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Dynamic spillover effects across petroleum spot and futures volatilities, trading volume and open interest

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Abstract

This paper examines the existence of dynamic spillover effects across petroleum based commodities and among spot-futures volatilities, trading volume and open interest. Realized volatilities of spot-futures markets are used as inputs to estimate a VAR model following Diebold and Yilmaz (2014, 2015) and distinguish dynamic spillovers in total and net effects. Results reveal the existence of large and time-varying spillovers among the spot-futures volatilities and across petroleum-based commodities when examined pairwise. In addition, speculative pressures, as reflected by futures trading volume, and hedging pressures, as reflected by open interest, are shown to transmit large and persistent spillovers to the spot and futures volatilities of crude oil and heating oil-gasoline markets, respectively.

Key words: Dynamic spillovers; spot and futures markets; petroleum markets; trading volume; open interest.

JEL classification: G11, G12, G20.

1. Introduction

The interest on cross-asset interdependencies in general and within the energy commodities market in particular has been stimulated during and after the period of the global financial crisis (Sadorsky, 2012; Mensi et al., 2014; Baruník et al., 2015; Alizadeh and Tamvakis, 2016). Apart from the historically remarkable and growing dependence of global industrial production on energy commodities, the interest on this specific asset class has been pronounced after 2000's also because of the substantial increase of their price volatility.^{1,2} This excess volatility has been linked with tight oil production from shale formations and the financialization of commodities markets (Baumeister and Kilian, 2012; Hamilton and Wu, 2015; Büyükkşahin and Robe, 2014; Singleton, 2013).³ For example, the increasing trend in commodity prices, which is often linked to the upward trend in crude oil, was followed by a sharp decline when the global financial crisis hit during 2007-2009 (Cevik and Sedik, 2011); a repeating pattern of large fluctuations also during the Eurozone debt crisis (2010-2013).⁴ Such notable price movements are often attributed to transaction costs, information asymmetries, supply-demand imbalances and other market microstructure issues which create information spillover relationships among commodities markets. The aforementioned reasons highlight the importance of modelling spillovers of information across energy commodities and among volatilities and trading characteristics for several market participants.

This paper provides novel empirical evidence on two distinct but interrelated research questions, stemming from two underlying research hypotheses. The first issue examined is the evolution, severity and direction of volatility spillovers between the spot and futures markets examined across petroleum-based commodities. This is motivated by

¹ According to British Petroleum's (BP) statistical review of world energy published in June 2015 referring to 2014 year-end, the global energy consumption experienced a growth of 0.9%, the smallest growth since 2009. However, world's dependence on energy commodities remains emphatic as the percentages of global energy consumption among all sources of energy is the following: crude oil and oil products (32.6%), coal (30%), natural gas (23.7%), hydroelectric energy (6.8%), nuclear energy (4.4%) and renewables (2.5%).

² The importance of petroleum-based commodities for the global economy and economic development has been highlighted as early as in Hamilton (1983). Furthermore, oil price shocks have been shown to affect the U.S. stock market (Kilian and Park, 2009).

³ The term "financialization" refers to the inclusion of commodities in investment portfolios for diversification purposes.

⁴ More recently, based on data from the U.S. Department of Energy, oil prices tumbled from 106.2\$/barrel in June 2014 to 26.55 \$/barrel in January 2016.

recent empirical evidence (see, for instance, Antonakakis et al., 2015) documenting large co-movements across asset classes which have led investors to rebalance their portfolios towards safer investments, increase their diversification through investing in different asset classes and hedge their positions in the spot market with opposite positions in the futures market. The related to the issue futures literature examines the relation between spot and futures markets and is dominated by the price discovery hypothesis (Chan, 1992; Ghosh, 1993) and the volatility spillover hypothesis (Tao and Green, 2012).

The second issue examined in this paper is the evolution, severity and direction of spillovers among spot and futures price volatility, trading volume and open interest for each individual petroleum-based commodity. This research question stems from the Mixture of Distributions Hypothesis (MDH) suggested in Clark (1973) and the Sequential Information Flow (SIF) developed in Copeland (1976). The MDH approach assumes that price changes and trading volume follow a joint probability distribution. Specifically, trading volume has been widely used as a measure for the rate of informational arrival. In contrast, the SIF approach assumes that information is released sequentially in the market, i.e. informed traders acquire the information first with the rest of the market following to eventually restore equilibria. Open interest is considered a proxy for the dispersion of investors' beliefs (Bessembinder et al., 1996) and as a proxy for the demand of futures contracts as hedging instruments (Aguenaou et al., 2011). Open interest has been shown to contain information about future economic activity which is different than the one contained in futures prices (Hong and Yogo, 2012).

Prior empirical studies have focused on the aforementioned hypotheses across futures markets but do not examine their validity over time for the important class of energy futures markets. Specifically, prior studies on the issue do not investigate the existence, severity and direction of dynamic spillovers across petroleum-based commodities and across spot-futures volatility, trading volume and open interest (Foster, 1995; Moosa and Silvapulle, 2000; Chevallier and Sévi, 2012; Alizadeh and Tamvakis, 2016). To the best of our knowledge, this paper is the first to investigate this issue by providing novel evidence regarding the existence of dynamic (time-varying) spillovers among spot-

futures volatilities when petroleum-based commodities are examined pairwise; and among spot-futures volatilities, futures trading volume and open interest when petroleum-based commodities are examined individually. The examined futures contracts are traded on the New York Mercantile Exchange (NYMEX) and include: West Texas Intermediate (WTI) crude oil (CL), New York harbor heating oil (HO) and Reformulated Blendstock for Oxygen Blending (RBOB) gasoline (XB). These futures contracts are included in the empirical analysis of this paper as they exhibit the highest trading volume and account for the vast majority of trades among all energy futures contracts traded in NYMEX (Alizadeh and Tamvakis, 2016).

Prior relevant studies on the research question of this paper include Baruník et al. (2015) who investigate dynamic volatility spillovers across futures markets of petroleum-based commodities. The authors reveal that after 2008 volatility spillovers increased substantially across petroleum-based commodities and exhibit asymmetric effects (positive or negative). However, the authors do not examine both spot-futures volatilities and trading activity measures, such as trading volume and open interest. Furthermore, Barunik and Krehlik (2016) extend the Diebold Yilmaz (DY) (2009; 2012; 2014) estimation framework and provide empirical evidence highlighting the importance of the proper measurement of dynamics across time and frequencies by emphasizing the important role of cross-sectional correlation in the connectedness origins. In another study, Alizadeh and Tamvakis (2016) investigate spillovers between returns and volatilities of energy futures contracts of different maturities and their corresponding trading volumes. The authors show that the state of the market (contango or backwardation) has an effect on the relationship between futures price volatility and changes of trading volume; making the relationship stronger when the market is in backwardation.⁵ However, one limitation of the previous empirical studies on the issue, with the exception of Barunik et al. (2015), is that they examine static spillover effects without capturing time-variation in spillovers and with no inference regarding “directional” spillovers which can reveal “from/to” receiving/transmitting patterns. This

⁵ Backwardation is the state of the market when the futures price is below the expected future spot price, i.e. in favour of traders being "net long" in their positions

is an important aspect as computing the average spillover effect over a long and turbulent period might mask potential cyclical movements in spillover effects.

The identification of dynamic spillover effects across petroleum based commodities and among spot and futures volatilities, trading volume and open interest has a number of important implications for several market participants.⁶ This is because volatility comprises a risk measure and therefore the existence of volatility spillovers across markets can induce a major impact on risk-averse investors (Doran and Ronn, 2008). In this way, the identification of spillovers between spot-futures volatilities and trading characteristics has important implications regarding trading strategies, hedging activities, asset allocation (portfolio construction/rebalancing) and forecasting prices of petroleum based commodities. Moreover, volatility spillovers measure market co-movements which are shown to be more intense during financial crises periods, i.e. volatility increases notably in one market and spills over to other markets (Reinhart and Rogoff, 2008).

This paper contributes to the existing literature in the following ways: First, it investigates for the first time the dynamic spillover effects across petroleum based commodities and among spot-futures volatilities, trading volume and open interest. Trading volume reflects speculative demand for futures, whereas open interest represents hedging activity (Bessembinder and Seguin, 1993). Second, the use of the DY approach enables the estimation of dynamic total and net spillovers; an important feature which has not been applied by the relevant literature on the issue with the exception of Barunik et al. (2015). However, Barunik et al. (2015) concentrate on futures markets volatilities only and not trading characteristics, such as the trading volume and open interest. Third, this paper evaluates whether futures trading volume and open interest carry relevant information for the future variation of spot and futures volatilities (forecast error variance – FEV) and vice versa.

⁶ This paper focuses on the existence of economic spillovers in the volatilities rather than in the returns of the spot-futures markets of petroleum-based commodities. This is due to the fact that volatilities appear to be more useful in assessing interdependencies since they are well-approximated as Gaussian rather than returns (for details on this, see, Diebold and Yilmaz, 2015).

The main empirical findings of this study can be summarized as follows. First, regarding the dynamic volatility spillovers between the spot-futures markets and across petroleum-based commodities when examined pairwise, results suggest that crude oil's futures volatility transmits considerable spillovers to futures volatilities of heating oil (25.8%) and gasoline (24.4%), but much lower shocks to the underlying market of spot crude oil volatility (around 11%). By contrast, heating oil's futures volatility transmits larger spillovers to heating oil's spot volatility (19.6%) rather than to crude oil's future volatility (15.2%), while gasoline's futures volatility transmits larger spillovers to crude oil's futures volatility (18.8%) rather than to gasoline's spot volatility (7.8%). Moreover, the total spillovers are increased during the period 2008 to 2009 and especially after the Lehman Brothers collapse in September 2008 for all pairs of commodities examined (crude oil – heating oil, crude oil – gasoline and heating oil – gasoline).

