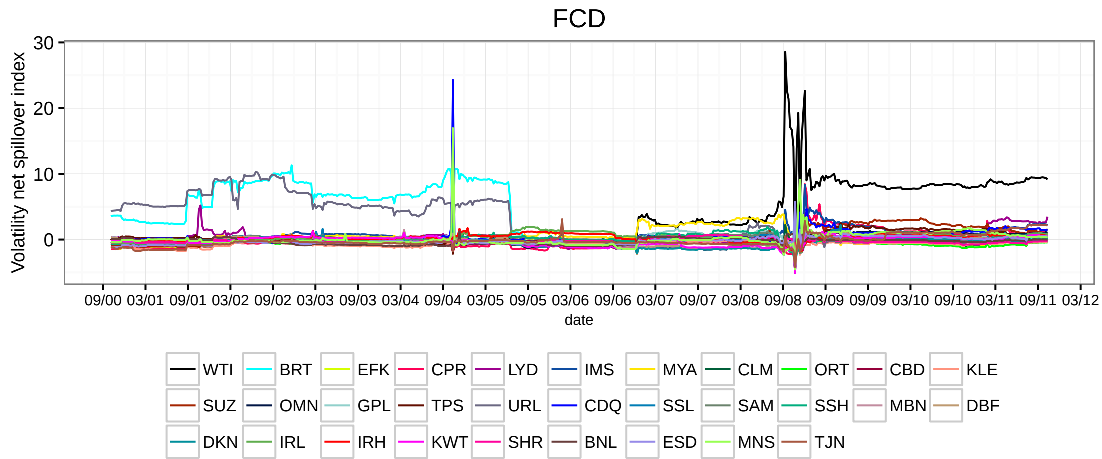


FIGURE B.5 (cont.): Pairwise net volatility spillover: the rest crudes(Cont.)





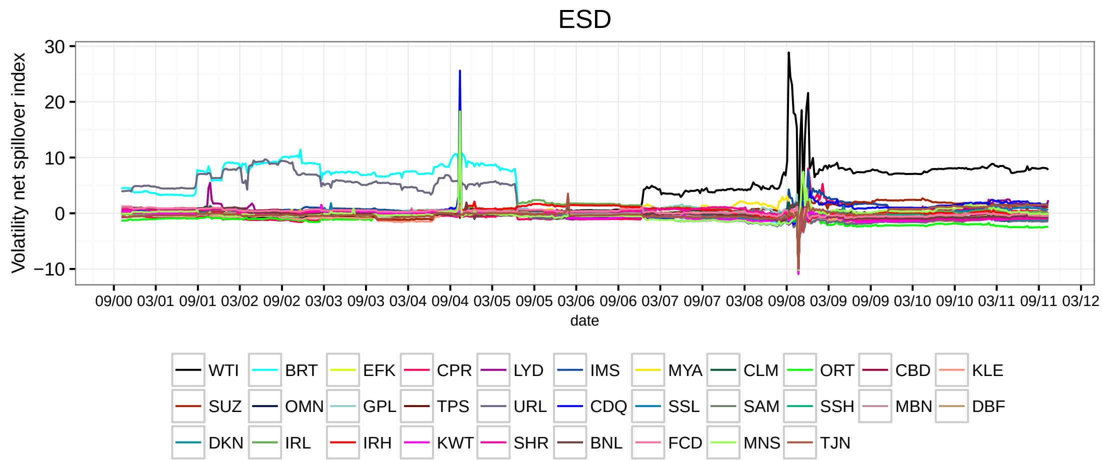
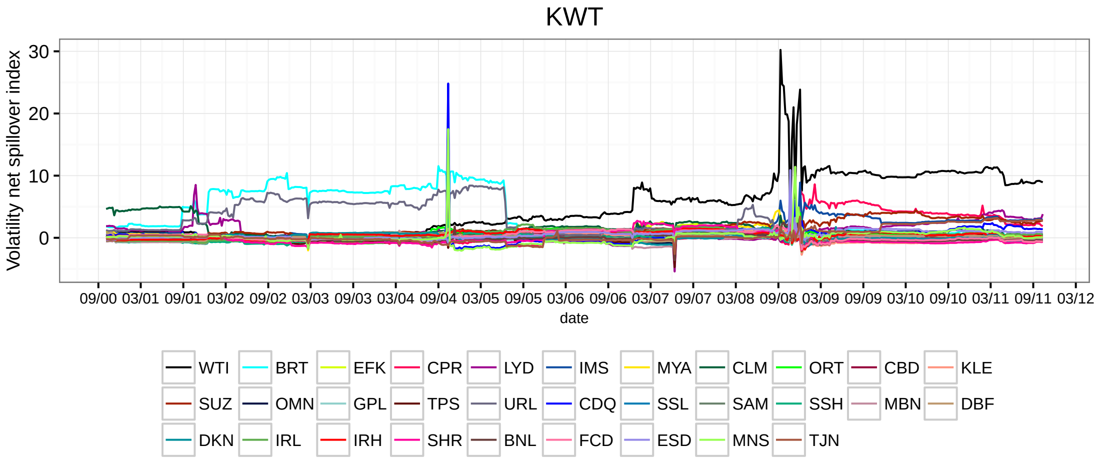
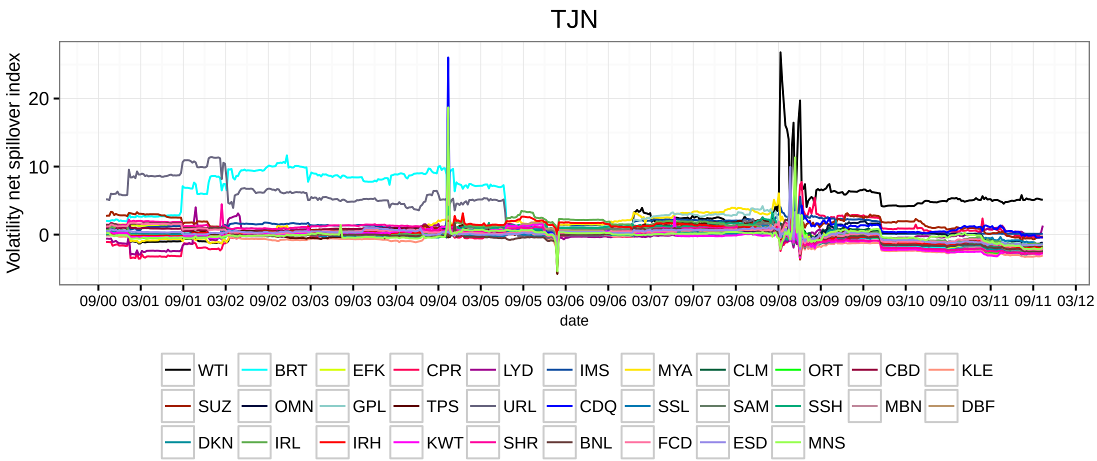