Second, regarding the dynamic spillovers among spot-futures volatilities, futures trading volume and futures open interest for each petroleum-based commodity individually, results suggest that in the crude oil market trading volume and futures volatility are transmitting large and persistent shocks to the open interest and the spot volatility. This result suggests that speculative pressures as reflected in futures trading volume contain a significant information regarding the future error variance of spot volatility and open interest. However, for heating oil and gasoline commodities, open interest and futures volatility are mainly transmitters to the spot volatility and trading volume. This result reveals the existence of hedging pressures as reflected by open interest for heating oil and gasoline commodities. Overall, the results of this paper extend the literature by providing clear cut evidence that futures markets volatilities lead spot markets volatilities across petroleum-based commodities. Furthermore, significantly time-varying spillovers are observed among spot-futures volatilities and trading characteristics of the petroleum-based commodities, as captured by the trading volume and open interest variables.

These findings are helpful for financial analysts, professional forecasters, risk managers and financial regulators participating in the energy spot and futures markets. For instance, risk managers may be interested in assessing the information content of open interest in

forecasting the risk of investments in spot and futures markets of heating oil and gasoline commodities. Also, the dominant importance of crude oil's futures volatility in transmitting shocks to the future error variance of heating oil's and gasoline's futures volatilities, can be used from portfolio managers to develop trading strategies across petroleum-based commodities. Finally, the finding that trading volume for the crude oil market and open interest for the heating oil and gasoline markets can explain a large percentage of future error variance of spot-futures volatilities can be used by professional forecasters to improve the accuracy and reliability of their forecasts.

The rest of this paper is organized as follows: Section 2 provides the literature review; Section 3 outlines the methodology; section 4 describes the dataset; section 5 presents and discusses the empirical results, whereas section 6 concludes the paper.

2. Literature Review

Responding to the increasing trend of commodities markets co-movements, several studies have examined the cross market information transmission between different commodities futures markets (Chuliá and Torró, 2008; Chng, 2009; Fung et al., 2010; Ding and Pu, 2012; Trujillo-Barrera et al., 2012). The general consensus of the aforementioned studies is that futures contracts on energy commodities exhibit high levels of interdependence with the equity futures markets. At the same time energy commodities exhibit interdependencies with other types of commodities, such as agricultural commodities which are closely related to energy commodities.

The literature devoted to the investigation of lead-lag relationships between oil's spot and futures markets is large. Several researchers have investigated empirically if crude oil's futures market is quicker in incorporating market-wide information when compared to the spot market (Chang and Lee, 2015; Chen et al., 2014; Huang et al., 2009; Bekiros and Diks, 2008; Silvapulle and Moosa, 1999). The empirical investigation of this issue commonly focuses on the issues of price discovery and volatility spillovers (Silber,

1985). Price discovery is the process where one market (typically the futures market) incorporates new information earlier than another market (typically the spot market). Due to the function of price discovery, oil futures prices are widely thought to lead spot prices. However, causality tests between spot and futures oil prices have led to mixed results (Chang and Lee, 2015; Chen et al., 2014; Huang et al., 2009; Bekiros and Diks, 2008; Silvapulle and Moosa, 1999).

In principle, energy futures markets are expected to be integrated and typically exhibit high degree of interdependence. This stems from the economic thought on substitutability and complementarity within energy commodities, stemming primarily from the excess co-movement hypothesis of Pindyck and Rotemberg (1990). For example, Haigh and Holt (2002) have revealed significant volatility spillovers within the petroleum-based commodities asset class. In addition, different petroleum-based commodities exhibit potential substitution effects (Chevallier and Ielpo, 2013) and economic linkages (Casassus et al., 2013).

Apart from the petroleum-related literature, a vast number of studies have been devoted to the investigation of spillovers among related futures markets. For example, in the agricultural commodities market, which has strong linkages with the energy commodities market (Nazlioglu et al., 2013), similar interdependencies have been identified as early as in Malliaris and Urrutia (1996). The authors provide evidence that the prices of six agricultural futures contracts exhibit significant interdependencies in the long-run. Also other studies investigate the relationship among related futures markets: Chng (2009) examine Japanese futures markets on natural gas, palladium and gasoline; Chuliá and Torró (2008) on DJ Euro Stoxx 50 index futures and Euro Bund futures markets; Fung et al. (2010) on US and Chinese aluminium and copper futures markets; Ding and Pu (2012) on US stock, bond and credit derivatives markets; Trujillo-Barrera et al. (2012) on US crude oil, ethanol and corn futures markets; Beckmann and Czudaj (2014) on US corn, cotton and wheat futures markets and Liu et al. (2014) on Chinese copper aluminium, natural rubber and soybean futures. The general consensus of the aforementioned studies

is that energy commodities futures markets exhibit pronounced interdependencies with the equity futures markets and related commodities futures markets, such as agricultural commodities.

In contrast to the previous studies on the issue, this paper investigates for the first time the dynamic volatility spillovers between spot-futures markets and across petroleum based commodities examined pairwise. The use of the DY approach enables the estimation of dynamic total and net spillovers; an important feature which has not been applied by the relevant literature on the issue with the exception of Barunik et al. (2015) who however concentrate on futures markets only.

2.1 Futures trading activity effects on volatility

Prior to 2000's, individual commodity futures contracts were liquid and have been traded on many commodities, but they mainly provided a risk premium for idiosyncratic commodity price risk (Bessembinder, 1992; De Roon et al., 2000); also they have exhibited low co-movements with each other (Erb and Harvey, 2006). For this reason, futures on commodities traditionally exhibit different characteristics from the financial assets, as the latter typically carry a systematic risk premium and are highly correlated with each other.

However, after 2000's, financial market participants recognized the pronounced segmentation of the commodities markets and the associated potential diversification benefits for their portfolios. The importance of the liquidity characteristics of energy futures is also highlighted by the fact that they have evolved into an important asset class used primarily by investors and traders for diversification, speculation and investment purposes. Hamilton (2009) has linked oil prices with large speculative trades and Lombardi et al. (2011) has shown that short-run destabilization in oil prices can be caused by financial investors. In order to reflect this pattern, the so-called "financialization" of commodities concept has emerged after 2000's in the general commodities futures markets literature (see among others, Tang and Xiong, 2012; Singleton, 2013 and Basak and Pavlova, 2015) and in the more specific petroleum

literature (Fratzscher et al., 2013). The diversification benefits have also enhanced the “financialization” of commodities markets mainly through increased trading on commodities indices. This process led to an increased degree of integration and interaction among energy commodities. For instance, specific events such as the global financial crisis increased the volatility and decreased the risk appetite in financial markets worldwide. Furthermore, Cashin and McDermott (2001) argue that increases in the volatilities of commodities prices have more important implications rather than a long-run downward trend. This is due to the fact that sharp movements in commodities prices have serious effects in terms of trade, real incomes and fiscal positions for countries heavily depended on commodities. Thus, the importance of futures commodities markets has grown significantly over time and has been further enhanced after the global financial crisis.

For the reasons explained above this paper focuses on investigating for the first time the evolution, severity and direction of spillovers among spot-futures volatilities, futures trading volume and futures open interest for each petroleum-based commodity individually. Specifically, trading volume reflects speculative demand for futures, whereas open interest represents mainly hedging activity (Bessembinder and Seguin, 1993). Thus, this paper evaluates whether futures trading volume and open interest carry relevant information for the future variation of spot and futures volatilities (forecast error variance – FEV) and vice versa.

3. Methodology

In order to empirically investigate the volatilities of spot and futures returns across petroleum-based commodities we use the realized volatility (RV) estimator.⁷ This is motivated by findings in volatility modelling literature. For example, Andersen et al. (2003) propose that realized volatility is free of tight parametric functional form assumptions and at the same time provides a consistent estimate of ex-post return

⁷ As a robustness test, we also employ the multivariate dynamic conditional correlation (DCC)-GARCH model introduced by Engle (2002) as an alternative to the realized volatility estimator. Since the results obtained through the DCC-GARCH model are qualitatively the same as with the realized volatility model, they are not reported in the paper to preserve space but are available from the authors upon request.

volatility. The literature on modelling volatility of petroleum-based assets also provides evidence in favour of the RV estimator, see for example, Sévi (2014). We calculate monthly realized volatility estimates by using a rolling window of twenty two trading days:

$$Vol_t = \sqrt{\sum_{\tau=1}^{n_t} r_{\tau t}^2} \quad (1)$$

where, r_t is the log-returns of futures contracts historical prices, n_t is the number of trading days in month t and τ indicates the particular day of that month ($\tau=1, \dots, n_t$). The resulting realized volatilities are used as inputs to measure volatility spillovers as explained in the next section of the paper.