FIGURE B.5 (cont.): Pairwise net volatility spillover: the rest crudes(Cont.)





Notes: This picture shows the pairwise net volatility spillover of the rest crudes in sample except WTI, Brent(BRT), Dubai Fateh(DBF), Russian Urals(URL) and Kuwait Blend(KWT), whose plots are in Figure 4.5. If the line stay above zero, it means the crude represented by the color of the line transmits shocks to the crude investigated, and vice versa.

Figure B.6: GARCH Volatility of crude oil series

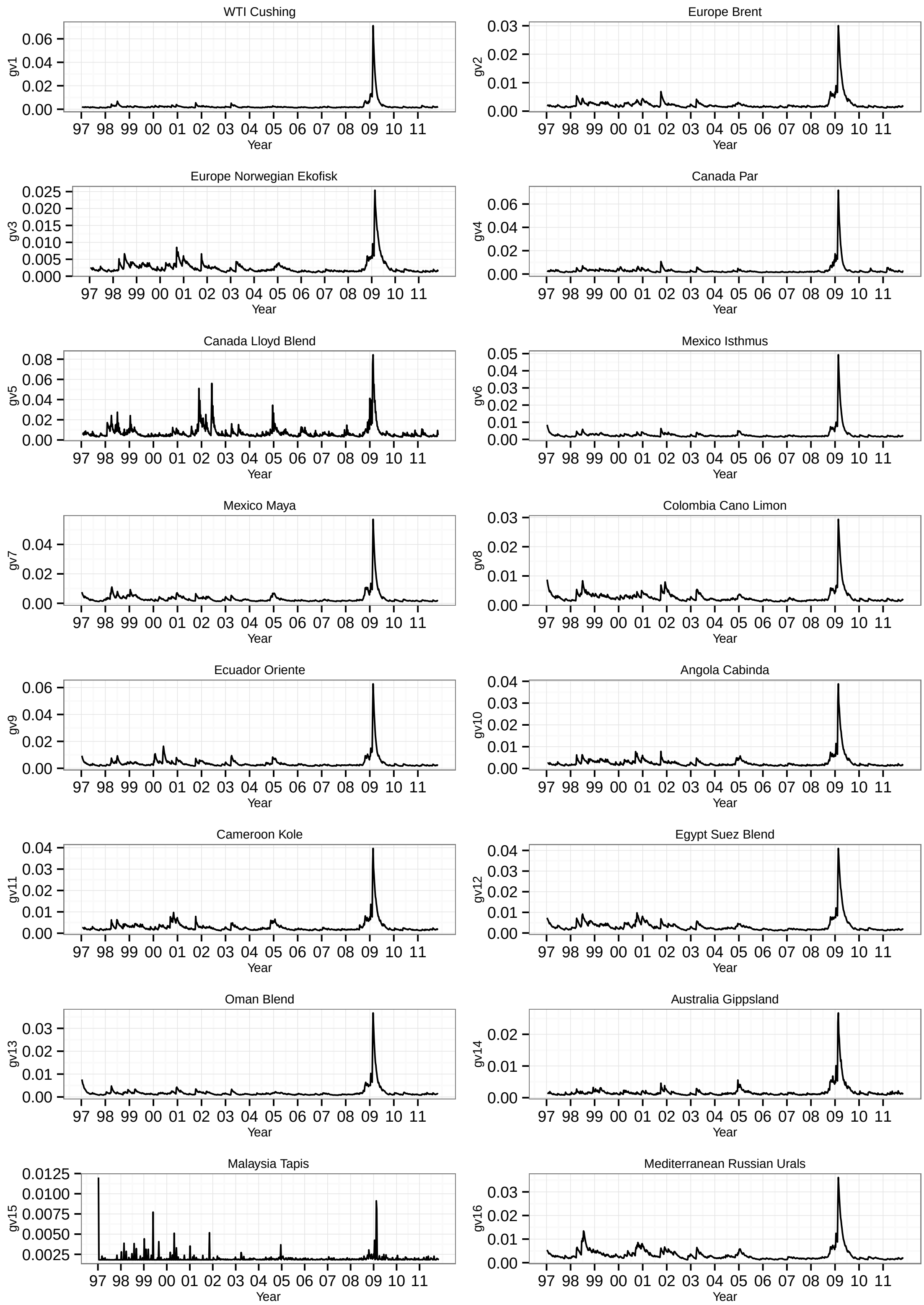
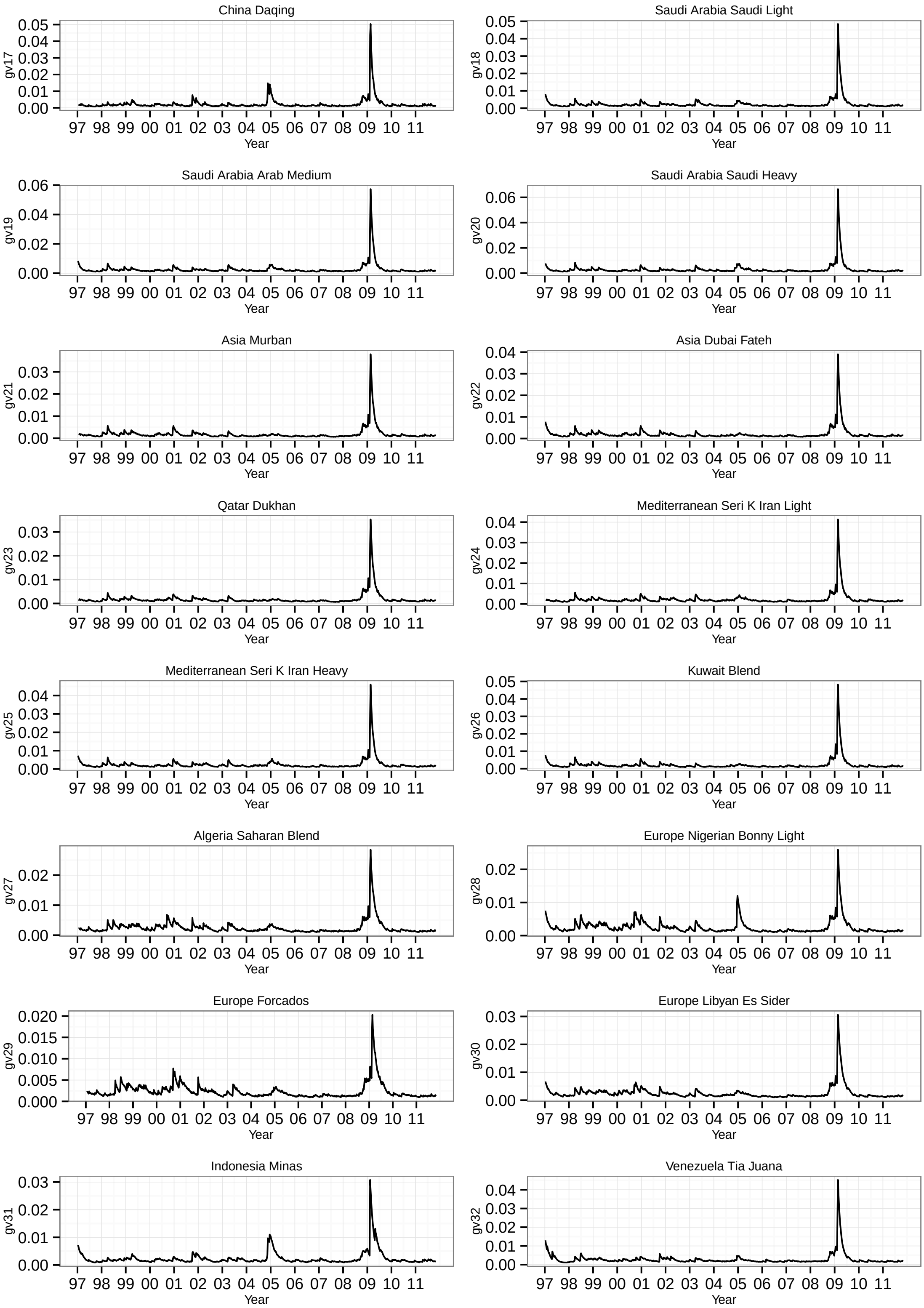