3.1 Measuring spillover effects

We use the spillover analysis originally introduced and subsequently extended in Diebold and Yilmaz (DY) (2009; 2012). The analysis is based on VAR modelling introduced originally by Sims (1980) and the resulting estimation of the well-known notion of variance decompositions. Specifically, the DY approach allows variable X_i to depend on its own shocks, shocks from the rest of the variables included in the estimation and an estimate of the average total spillover (across all variables included in the estimation). In this way, it provides estimates of the contributions of shocks from/to individual variables from/to the forecast error variances of all the variables in the model. Since its analytical tractability, this method has been used in several contexts (see, for example, Yarovaya et al., 2016a; 2016b). Formally, the model can be written as the following j-order N-variable VAR:

$$Y_t = \sum_{j=1}^J \Phi_j Y_{t-1} + \varepsilon_t \quad (2)$$

where, $Y_t = (Y_{1t}, Y_{2t}, \dots, Y_{Nt})$ is the vector of the N endogenous variables, Φ_j is a $N \times N$ parameter matrix and ε_t is the vector of disturbances which are independently and identically distributed over time. A useful alternative specification that is based on (2) is the moving average representation that is equal to:

$$Y_t = \sum_{j=0}^{\infty} A_j \varepsilon_{t-1} + \varepsilon_t \quad (3)$$

where, $A_j = \Phi_1 A_{j-1} + \Phi_2 A_{j-2} + \dots + \Phi_p A_{j-p}$. This variance decomposition transformation of the moving average coefficients captures the dynamics of the system. However, since VAR innovations are typically contemporaneously correlated, Cholesky factorization is used as an identification scheme to achieve orthogonality. This makes the results depend on the ordering of the variables. Thus, we follow Diebold and Yilmaz (2012) who use the generalized VAR modelling approach based on Koop *et al.* (1996) and Pesaran and Shin (1998). Following the generalized autoregressive framework approach forces forecast-error variance decompositions to be invariant to the ordering of variables, in contrast to the Cholesky-factor identification typically used in the estimation of VAR models and in Diebold and Yilmaz (2009). More precisely, the ij entry of the H -step-ahead variance decomposition is equal to:

$$z_{ij}(H) = \frac{\sigma_{jj}^{-1} \sum_{h=0}^{H-1} (\acute{e}_i A_h \Sigma e_j)^2}{\sum_{h=0}^{H-1} (\acute{e}_i A_h \Sigma \acute{A}_h e_i)} \quad (4)$$

where, σ_{jj} is the standard deviation of e for the j^{th} equation, Σ is the variance matrix of the error vector e and e_i is a vector with ones in j^{th} elements and zeros otherwise. The drawback of the generalized VAR modelling is that the own and cross-variable variance contributions shares are not equal to one. In order to overcome this issue, each entry of the variance decomposition matrix is normalized as:

$$\tilde{z}_{ij}(H) = \frac{z_{ij}(H)}{\sum_{j=1}^N z_{ij}(H)} \quad (5)$$

where, $\sum_{j=1}^N \tilde{z}_{ij}(H) = 1$ and $\sum_{i,j=1}^N \tilde{z}_{ij}(H) = N$. Given the above the total spillover index (SI) is computed as:

$$SI = \frac{\sum_{i,j=1, i \neq j}^N \tilde{z}_{ij}(H)}{\sum_{i,j=1}^N \tilde{z}_{ij}(H)} \times 100 \quad (6)$$

SI shows the average contribution of spillovers from shocks to all variables to the total forecast error variance. Alternatively, the spillover index gives the degree of the

connectedness of the J-variables system. The main advantage of spillover analysis is that the directional spillovers can be easily calculated. More precisely, the gross directional spillovers (DS) received by variable i from all the other variables are defined as:

$$DS_{i \leftarrow j}(H) = \frac{\sum_{j=1, i \neq j}^N \tilde{z}_{ij}(H)}{\sum_{j=1}^N z_{ij}(H)} \times 100 \quad (7)$$

Also, the directional spillovers transmitted by the variable i to all the other variables are defined as:

$$DS_{i \rightarrow j}(H) = \frac{\sum_{j=1, j \neq i}^N \tilde{z}_{ji}(H)}{\sum_{j=1}^N z_{ji}(H)} \times 100 \quad (8)$$

Finally, in order to examine whether one variable is net receiver or transmitter of shocks, the net spillover effects (NS) are calculated as:

$$NS = DS_{i \rightarrow j}(H) - DS_{i \leftarrow j}(H) \quad (9)$$

All the measures above can be estimated in a static way, i.e. the whole period of study can be utilized to calculate them. However, the period that we examine in this study contains certain sub-periods of special interest, like the global financial crisis. Therefore, static analysis may omit several aspects of stress transmission. For this reason, spillovers are calculated by using a rolling estimation window of 200 days with 10-days H-step-ahead error variances in forecasting, which comprise an adequate number of observations to obtain robust VAR estimates and at the same time capture the dynamics of petroleum-based commodities.^{8,9}

⁸ Different rolling window estimates (50, 100 and 200 days) and horizon h-values (10 and 20 days) have been used as robustness tests for the results reported. In all cases, the results are not changing significantly due to alternative rolling window and time horizon selections. Similar alternative values of rolling window estimates and horizon h-values are also adopted by previous studies in the literature as robustness tests (see, for instance, Diebold Yilmaz, 2009; 2012 and Antonakakis et al. 2015).

⁹ One shortcoming of the DY approach is that it does not capture potential asymmetries in spillovers. Barunik et al. (2015) and Barunik and Krehlik (2016) provide efforts towards the direction of capturing asymmetry effects in spillovers.

4. Data description

Daily time series of closing spot prices, futures prices, futures total volume and futures open interest are examined. Spot prices are from U.S. Energy Information Administration (EIA) and futures prices, trading volume and open interest are obtained through Bloomberg data vendor. The 1-month (next month delivery) futures contracts traded on the New York Mercantile Exchange (NYMEX) are examined for crude oil, heating oil and gasoline contracts.¹⁰ Returns are calculated as the continuously compounded day-to-day difference on commodities prices. The sample spans the period from March 1, 2006 to June 19, 2015.¹¹ The time period examined spans close to a decade of data and includes the period of the global financial crisis, thus being representative of both up and down states of the business cycle. As a futures contract approaches its expiration, investors close their positions and open new positions in the next near contract. However, typically there is low open interest and high price volatility during the last trading days of futures contracts. For this reason, this paper uses front month futures contract prices which roll over five days before contract's expiration. After filtering the data for holidays, missing values and non-trading days, the final sample contains 2,341 daily observations. The daily trade volume measures the number of contracts traded on a given day. Open interest represents the total number of futures contracts either long or short that have been entered into and not yet offset by delivery. Each open transaction has a buyer and seller, but for the calculation of open interest only one side of the contract is counted.

Panel A of Table 1 presents the descriptive statistics for the daily returns of spot and futures (near month) markets across petroleum-based commodities. As observed the mean returns are close to zero but positive for all spot and futures returns examined apart from those of crude oil. Next, standard deviations reported are similar across spot-futures returns and petroleum-based commodities. Panel B of Table 1 presents the descriptive

¹⁰ The standard NYMEX (CL) futures contract size is for 1,000 barrels of the underlying commodity (crude oil).

¹¹ Near month futures prices on crude oil are available since March 1983, for heating oil since July 1986 and for gasoline since October 2005 but with several gaps until March 1, 2006. In order to obtain a common time period for all the time series examined we restrict our analysis to the period March 1, 2006 to June 19, 2015.

statistics for the futures trading volume and futures open interest across petroleum-based commodities. The mean values of both futures trading volume and futures open interest are much larger for the crude oil contract rather than for the heating oil and gasoline contracts. The same pattern holds for the standard deviations of these time series. Jarque and Bera (1980) normality test strongly rejects the null hypothesis of normality at the 5% significance level for all the time series examined in Panels A and B of Table 1. Finally, the p-values of the Augmented Dickey and Fuller (1981) (ADF) unit root test suggest that spot-futures returns, trading volume and open interest time series are $I(0)$.

Please insert Table 1 here

Figure 1 depicts time series plots for the realized variances of spot-futures markets obtained after calculating the realized volatility estimates. As observed, the realized variances estimates of spot and futures markets exhibit a substantial increase after September 2008 and until August 2009 across all petroleum-based commodities examined. Next, Figure 2 depicts time series plots for the futures trading volume and futures open interest of the petroleum-based commodities examined. As observed, futures trading volume and futures open interest values are much larger for crude oil rather than for heating oil and gasoline commodities. The realized volatility estimates of the spot and futures returns across petroleum-based commodities are used as inputs for the estimation of the generalized VAR framework of Diebold and Yilmaz (2012).

Please insert Figure 1 here

Please insert Figure 2 here

5. Empirical results and discussion

The results of this paper are presented in two separate sections in order to address the two distinct but interrelated research questions examined empirically in this paper. These research questions are: first, the evolution, severity and direction of volatility spillovers of spot-futures markets when petroleum-based commodities are examined pairwise and

second, the evolution, severity and direction of spillovers among spot-futures volatilities, futures trading volume and futures open interest for each individual petroleum-based commodity. Following this rationale, section 5.1 presents the results for the four-variate VARs between spot-futures realized volatilities examined pairwise for all possible pairs of the petroleum-based commodities examined, i.e. for the pairs: crude oil – heating oil, crude oil – gasoline and heating oil – gasoline. Furthermore, section 5.2 reports the results for the four-variate VAR models which include spot-futures realized volatilities, trading volume and open interest for each individual petroleum-based commodity.

5.1 Spot-futures volatility spillovers of petroleum based commodities - examined pairwise

The static (average) spillovers of the four-variate VAR models estimated for the following pairs of commodities: crude oil – heating oil, crude oil – gasoline and heating oil – gasoline, are presented in panels A1, A2 and A3 of Table 2, respectively. As observed, the average value of the total volatility spillover index is equal to 23.90%, 19.20% and 19.90% for panels A1, A2 and A3 of Table 2, respectively.

Regarding the static net spillovers, panel A1 of Table 2 suggests that the futures markets of crude oil is on average a net transmitter of shocks equal to 36% (=52%-16%), whereas the futures market of the heating oil transmits a lower 12% (=38%-26%) of shocks to the rest of the examined markets. Lower net spillovers are observed among the spot-futures volatilities of the pair crude oil – gasoline reported in panel A2. Specifically, the crude oil futures market is a transmitter of smaller shocks equal to 21% (=42%-21%) to the rest of the examined markets and the gasoline futures market transmits only 3% (=29%-26%) of shocks. Finally, panel A3 shows that the heating oil futures market is a net transmitter of shocks equal to 14% (=35%-21%) to the rest of the examined markets, whereas the gasoline futures market transmits a higher 17% (=34%-17%) of shocks.