Figure B.6 (cont.): GARCH Volatility of crude oil series(Cont.)



References

Adelman, M. A. (1984). International oil agreements. *The Energy Journal*, 1–9.

Alizadeh, S., Brandt, M. W., & Diebold, F. X. (2002). Range-based estimation of stochastic volatility models. *The Journal of Finance*, *57*(3), 1047–1091.

Allen, F., & Gale, D. (2000). Financial contagion. *Journal of Political Economy*, *108*(1), 1–33.

AlMadi, M. S., & Zhang, B. (2011). Lead–lag relationships between world crude oil benchmarks: evidence from west texas intermediate, brent, dubai and oman. *International Research Journal of Finance and Economics*, *80*, 13–26.

Alter, A., & Beyer, A. (2014). The dynamics of spillover effects during the european sovereign debt turmoil. *Journal of Banking & Finance*, *42*, 134–153.

Andrews, D. W. (1993). Tests for parameter instability and structural change with unknown change point. *Econometrica: Journal of the Econometric Society*, 821–856.

Bacon, R., & Tordo, S. (2004). Crude oil prices: Predicting price differentials based on quality.

Bahree, B., & Gold, R. (2006). Saudi heavy oil may help in global energy crunch. *The Wall Street Journal Europe*, *24*(111), 1–2.

Banerjee, A., Lumsdaine, R. L., & Stock, J. H. (1992). Recursive and sequential tests of the unit-root and trend-break hypotheses: theory and international evidence. *Journal of Business & Economic Statistics*, *10*(3), 271–287.

Barassi, M. R., Caporale, G. M., & Hall, S. G. (2005). Interest rate linkages: a kalman filter approach to detecting structural change. *Economic Modelling*, *22*(2), 253–284.

Baum, C. F. (2004). Topics in time series regression modeling. In *United kingdom stata users' group meetings 2004*.

BBC. (2009). *Oil price rises on Gaza conflict.* http://news.bbc.co.uk/1/hi/7811043.stm. (Accessed: 2016-07-28)

Bekiros, S. D., & Diks, C. G. (2008). The relationship between crude oil spot and futures prices: Cointegration, linear and nonlinear causality. *Energy Economics*, *30*(5), 2673–2685.

Ben-David, D., Lumsdaine, R. L., & Papell, D. H. (2003). Unit roots, postwar slowdowns and long-run growth: Evidence from two structural breaks. *Empirical Economics*, *28*(2), 303–319.

Bentzen, J. (2007). Does opec influence crude oil prices? testing for co-movements and causality between regional crude oil prices. *Applied Economics*, *39*(11), 1375–1385.

Bertrand, M., Duflo, E., & Mullainathan, S. (2002). *How much should we trust differences-in-differences estimates?* (Tech. Rep.). National Bureau of Economic Research.

Bollerslev, T. (1986). Generalized autoregressive conditional heteroskedasticity. *Journal of Econometrics*, *31*(3), 307–327.

Breusch, T. S., & Pagan, A. R. (1980). The lagrange multiplier test and its applications to model specification in econometrics. *The Review of Economic Studies*, *47*(1), 239–253.

Brunetti, C., & Gilbert, C. L. (2000). Bivariate figarch and fractional cointegration. *Journal of Empirical Finance*, *7*(5), 509–530.

Bubák, V., Kočenda, E., & Žikeš, F. (2011). Volatility transmission in emerging european foreign exchange markets. *Journal of Banking & Finance*, *35*(11), 2829–2841.

Calvo, S. G., & Reinhart, C. M. (1996). Capital flows to latin america: is there evidence of contagion effects? *World Bank Policy Research Working Paper*(1619).