Overall, the static (average) spillovers between the spot-futures volatilities and across petroleum-based commodities examined pairwise reveal the following: First, crude oil futures market transmit larger volatility spillovers to the futures markets of the rest petroleum-based commodities (heating oil and gasoline) rather than to the underlying

asset, i.e. the spot market of crude oil. The same result (albeit weaker in magnitude) holds also for the gasoline futures market, as it transmits volatility spillovers mainly to the futures markets of the rest of petroleum-based commodities (crude oil and heating oil) rather than to its underlying market, i.e. the spot market of gasoline. In contrast, the futures market of heating oil transmits larger volatility spillovers on average to its underlying market, i.e. the spot market of heating oil, rather than to the futures markets of crude oil and gasoline.

Regarding the investigation of dynamic volatility spillovers, Figures 3a, 3b and 3c depict the total volatility spillover index for the spot-futures volatilities of the pairs: crude oil - heating oil, crude oil – gasoline and heating oil – gasoline, respectively. As observed in Figure 3a, the index experiences a notable increase (reaching values just below 50%) over the period late-2006 to late-2008. Then the index experiences another increasing rally from mid-2009 until mid-2013, when from just over 30% increased to more than 50%, with a short correction period during 2011. After mid-2013 the index experienced a severe drop and high volatility, as it dropped sharply until early-2014 to reach a minimum of 12%. Next, Figure 3b presents the total volatility spillover index for the spot-futures market between crude oil and gasoline commodities. As observed, the index declines from values around 30% to values close to 10% during the 2006 to early-2008 period. Subsequently, the index starts an increasing rally with substantial volatility during the period mid-2008 (values of around 10%) until early-2012 (values of around 40%). Next, the index exhibits a decline over the period early 2012 (values of around 40%) to mid-2013 (values of around 10%) to increase again moderately during the period mid-2013 until the end of the sample period examined mid-2015 (values close to 25%). Finally for the heating oil – gasoline pair, Figure 3c depicts the total volatility spillover index which increases from values of around 22% in mid-2007 to values of around 50% in early-2009. Then, the index experiences a significant drop until end-2009 (values of around 27%) to rise again rapidly to values close to 60% in early-2012 (with a short correction period during 2011). Finally, the index declines progressively from 60% in early-2012 to around 12% in early-2015.

Overall, the spillover indices depicted in Figures 3a to 3c reveal the existence of large dynamic volatility spillovers with considerable variations over time between the spot-futures volatilities when petroleum-based commodities are examined pairwise. Specifically, Figures 3a to 3c reveal that when examined pairwise the total spillovers among the spot-futures volatilities between crude oil and oil products (heating oil and gasoline) increase substantially and exhibit high volatility during the period 2007-2011. In addition, total volatility spillover indices for all the pairs of petroleum-based commodities examined increase notably during the period of the global financial crisis (2007-2009). In contrast, a common decrease of the index across all petroleum-based commodities is observed during the period 2011 to 2014, followed by a sharp increase after 2014.

Please insert Figure 3 here

Apart from the dynamic total volatility spillover index presented in Figures 3a, 3b and 3c, the net spillover indices are estimated and presented in Figures 4a, 4b and 4c. Specifically, Figure 4a depicts the net spillover indices for the spot-futures volatilities between crude oil and heating oil. Net spillovers for the futures markets of both the crude oil and the heating oil exhibit positive values for the whole period examined, with very few exceptions for short periods of time. This result shows that the future markets of crude oil and heating oil are primarily net transmitters of volatility spillovers to each other and their corresponding spot markets. This effect is more pronounced for the futures volatility of crude oil when compared with the futures volatility of heating oil. Similarly, Figure 4b reveals that futures volatilities of crude oil and gasoline commodities also transmit spillovers (positive values) to each other and their corresponding spot markets for the largest part of the period examined, albeit this effect is less pronounced when compared to the pair crude oil-heating oil (Figure 4a). Last, Figure 4c presents the results for the heating oil - gasoline pair, which are similar to the ones presented for the crude oil – heating oil pair (Figure 4a), i.e. the net volatility spillovers remain positive (transmitters of shocks) for the futures volatilities of heating oil and gasoline, while the

corresponding spot volatility spillovers are negative (receivers of shocks), especially for the spot volatility of heating oil.

Please insert Figure 4 here

5.1.1 Discussion of the results: spot-futures volatility spillovers of petroleum based commodities - examined pairwise

Overall, the results presented in Figures 4a to 4c can be interpreted as follows. Futures volatility of crude oil has a dominant position among all spot-futures markets and across petroleum-based commodities in transmitting shocks to the rest of the examined markets (Figures 4a and 4b). In other words, futures volatility of crude oil is shown to explain a significant proportion of future error variance of futures volatilities for heating oil and gasoline; and to a lesser extent of the corresponding spot markets. This result is in line with (Hammoudeh et al., 2003) who show that the 1-month futures prices have the most predictive information content that may help explain future movements and volatility of the crude oil spot market.

Regarding the magnitude of the estimated spillovers, the largest spillovers are observed for the pair crude oil – heating oil, where the futures markets are mainly transmitters and their corresponding spot markets are mainly receivers of future error variance shocks. In addition, futures volatility of heating oil is a stronger transmitter of shocks to the spot-futures volatilities across petroleum commodities when compared with the transmitted shocks coming from futures volatility of gasoline. The interactions (spillovers) between crude oil-heating oil and heating oil-gasoline pairs are overall larger and more persistent than the ones observed for the crude oil-gasoline pair.

The above results provide a dynamic investigation of volatility spillovers across petroleum based commodities and reveal that large and time-varying volatility spillovers are observed across petroleum-based commodities when examined pairwise. This evidence suggests the presence of strong information flows across petroleum-based commodities which can be linked with traders' decisions for cross-asset trades.

Furthermore, the results presented also point to the pronounced “financialization” of petroleum-based commodities due to the existence of strong interdependencies among the volatilities of their futures markets. Evidence presented also suggest that futures investors and traders in petroleum-based commodities should monitor market news in all crude oil, heating oil and gasoline markets as their futures volatilities exhibit large volatility spillovers among themselves.

5.2 Spillovers among spot-futures volatilities, trading volume and open interest of petroleum-based commodities examined individually

This section presents the results for the dynamic spillovers among spot-futures volatilities, trading volume and open interest, when the petroleum-based commodities are examined individually. Panels B1, B2 and B3 of Table 2 report the static (average) spillovers for crude oil, heating oil and gasoline and the average values of the total volatility spillover indices are equal to 21.70%, 25.10% and 22.10%, respectively. These values indicate that considerable spillovers exist on average among the volatilities of spot-futures volatilities, trading volume and open interest for individual petroleum-based commodities. For example, in Panel B1 of Table 2 futures crude oil trading volume “FCLVOL” and open interest “FCLOI” transmit/receive spillovers over 30% to/from each other. However, panels B2 and B3 of Table 2 reveal different results. Specifically, for heating oil and gasoline commodities the transmitted spillovers from futures open interest to futures trading volume are equal to 47.9% and 51.5%, which is more than double the spillovers transmitted from trading volume to open interest, equal to 22.2% and 17.9%, respectively. Last, spot-futures volatilities transmit/receive negligible spillovers to/from futures trading volume and futures open interest for all the individual petroleum based commodities.

Next, dynamic volatility spillovers are presented in Figures 5a to 5c, which depict the total spillover indices for the individual crude oil, heating oil and gasoline markets, respectively. Specifically, in Figure 5a the total spillover index for crude oil exhibits relatively modest fluctuations around the value of 30% and within the range of 22-37%. The index exhibits a notable increase during the Lehman Brothers collapse in September

2008 (values close to 36%) and subsequently it drops to values around 20-25% during the period mid-2013 to mid-2014. Next, in Figure 5b for the heating oil, the total spillover index rises progressively from values less than 30% during 2007 to values close to 50% in mid-2011 and subsequently drops after mid-2013 to reach values less than 30% in early-2015. Finally, in Figure 5c for the gasoline, the index exhibits overall larger fluctuations and evolves within the range of 18-40% for the whole period examined. In particular, the index builds up after mid-2008 (reaching values over 30% in early-2009) and later during the years 2011 to 2013 when from around 22% in early-2011 reaches 40% in late-2011.

Please insert Figure 5 here

Apart from the dynamic total volatility spillover indices presented, the net spillover indices are estimated and presented in Figures 6a, 6b and 6c for crude oil, heating oil and gasoline, respectively. Specifically, for crude oil, Figure 6a depicts the net spillover indices for spot-futures volatilities, trading volume and open interest. As observed, trading volume transmits modest spillovers (values of 5-10%) to the rest of the examined markets, i.e. spot and futures volatilities and open interest. The volatility of crude oil future market is also transmitting spillovers to the rest of the markets examined, albeit smaller in magnitude (0-5%). Next, Figure 6b for heating oil, reveals that the largest spillovers (within the 8-22% range) are transmitted historically from the futures volatility to the rest of the examined markets. Similarly, open interest transmits spillovers to the rest of the examined markets, albeit smaller in magnitude (within the 2-15% range). Finally, for the gasoline market (Figure 6c), open interest transmits large (within the 8-16% range) and persistent spillovers to the rest of the examined markets, whereas futures volatility is both a receiver and transmitter of shocks from/to the rest of the markets and during the examined period.

Please insert Figure 6 here

5.2.1 Discussion of the results: spillovers among spot-futures volatilities, trading volume and open interest of petroleum-based commodities examined individually

Overall, relatively large and significantly time-varying spillovers are observed among spot-futures volatilities, trading volume and open interest when the petroleum-based commodities are examined individually. For crude oil, the largest spillovers are historically transmitted from trading volume to the rest of the variables examined (Figure 6a), i.e. futures volatility, spot volatility and open interest. This result has two implications: first, it reveals the existence of large speculative pressures in the futures market of crude oil as trading volume reflects the demand for speculative trades; second, consistent with the SAI hypothesis by (Copeland, 1976) trading volume transmits shocks to the future error variance of the futures volatility.¹² Therefore, trading volume can significantly contribute to forecasting methods of spot and futures volatilities. Moreover, futures volatility also transmits significant shocks to the rest of the variables examined and in this way highlights the pronounced financialization of the crude oil market (Figure 6a).

In contrast, for heating oil and gasoline (Figs. 6b and 6c), results reveal that open interest has a significant role in transmitting shocks to the future error variance of the variables examined. Specifically, in the case of heating oil, futures volatility transmits the largest shocks to the rest of the variables (followed by open interest), while for the gasoline market, open interest transmits the largest shocks to the rest of the variables (followed by futures volatility). These results reveal that for heating oil and gasoline commodities, which are products of the generic crude oil commodity, hedging pressures as reflected by open interest are more important when compared to speculative pressures as reflected by trading volume. Consistent with expectations, the hedging pressures are more pronounced during the period of the global financial crisis - when open interest transmits the largest recorded shocks to the future error variance of the rest of the variables for the sample period examined (Figs. 6b and 6c). Therefore, traders and investors in heating oil and gasoline commodities should take into account possible changes in open interest when

¹² SAI hypothesis supports that trading volume, being a proxy of price-relevant new information, has high explanatory power for futures volatility. Thus, trading volume of futures contracts in previous periods can guide stock market participants to reduce the risk of their positions.

forecasting their spot-futures volatilities, on this see also Lucia and Pardo (2010) for futures equity markets. In addition, the results presented suggest the pronounced financialization of heating oil and gasoline markets as their futures volatility has a leading role in transmitting shocks to the rest of the examined variables. The difference in the results obtained for crude oil and heating oil-gasoline markets can be attributed to the observed asymmetry of the relation between futures volatility and trading volume for the crude oil market but not for the heating oil and gasoline markets, see also Alizadeh and Tamvakis (2016). Specifically, the authors show that the relationship between the two is positive and more sensitive when the market is in backwardation.

6. Conclusions

This paper is the first to investigate the existence, the severity and the direction of time-varying spillover effects across petroleum-based commodities and among their spot-future markets volatilities, trading volume and open interest. The empirical results presented reveal the importance of computing dynamic spillovers for the petroleum-based commodities as the static spillovers computed are missing the set of dynamics within and between these markets. Specifically, futures volatility of crude oil is shown to transmit large and persistent spillovers to the futures volatilities of heating oil and gasoline commodities. Furthermore, open interest and futures volatility transmit substantial spillovers to spot volatility and trading volume over time for heating oil and gasoline commodities, indicating the existence of substantial hedging pressures within these markets. In contrast, for the crude oil market, trading volume and futures volatility transmit substantial spillovers to spot volatility and open interest over time, indicating the existence of substantial speculative activities in this market. Overall, the results reported reveal that for the heating oil and gasoline commodities, hedging pressures as reflected by open interest are more important when compared to speculative pressures as reflected by trading volume. Therefore, traders and investors in heating oil and gasoline commodities should take into account possible changes in open interest when forecasting their spot-futures volatilities.

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Table 1: Descriptive statistics of spot and futures markets daily returns, futures trading volume and futures open interest for crude oil (CL), heating oil (HO) and gasoline (XB) commodities – Sample period 2006:03-2015:06

Panel A: Spot and futures markets returns						
Statistic	Spot Market			Futures Market		
	CL>Returns	HO>Returns	XB>Returns	CL>Returns	HO>Returns	XB>Returns
Mean	-9.81E-06	7.50E-06	9.19E-05	-1.66E-05	2.85E-05	5.74E-05
Median	0.001	0.000	0.001	0.001	0.001	0.001
Standard Deviation	0.023	0.021	0.029	0.023	0.025	0.023
Skewness	0.045	-0.142	0.124	0.075	-0.556	-0.253
Kurtosis	8.443	6.034	7.191	8.438	9.194	6.447
J-B [p-value]	0.000	0.000	0.000	0.000	0.000	0.000
ADF [p-value]	0.000	0.000	0.000	0.000	0.000	0.000
Observations	2341	2341	2341	2341	2341	2341

Panel B: Futures trading volume and futures open interest						
Statistic	Volume			Open Interest		
	FCLVOL	FHOVOL	FXBVOL	FCLOI	FHOOI	FXBOI
Mean	254700.315	37643.157	36812.743	228223.353	50810.585	49930.813
Median	259243	36158	37215	255959	49846	48015
Standard Deviation	106142.863	16885.253	17923.635	112691.321	28281.092	30861.794
Skewness	0.054	0.323	-0.000	-0.405	0.125	0.254
Kurtosis	3.336	2.745	2.703	2.282	2.078	2.197

J-B [p-value]	0.000	0.000	0.000	0.000	0.000	0.000
ADF [p-value]	0.001	0.045	0.036	0.000	0.003	0.003
Observations	2341	2341	2341	2341	2341	2341

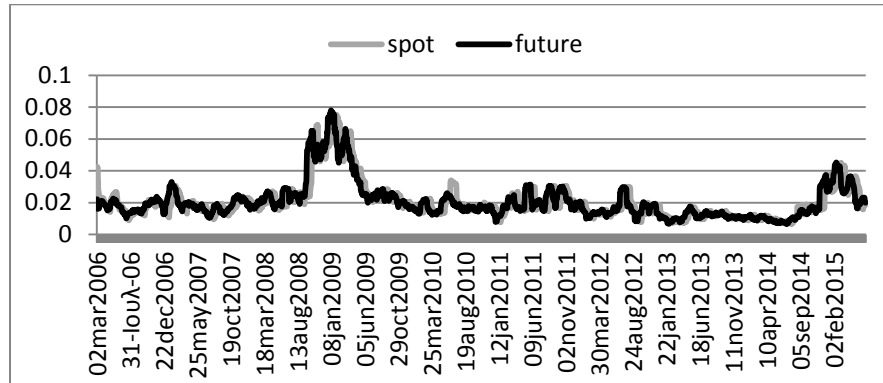
Note: FCLVOL, FHOVOL and FXBVOL refer to futures crude oil volume, futures heating oil volume and futures gasoline volume, respectively. FCLOI, FHOOI and FXBOI refer to futures crude oil open interest, futures heating oil open interest and futures gasoline open interest, respectively. Returns are the daily continuously compounded returns. Mean refers to the arithmetic average and Median to the value of the 50th percentile. Standard deviation is the daily standard deviation of the respective time series. Min and max are the minimum and maximum values of the sample data, respectively. Skewness and kurtosis are the estimated centralized third and fourth moments of the data. J-B is the Jarque and Bera (1980) test for normality; the statistic is $\chi^2(2)$ distributed. ADF is the Augmented Dickey and Fuller (1981) test. The ADF regressions include an intercept term. The lag length of the ADF test is determined by minimizing Schwarz's (1978) Bayesian Information Criterion (SBIC). Numbers in square brackets [.] indicate p-values.

Table 2: Static (average) volatility spillovers between spot-futures and across petroleum based commodities – examined pairwise (Panel A1: CL-HO, Panel A2: CL-XB, Panel A3: HO-XB) and spot-futures volatilities, futures trading volume and open interest across petroleum based commodities – examined individually (Panel B1: CL, Panel B2: HO, Panel B3: XB)