Candelon, B., Joëts, M., & Tokpavi, S. (2013). Testing for granger causality in distribution tails: An application to oil markets integration. *Economic Modelling*, *31*, 276–285.

Chai, J., Wang, S., & Xiao, B. (2013). Abrupt changes of global oil prices. *Journal of Systems Science and Information*, *1*(1), 38–59.

Chang, C.-L., McAleer, M., & Tansuchat, R. (2009). Modeling conditional correlations for risk diversification in crude oil markets. *Available at SSRN 1401331*.

Chang, C.-L., McAleer, M., & Tansuchat, R. (2010). Analyzing and forecasting volatility spillovers, asymmetries and hedging in major oil markets. *Energy Economics*, *32*(6), 1445–1455.

Christiano, L. J. (1992). Searching for a break in gnp. *Journal of Business & Economic Statistics*, *10*(3), 237–250.

Christy, S. (2004). Increasing russian crude oil exports changing worldwide trade patterns. *Oil & Gas Journal*, *102*(5), 54–56.

Clemente, J., Montañes, A., & Reyes, M. (1998). Testing for a unit root in variables with a double change in the mean. *Economics Letters*, *59*(2), 175–182.

Consilience. (2014). *The brent oil price marker: Future prospects* (Tech. Rep.). Author.

Corsetti, G., Pesenti, P., & Roubini, N. (1999). What caused the asian currency and financial crisis? *Japan and the World Economy*, *11*(3), 305–373.

Corsetti, G., Pesenti, P., Roubini, N., & Tille, C. (2000). Competitive devaluations: toward a welfare-based approach. *Journal of International Economics*, *51*(1), 217–241.

Dickey, D. A., & Fuller, W. A. (1979). Distribution of the estimators for autoregressive time series with a unit root. *Journal of the American Statistical Association*, *74*(366a), 427–431.

Didier, T., Love, I., & Martinez Peria, M. S. (2010). What explains stock markets' vulnerability to the 2007-2008 crisis? *World Bank Policy Research Working Paper Series, Vol.*

Diebold, F. X., & Yilmaz, K. (2009a). Equity market spillovers in the americas. *Journal Economía Chilena (The Chilean Economy)*, *12*(2), 55–65.

Diebold, F. X., & Yilmaz, K. (2009b). Measuring financial asset return and volatility spillovers, with application to global equity markets*. *The Economic Journal*, *119*(534), 158–171.

Diebold, F. X., & Yilmaz, K. (2012). Better to give than to receive: Predictive directional measurement of volatility spillovers. *International Journal of Forecasting*, *28*(1), 57–66.

Diebold, F. X., & Yılmaz, K. (2013). *Measuring the dynamics of global business cycle connectedness* (Tech. Rep.).

Diebold, F. X., & Yılmaz, K. (2014). On the network topology of variance decompositions: Measuring the connectedness of financial firms. *Journal of Econometrics*.

Diebold, F. X., & Yilmaz, K. (2015a). *Financial and macroeconomic connectedness: A network approach to measurement and monitoring.* Oxford University Press.

Diebold, F. X., & Yilmaz, K. (2015b). Trans-atlantic equity volatility connectedness:

US and European financial institutions, 2004–2014. *Journal of Financial Econometrics*, *14*(1), 81–127.

Dornbusch, R., Park, Y. C., & Claessens, S. (2000). Contagion: understanding how it spreads. *The World Bank Research Observer*, *15*(2), 177–197.

Eberhardt, M., et al. (2011). Panel time-series modeling: New tools for analyzing xt data. In *2011 uk stata users group meeting.*

Eberhardt, M., Teal, F., et al. (2010). Productivity analysis in global manufacturing production.

EIA. (2013). *Mexico Week: Crude oil moving north, products moving south characterizes U.S.-Mexico trade.* http://www.eia.gov/todayinenergy/detail.cfm?id=11271. (Accessed: 2016-07-28)

EIA. (2015). *Mexico.* http://www.eia.gov/beta/international/analysis.cfm?iso=MEX. (Accessed: 2016-07-28)

Einloth, J. T. (2009). Speculation and recent volatility in the price of oil. *Available at SSRN 1488792*.

Elder, J., Miao, H., & Ramchander, S. (2014). Price discovery in crude oil futures. *Energy Economics*, *46*, S18–S27.

Engle III, R. F., Ito, T., & Lin, W.-L. (1988). *Meteor showers or heat waves? heteroskedastic intra-daily volatility in the foreign exchange market.* National Bureau of Economic Research Cambridge, Mass., USA.

Express, T. F. (2003). *Forecasting the impact of Iraq showdown.* http://archive.financialexpress.com/news/forecasting-the-impact-of-iraq-showdown/78023/0. (Accessed: 2015-06-11)

Fan, Y., Zhang, Y.-J., Tsai, H.-T., & Wei, Y.-M. (2008). Estimating 'value at risk'of crude oil price and its spillover effect using the ged-garch approach. *Energy Economics*, *30*(6), 3156–3171.