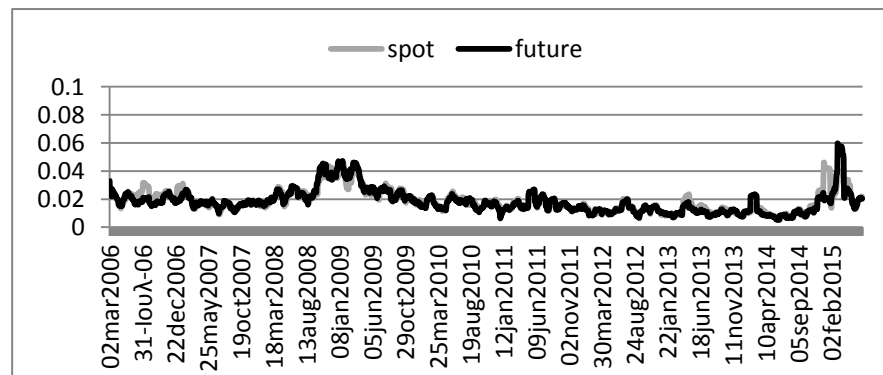
Panel A1						Panel B1							
	RVCLSPOT	RVCLFUT	RVHOSPOT	RVHOFUT	From Others	Net Result	RVCLSPOT	RVCLFUT	FCLVOL	FCLOI	From Others	Net Result	
RVCLSPOT	85.0	11.3	0.2	3.5	15	-11 (receiver)	RVCLSPOT	87.5	12.2	0.3	0.0	13	-12 (receiver)
RVCLFUT	0.7	84.0	0.1	15.2	16	36 (transmitter)	RVCLFUT	0.8	94.1	4.5	0.5	6	9 (transmitter)
RVHOSPOT	3.0	15.3	62.0	19.6	38	-37 (receiver)	FCLVOL	0.1	2.7	62.9	34.3	37	-1 (receiver)
RVHOFUT	0.3	25.8	0.3	73.6	26	12 (transmitter)	FCLOI	0.2	0.5	30.8	68.6	31	4 (transmitter)
Contribution to others	4	52	1	38	96		Contribution to others	1	15	36	35	87	
Contribution including own	89	136	63	112	23.9%		Contribution including own	89	109	99	103	21.7%	
Panel A2						Panel B2							
	RVCLSPOT	RVCLFUT	RVXBSPT	RVXBFUT	From Others	Net Result	RVHOSPOT	RVHOFUT	FHOVOL	FHOOI	From Others	Net Result	
RVCLSPOT	86.0	11.0	0.2	2.8	14	-12 (receiver)	RVHOSPOT	76.2	21.7	1.2	0.8	24	-22 (receiver)
RVCLFUT	0.8	78.7	1.7	18.8	21	21 (transmitter)	RVHOFUT	1.6	95.8	2.0	0.6	4	20 (transmitter)
RVXBSPT	0.6	7.0	84.6	7.8	15	-12 (receiver)	FHOVOL	0.1	1.3	50.6	47.9	49	-24 (receiver)
RVXBFUT	0.7	24.4	1.0	73.9	26	3 (transmitter)	FHOOI	0.1	0.7	22.2	77.0	23	26 (transmitter)
Contribution to others	2	42	3	29	77		Contribution to others	2	24	25	49	100	
Contribution including own	88	121	88	103	19.20%		Contribution including own	78	120	76	126	25.1%	
Panel A3						Panel B3							
	RVHOSPOT	RVHOFUT	RVXBSPT	RVXBFUT	From Others	Net Result	RVXBSPT	RVXBFUT	FXBVOL	FXBOI	From Others	Net Result	
RVHOSPOT	70.6	18.6	3.4	7.3	29	-24 (receiver)	RVXBSPT	90.8	7.8	0.9	0.5	9	-7 (receiver)
RVHOFUT	1.0	79.5	0.7	18.8	21	14 (transmitter)	RVXBFUT	1.7	93.5	3.2	1.7	6	5 (transmitter)
RVXBSPT	2.3	1.8	87.6	8.3	12	-6 (receiver)	FXBVOL	0.1	1.7	46.7	51.5	53	-31 (receiver)
RVXBFUT	1.4	14.4	1.6	82.6	17	17 (transmitter)	FXBOI	0.1	1.3	17.9	80.7	19	35 (transmitter)
Contribution to others	5	35	6	34	80		Contribution to others	2	11	22	54	88	
Contribution including own	75	114	93	117	19.9%		Contribution including own	93	104	69	134	22.1%	

Note: Each entry of this table represents static (average) spillovers. Specifically, Panel A1 refers to spillovers among the following realized volatilities: crude oil spot (RVCLSPOT), crude oil future (RVCLFUT), heating oil spot (RVHOSPOT) and heating oil future (RVHOFUT). Panel A2 refers to spillovers among the following realized volatilities: crude oil spot (RVCLSPOT), crude oil future (RVCLFUT), gasoline spot (RVHOSPOT) and gasoline future (RVHOFUT). Panel A3 refers to spillovers among the following realized volatilities: heating oil spot (RVCLSPOT), heating oil future (RVCLFUT), gasoline spot (RVHOSPOT) and gasoline future (RVHOFUT). Panel B1 refers to spillovers among crude oil's realized volatility for the spot (RVCLSPOT) and future (RVCLFUT) markets, volume (FCLVOL) and open interest (FCLOI). Panel B2 refers to spillovers among heating oil's realized volatility for the spot (RVHOSPOT) and future (RVHOFUT) markets, volume (FHOVOL) and open interest (FHOOI). Panel B3 refers to spillovers among gasoline's realized volatility for the spot (RVXBSPT) and future (RVXBFUT) markets, volume (FXBVOL) and open interest (FXBOI).

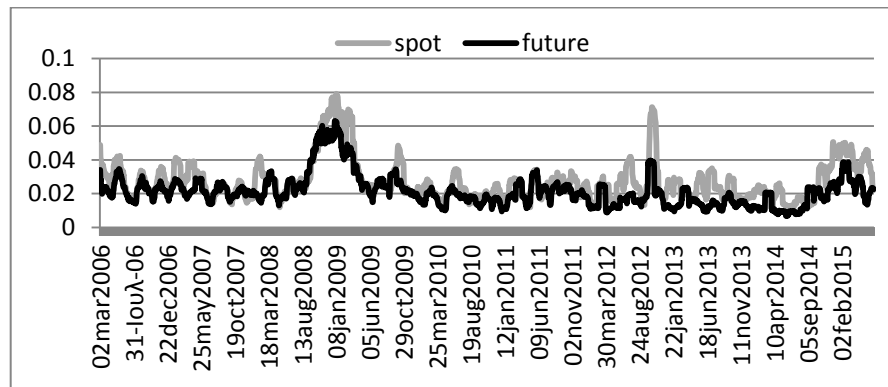
Figure 1: Spot and futures realized variances for crude oil (CL), heating oil (HO) and gasoline (XB) commodities



(a) Crude oil (CL)



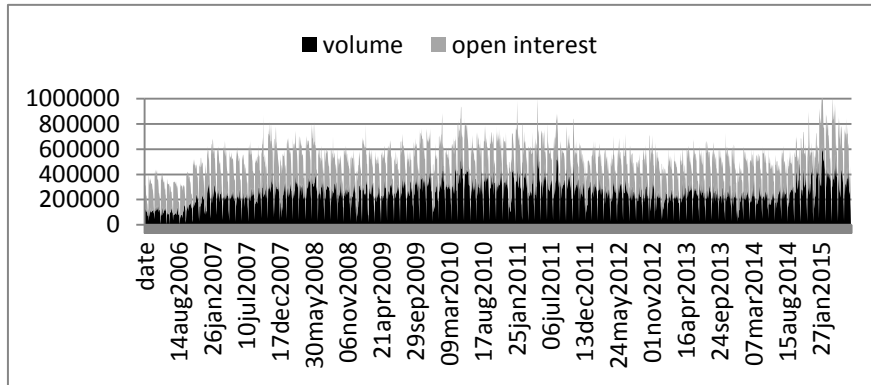
(b) Heating oil (HO)



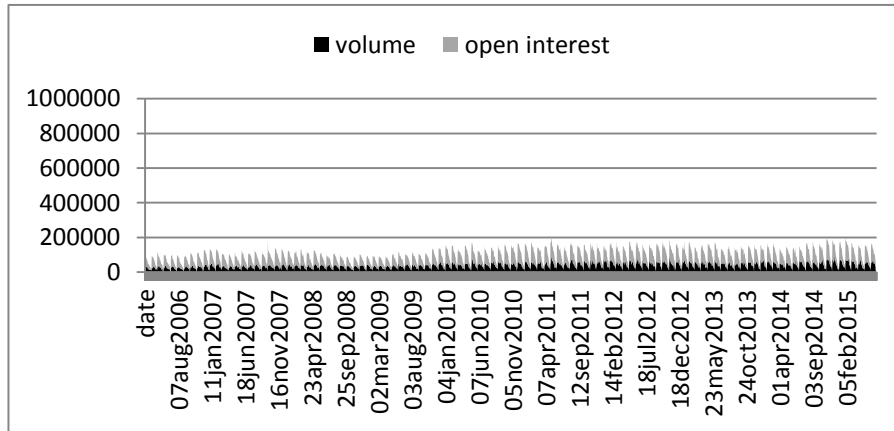
(c) Gasoline (XB)

Note: Each Figure depicts the spot and futures realized variances for the following petroleum-based commodities: crude oil (CL), heating oil (HO) and gasoline (XB). The grey colour lines depict the spot realized variances and the black colour lines depict the futures realized variances.

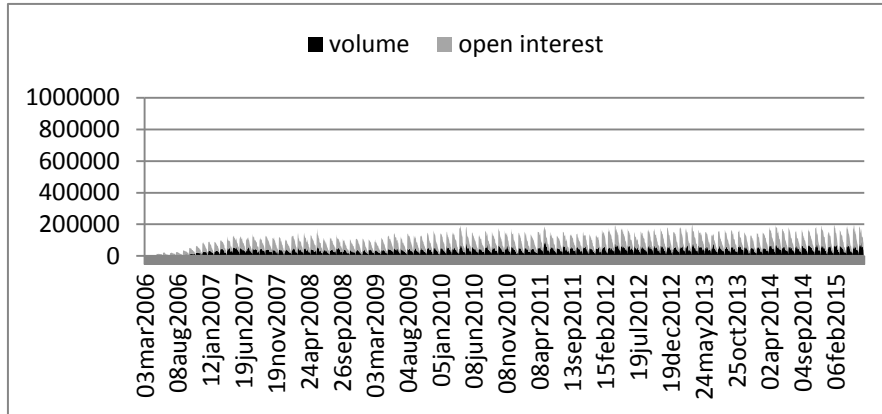
Figure 2: Futures trading volume and futures open interest for crude oil (CL), heating oil (HO) and gasoline (XB) commodities



(a) Crude oil (CL)



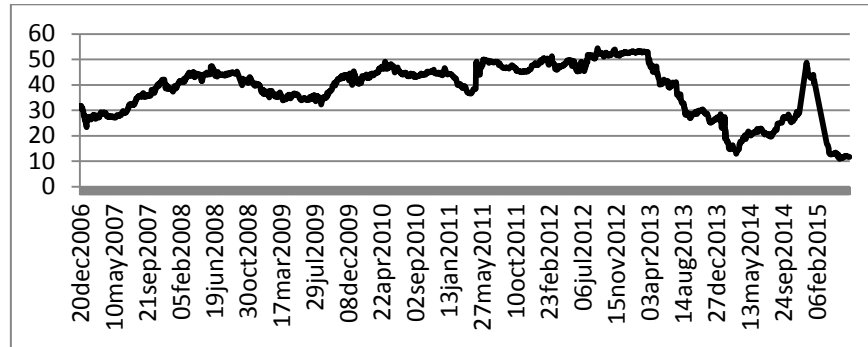
(b) Heating oil (HO)



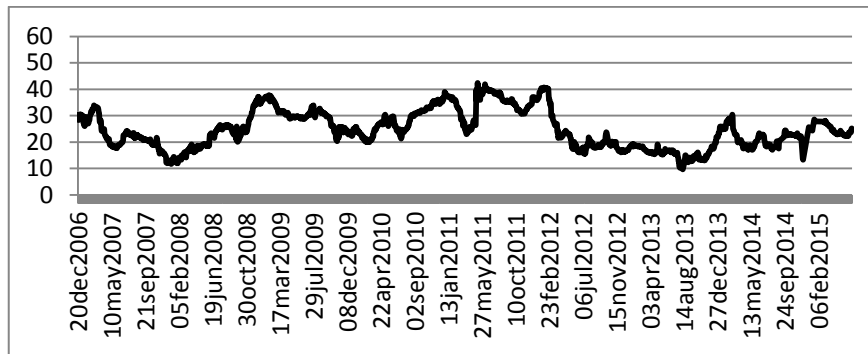
(c) Gasoline (XB)

Note: Each Figure contains futures trading volume and futures open interest for crude oil (CL), heating oil (HO) and gasoline (XB). The grey colour bars depict futures open interest and the black colour bars depict futures trading volume.

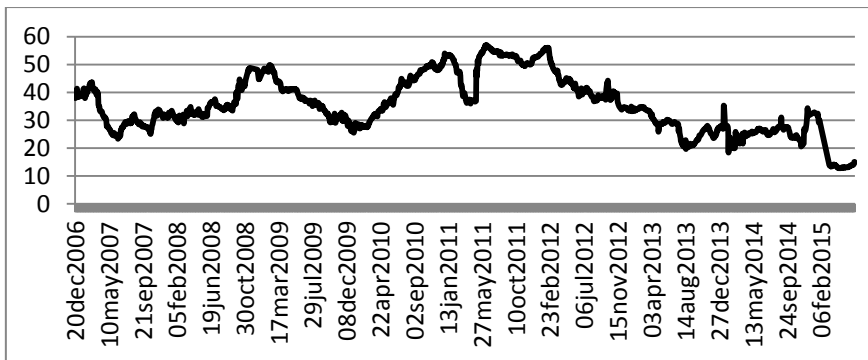
Figure 3: Total volatility spillover indices for spot-futures realized volatilities of petroleum-based commodities - examined pairwise



(a) Crude oil and heating oil – A1



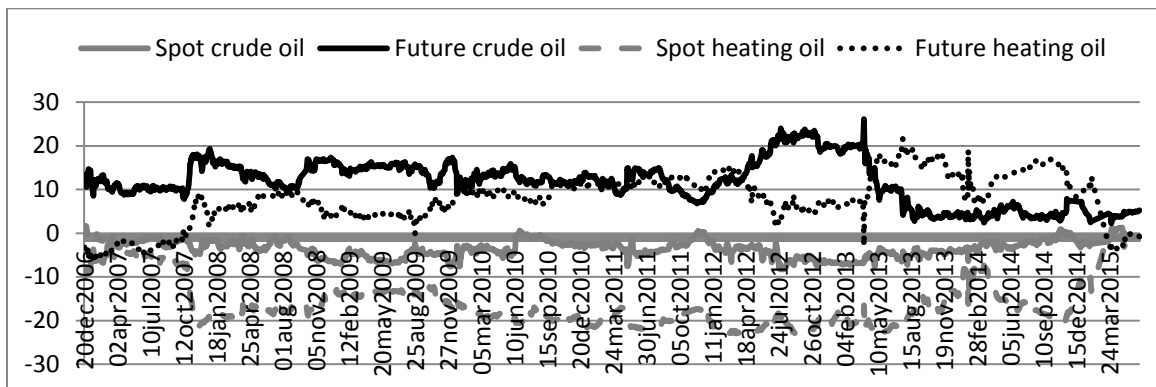
(b) Crude oil and gasoline – A2



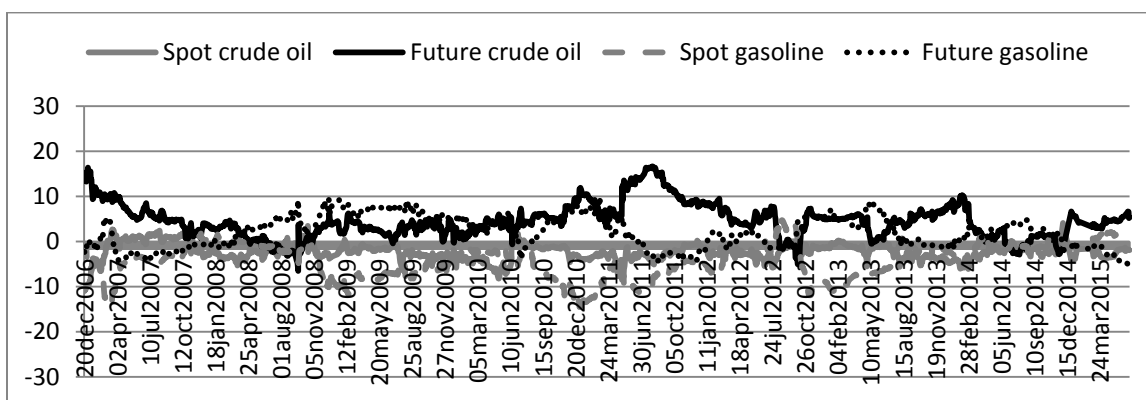
(c) Heating oil and gasoline– A3

Note: Each subplot depicts the (dynamic) total spillover index between spot-futures volatilities of petroleum-based commodities examined pairwise. Specifically, subplot 3a (A1) presents total spillovers among the following price volatilities; crude oil spot (RVCLSPOT), crude oil future (RVCLFUT), heating oil spot (RVHOSPOT) and heating oil future (RVHOFUT). Subplot 3b (A2) plots total spillovers among the following price volatilities; crude oil spot (RVCLSPOT), crude oil future (RVCLFUT), gasoline spot (RVXBSPOT) and gasoline future (RVXBFUT). Subplot 3c (A3) shows spillovers among the following price volatilities; heating oil spot (RVHOSPOT), heating oil future (RVHOFUT), gasoline spot (RVXBSPOT) and gasoline future (RVXBFUT).

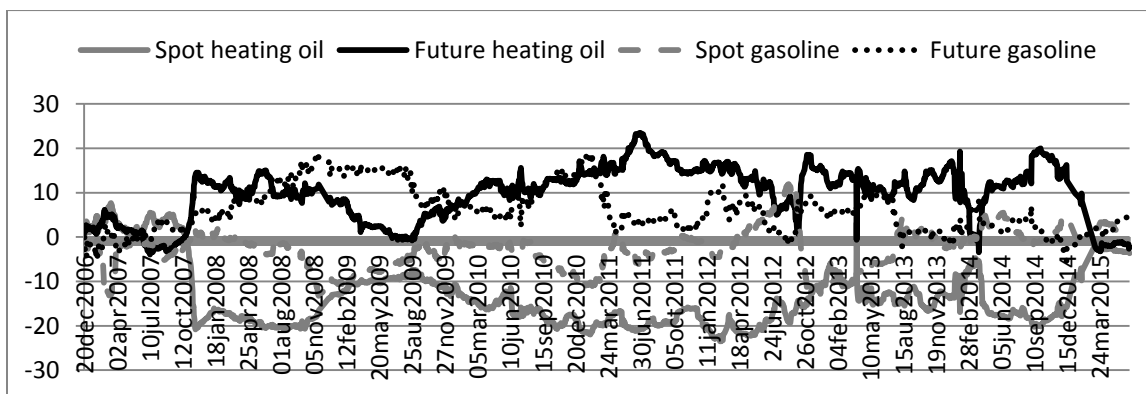
Figure 4: Net volatility spillovers for spot-futures realized volatilities of petroleum-based commodities - examined pairwise