Fattouh, B. (2007a). Opec pricing power. *Oxford Institute for Energy Studies, WPM*, *31*.

Fattouh, B. (2007b). Wti benchmark temporarily breaks down: is it really a big deal. *Middle East Economic Survey*, *49*(20), 14.

Fattouh, B. (2010). The dynamics of crude oil price differentials. *Energy Economics*, *32*(2), 334–342.

Feng-bin, L., Yi, L., Shuan-hong, W., & Shou-yang, W. (2008). Information spillovers among international crude oil markets—an empirical analysis based on ccf method and ecm. *Systems Engineering-Theory & Practice*, *28*(3), 25–34.

Fernández-Rodríguez, F., Gómez-Puig, M., & Sosvilla-Rivero, S. (2015). Volatility spillovers in emu sovereign bond markets. *International Review of Economics & Finance*, *39*, 337–352.

Fletcher, S. (2011). Price dislobatoin in benchmark crudes. *Oil and Gas Journal*.

Forbes, K., & Rigobon, R. (2001). Measuring contagion: conceptual and empirical issues. In *International financial contagion* (pp. 43–66). Springer.

Forbes, K. J. (2012). The'big c': Identifying and mitigating contagion.

Forbes, K. J., & Rigobon, R. (2002). No contagion, only interdependence: measuring stock market comovements. *The Journal of Finance*, *57*(5), 2223–2261.

Fujiwara, I., & Takahashi, K. (2012). Asian financial linkage: Macro-finance dissonance. *Pacific Economic Review*, *17*(1), 136–159.

Garman, M. B., & Klass, M. J. (1980). On the estimation of security price volatilities from historical data. *Journal of Business*, 67–78.

Ghoshray, A., & Trifonova, T. (2014). Dynamic adjustment of crude oil price spreads.

Energy Journal, *35*(1).

Ghysels, E., Santa-Clara, P., & Valkanov, R. (2004). The MIDAS touch: Mixed data sampling regression models. *Finance*.

Giulietti, M., Iregui, A. M., & Otero, J. (2014). Crude oil price differentials, product heterogeneity and institutional arrangements. *Energy Economics*, *46*, S28–S32.

González, P. F., Landajo, M., & Presno, M. (2014). Multilevel lmdi decomposition of changes in aggregate energy consumption. a cross country analysis in the eu-27. *Energy Policy*, *68*, 576–584.

Gregory, A. W., & Hansen, B. E. (1996). Residual-based tests for cointegration in models with regime shifts. *Journal of Econometrics*, *70*(1), 99–126.

Gülen, S. G. (1999). Regionalization in the world crude oil market: further evidence. *The Energy Journal*, 125–139.

Hamilton, J. D. (2009). *Causes and consequences of the oil shock of 2007-08* (Tech. Rep.). National Bureau of Economic Research.

Hamilton, J. D. (2014). *The Changing Face of World Oil Markets* (NBER Working Papers No. 20355). National Bureau of Economic Research, Inc. Retrieved from http://ideas.repec.org/p/nbr/nberwo/20355.html

Hammoudeh, S., & Li, H. (2004). The impact of the asian crisis on the behavior of us and international petroleum prices. *Energy Economics*, *26*(1), 135–160.

Hasbrouck, J. (1995). One security, many markets: Determining the contributions to price discovery. *The Journal of Finance*, *50*(4), 1175–1199.

Hong, Y. (2001). A test for volatility spillover with application to exchange rates. *Journal of Econometrics*, *103*(1), 183–224.

Hong, Y., Liu, Y., & Wang, S. (2009). Granger causality in risk and detection of extreme risk spillover between financial markets. *Journal of Econometrics*, *150*(2), 271–287.

Hume, N. (2014). Call for brent reform. *Financial Times*.

Huppmann, D., & Holz, F. (2012). Crude oil market power-a shift in recent years? *Energy Journal*, *33*(4), 1–22.

Hwang, E., Min, H.-G., Kim, B.-H., & Kim, H. (2013). Determinants of stock market comovements among us and emerging economies during the us financial crisis. *Economic Modelling*, *35*, 338–348.

Ji, Q., & Fan, Y. (2014). Evolution of the world crude oil market integration: A graph theory analysis. *Energy Economics*.

Ji, Q., & Guo, J.-F. (2015). Oil price volatility and oil-related events: An internet concern study perspective. *Applied Energy*, *137*, 256–264.

Ji, Q., Zhang, H.-Y., & Fan, Y. (2014). Identification of global oil trade patterns: an empirical research based on complex network theory. *Energy Conversion and Management*, *85*, 856–865.