(a) Crude oil and heating oil – A1



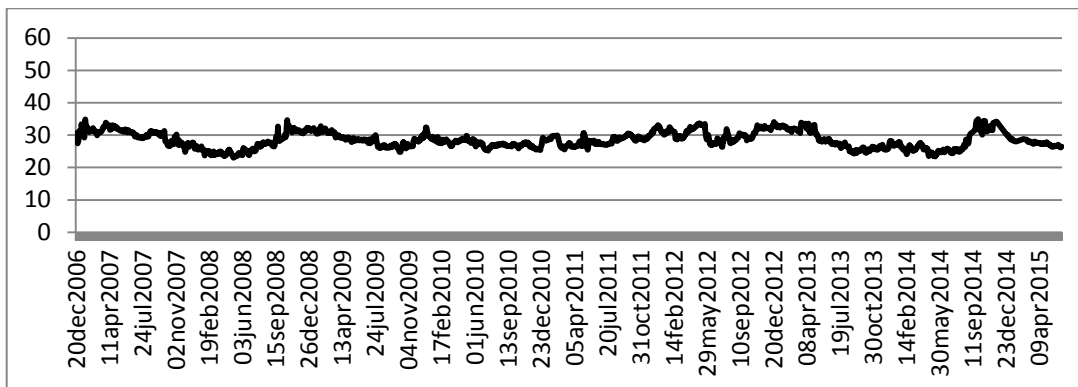
(b) Crude oil and gasoline – A2



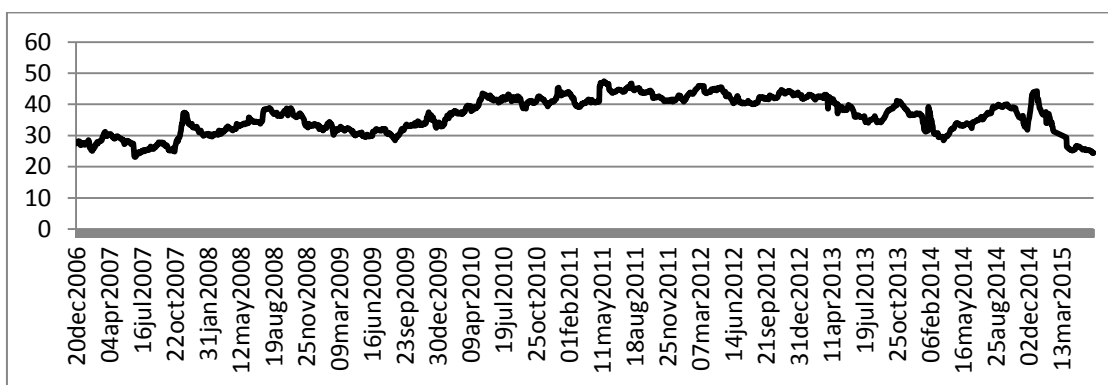
(c) Heating oil and gasoline – A3

Note: Each subplot depicts the (dynamic) net spillover index between spot-futures volatilities of petroleum-based commodities examined pairwise. Specifically, subplot 4a (A1) shows net spillovers among the following price volatilities; crude oil spot (RVCLSPOT), crude oil future (RVCLFUT), heating oil spot (RVHOSPOT) and heating oil future (RVHOFUT). Subplot 4b (A2) presents net spillovers among the following price volatilities; crude oil spot (RVCLSPOT), crude oil future (RVCLFUT), gasoline spot (RVXBSPOT) and gasoline future (RVXBFUT). Subplot 4c (A3) depicts net spillovers among the following price volatilities; heating oil spot (RVHOSPOT), heating oil future (RVHOFUT), gasoline spot (RVXBSPOT) and gasoline future (RVXBFUT). Positive (negative) values indicate volatility spillovers transmitters (receivers).

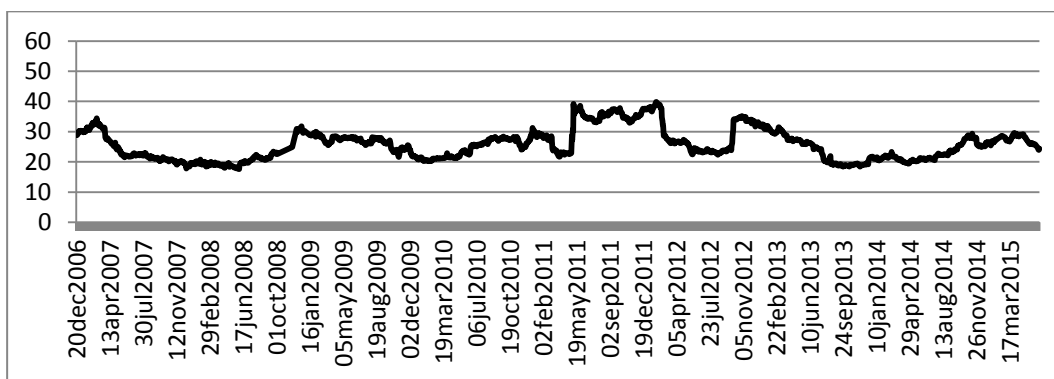
Figure 5: Total volatility spillovers for spot-futures realized volatilities, trading volume and open interest of petroleum-based commodities - examined individually



(a) Crude oil – B1



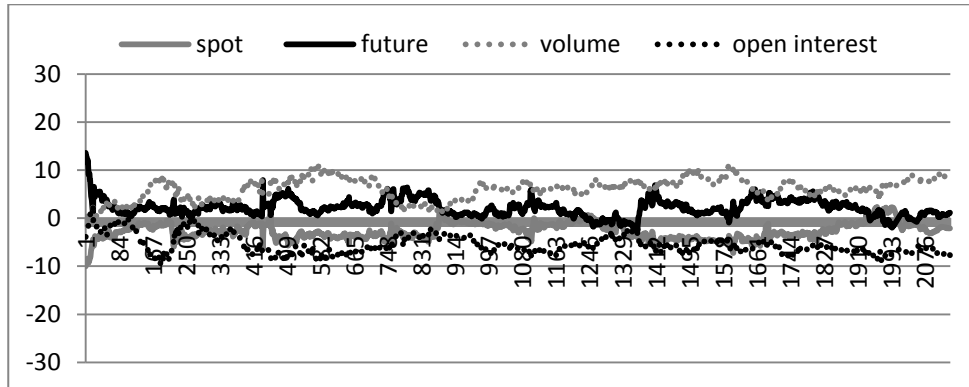
(b) Heating oil – B2



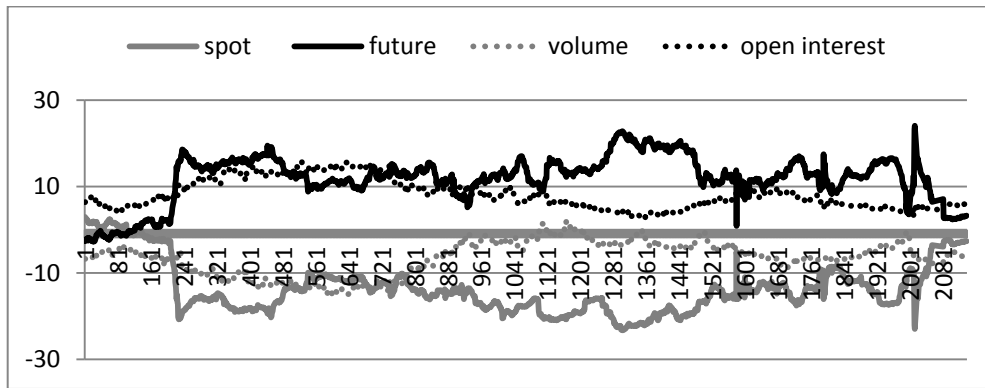
(c) Gasoline – B3

Note: Each subplot depicts the (dynamic) total spillover index among spot-futures volatilities, trading volume and open interest of petroleum-based commodities examined individually. Specifically, subplot 5a (B1) presents total spillovers among crude oil's: spot (RVCLSPOT) and future (RVCLFUT) price volatility, futures trading volume (FCLVOL) and futures open interest (FCLOI). Subplot 5b (B2) depicts total spillovers among heating oil's: spot (RVHOSPT) and future (RVHOFUT) price volatility, futures trading volume (FHOVOL) and futures open interest (FHOOI). Subplot 5c (B3) shows total spillovers among gasoline's: spot (RVXBSPT) and future (RVXBFUT) price volatility, futures trading volume (FXBVOL) and futures open interest (FXBOI).

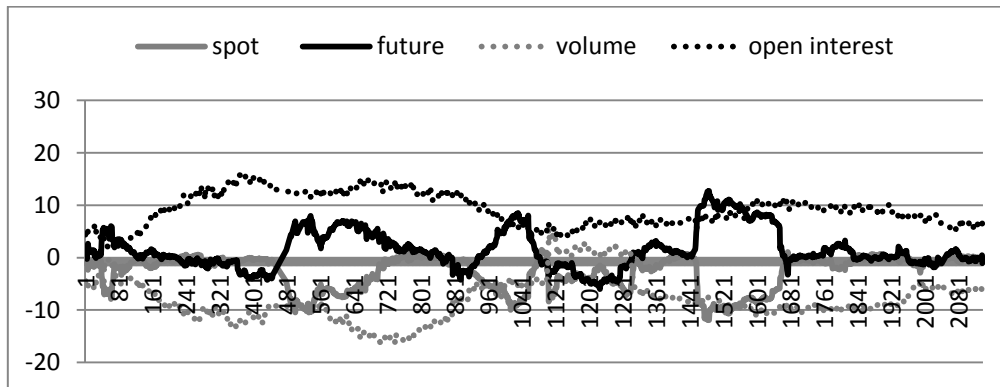
Figure 6: Net volatility spillovers for spot-futures realized volatilities, trading volume and open interest of petroleum-based commodities - examined individually



(a) Crude oil – B1



(b) Heating oil – B2



(c) Gasoline – B3

Note: Each subplot depicts the (dynamic) net spillover index between spot-futures volatilities, trading volume and open interest of petroleum-based commodities examined individually. Specifically, subplot 6a (B1) shows spillovers among crude oil's: spot (RVCLSPOT) and future (RVCLFUT) price volatility, futures trading volume (FCLVOL) and futures open interest (FCLOI). Subplot 6b (B2) depicts spillovers among heating oil's: spot (RVHOSPOT) and future (RVHOFUT) price volatility, futures trading volume (FHOVOL) and futures open interest (FHOOI). Subplot 6c (B3) presents spillovers among gasoline's: spot (RVXBSPT) and future (RVXBFUT) price volatility, futures trading volume (FXBVOL) and futures open interest (FXBOI). Positive (negative) values indicate volatility spillovers transmitters (receivers).