Jin, X., Lin, S. X., & Tamvakis, M. (2012). Volatility transmission and volatility impulse response functions in crude oil markets. *Energy Economics*, *34*(6), 2125–2134.

Johansson, A. C. (2008). Interdependencies among asian bond markets. *Journal of Asian Economics*, *19*(2), 101–116.

Kao, C.-W., & Wan, J.-Y. (2012). Price discount, inventories and the distortion of wti benchmark. *Energy Economics*, *34*(1), 117–124.

Katusa, M. (2011). The libyan crisis: where are oil prices going? *Forbes*.

Kaufmann, R. K., & Ullman, B. (2009). Oil prices, speculation, and fundamentals: Interpreting causal relations among spot and futures prices. *Energy Economics*, *31*(4), 550–558.

Kim, H.-J., & Siegmund, D. (1989). The likelihood ratio test for a change-point in simple linear regression. *Biometrika*, *76*(3), 409–423.

Kleit, A. N. (2001). Are regional oil markets growing closer together?: An arbitrage cost approach. *The Energy Journal*, 1–15.

Klößner, S., & Wagner, S. (2012). *Robustness and computation of spillover measures for financial asset returns and volatilities* (Tech. Rep.). Working Paper.

Klößner, S., & Wagner, S. (2014). Exploring all var orderings for calculating spillovers? yes, we can!—a note on diebold and yilmaz (2009). *Journal of Applied Econometrics*, *29*(1), 172–179.

Koop, G., Pesaran, M. H., & Potter, S. M. (1996). Impulse response analysis in nonlinear multivariate models. *Journal of Econometrics*, *74*(1), 119–147.

Leelahaphan, T., Prukumpai, S., & Sethapramote, Y. (2015). Determinants of return and volatility spillovers in the international equity markets. *Unpublised Working Paper*.

Lehmann, B. N. (2002). Some desiderata for the measurement of price discovery across markets. *Journal of Financial Markets*, *5*(3), 259–276.

Li, R., & Leung, G. C. (2011). The integration of china into the world crude oil market since 1998. *Energy Policy*, *39*(9), 5159–5166.

Lin, S. X., & Tamvakis, M. N. (2001). Spillover effects in energy futures markets. *Energy Economics*, *23*(1), 43–56.

Lin, S. X., & Tamvakis, M. N. (2004). Effects of nymex trading on ipe brent crude futures markets: a duration analysis. *Energy Policy*, *32*(1), 77–82.

Lu, F.-b., Hong, Y.-m., Wang, S.-y., Lai, K.-k., & Liu, J. (2014). Time-varying granger causality tests for applications in global crude oil markets. *Energy Economics*, *42*, 289–298.

Lumsdaine, R. L., & Papell, D. H. (1997). Multiple trend breaks and the unit-root hypothesis. *Review of Economics and Statistics*, *79*(2), 212–218.

Masters, M. W. (2008). Testimony of michael w. masters, managing member/portfolio manager, masters capital management, llc. *Testimony before the US Senate Committee on Homeland Security and Governmental Affairs (hsgac. senate. gov- /public/_files/052008Masters. pdf)*.

McMillan, D. G., & Speight, A. E. (2010). Return and volatility spillovers in three euro exchange rates. *Journal of Economics and Business*, *62*(2), 79–93.

Montepeque, J. (2005). Sour crude pricing: a pressing global issue. *Middle East Economic Survey*, *48*(1.42).

Nelson, C. R., & Plosser, C. R. (1982). Trends and random walks in macroeconmic time series: some evidence and implications. *Journal of monetary economics*, *10*(2), 139–162.

Norris, M. (2008). *Contango in oil market explained.* http://www.npr.org/templates/story/story.php?storyId=98410267. (Accessed: 2016-07-11)

Parkinson, M. (1976). The random walk problem: Extreme value method for estimating the variance of the displacement (diffusion constant). *University of Florida*.

Perron, P. (1989). The great crash, the oil price shock, and the unit root hypothesis. *Econometrica: Journal of the Econometric Society*, 1361–1401.

Perron, P. (1997). Further evidence on breaking trend functions in macroeconomic variables. *Journal of Econometrics*, *80*(2), 355–385.

Perron, P., & Vogelsang, T. J. (1992). Nonstationarity and level shifts with an application to purchasing power parity. *Journal of Business & Economic Statistics*, *10*(3), 301–320.

Pesaran, H. H., & Shin, Y. (1998). Generalized impulse response analysis in linear multivariate models. *Economics Letters*, *58*(1), 17–29.

Pesaran, M. H. (2006). Estimation and inference in large heterogeneous panels with a multifactor error structure. *Econometrica*, *74*(4), 967–1012.

Pesaran, M. H., & Smith, R. (1995). Estimating long-run relationships from dynamic heterogeneous panels. *Journal of econometrics*, *68*(1), 79–113.

Platts. (2013). *International oil trade flows: The shifting landscape.* http://www.platts.com/IM.Platts.Content/ProductsServices/ConferenceandEvents/2013/pc001/presentations/Sushant_Gupta.pdf. (Accessed: 2016-07-28)

Platts. (2014). *Dated brent as a solution to pricing of crude oil in asia* (Tech. Rep.). Author.

Prasad, N., Grant, A. R., & Kim, S.-J. (2014). Time varying volatility indexes and their determinants: Evidence from developed and emerging stock markets. *Available at SSRN 2496751*.

Pretorius, E. (2002). Economic determinants of emerging stock market interdependence. *Emerging Markets Review*, *3*(1), 84–105.

PWC. (2014). *Oil and gas in Indonesia.* https://www.pwc.com/id/en/publications/assets/oil_and_gas_guide_2014.pdf. (Accessed: 2016-07-11)

Quandt, R. E. (1960). Tests of the hypothesis that a linear regression system obeys two separate regimes. *Journal of the American Statistical Association*, *55*(290), 324–330.

Rempel, H. (2011). Geographical distribution of oil and natural gas deposits-different means of transportation to the consumption centers. In *1st pipeline technology conference 2006.*

Ripple, R. (2001). Us west coast petroleum industry in the 1990s: Isolated or globally integrated. *Oil, Gas and Energy Quarterly*, *50*, 105–139.

Ripple, R. D., & Wilamoski, P. R. (1995). Is the world oil market 'one great pool?': revisited. *OPEC review*, *19*(4), 283–292.

Sauer, D. G. (1994). Measuring economic markets for imported crude oil. *The Energy Journal*, 107–123.

Schmidheiny, K. (2015). *Panel data: fixed and random effects.* http://kurt.schmidheiny.name/teaching/panel.pdf. (Accessed: 2016-07-28)

Shinagawa, Y. (2014). Determinants of financial market spillovers: The role of portfolio diversification, trade, home bias, and concentration.

Skintzi, V. D., & Refenes, A. N. (2006). Volatility spillovers and dynamic correlation in european bond markets. *Journal of International Financial Markets, Institutions and Money*, *16*(1), 23–40.

Soriano, P., & Climent, F. J. (2005). Volatility transmission models: a survey. *Available at SSRN 676469*.

Sun, M., Gao, C., & Shen, B. (2014). Quantifying china's oil import risks and the impact on the national economy. *Energy Policy*, *67*, 605–611.

Syllignakis, M. N., & Kouretas, G. P. (2011). Dynamic correlation analysis of financial contagion: Evidence from the central and eastern european markets. *International Review of Economics & Finance*, *20*(4), 717–732.

Syriopoulos, T. (2007). Dynamic linkages between emerging european and developed stock markets: Has the emu any impact? *International Review of Financial Analysis*, *16*(1), 41–60.

Tsay, R. S. (2013). *Multivariate time series analysis: with r and financial applications.* John Wiley & Sons.

Wang, Z., Yang, J., & Li, Q. (2007). Interest rate linkages in the eurocurrency market:

Contemporaneous and out-of-sample granger causality tests. *Journal of International Money and Finance*, *26*(1), 86–103.

Weiner, R. J. (1991). Is the world oil market" one great pool"? *The Energy Journal*, 95–107.

Wlazlowski, S., Hagströmer, B., & Giulietti, M. (2011). Causality in crude oil prices. *Applied Economics*, *43*(24), 3337–3347.

WTRG. (2011). *Oil price history and analysis.* http://www.wtrg.com/prices.htm. (Accessed: 2016-07-11)

Xie, H. (2014). *Sovereign credit risk spillover* (Unpublished doctoral dissertation). University of Nottingham.

Zhang, B., & Wang, P. (2014). Return and volatility spillovers between china and world oil markets. *Economic Modelling*, *42*, 413–420.

Zhang, H.-Y., Ji, Q., & Fan, Y. (2015). What drives the formation of global oil trade patterns? *Energy Economics*, *49*, 639–648.

Zhang, Y.-J., & Zhang, L. (2015). Interpreting the crude oil price movements: Evidence from the markov regime switching model. *Applied Energy*, *143*, 96–109.

Zheng, T., & Zuo, H. (2013). Reexamining the time-varying volatility spillover effects: A markov switching causality approach. *The North American Journal of Economics and Finance*, *26*, 643–662.

Zivot, E., & Andrews, D. W. K. (2002). Further evidence on the great crash, the oil-price shock, and the unit-root hypothesis. *Journal of Business & Economic Statistics*, *20*(1), 25–44.