Impact of allowance submissions in European carbon emission markets

Dennis Philip* and Yukun Shi†

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Abstract

This paper studies the impact of the April allowance submissions mandate under the European Union emission trading scheme (EU ETS) in carbon emission markets. Using intraday order flow data, we test for the cross-market efficiency of spot-futures dynamics and find that the equilibrium level, adjustment speed and no-arbitrage boundaries of the spot and futures relationship shift subsequent to the submission date. In addition, our results show that the allowance submissions affect the price discovery process, with the carbon spot market providing stronger price leadership in the periods before the submission date and the futures market playing the predominant informational role thereafter. Using the heterogeneous autoregressive realized volatility (HAR-RV) model, we also find a change in volatility spillovers before the submission date, particularly from the spot to the futures market. Overall, the results suggest that the April allowance submissions have significant impact on the time series dynamics of spot and futures carbon emission markets.

JEL Classification: G13, G17, G18

Key Words: Carbon allowance submission; Carbon emission markets; EU ETS; Mispricing; Price discovery; Volatility spillovers.

* Durham University Business School, Mill Hill Lane, DH1 3LB, UK; dennis.philip@durham.ac.uk; Tel: +44 (0) 191 33 45133; Fax: +44 (0) 191 33 45201.
† Middlesex University, The Burroughs, London NW4 4BT, UK; y.shi@mdx.ac.uk.

1. Introduction

Carbon emission markets, which are designed to reduce emissions of global greenhouse gases (GHG), have experienced rapid ongoing development even during the recent recession and have attracted considerable attention from policy makers and investors. The European Union Emission Trading Scheme (EU ETS), accounting for around 84% of the total value of the global carbon market, is the most influential and successful emission trading market in the world (World Bank, 2012). By March 31 of each year, operating firms report information about their realized emissions from the preceding year, and subsequently the aggregate figures on the emissions realized are announced by the European Commission. Under the EU ETS, by April 30, operating firms are required to surrender sufficient carbon allowances to cover their annual emissions.

Firms with spare allowances have the incentive to sell their allowances on the exchange for cash before the submission date. On the other hand, firms that emit more than their allotted allowance will want to buy allowances from firms with spares before the submission date to avoid the heavy penalty. This would mean that the trading activities in the spot and futures emission market should be pronounced during the period before the submission date, as compared with periods thereafter. Moreover, since the surrendered carbon allowances are no long available to trade, the inventory level of allowances in the market decreases significantly as we near the April submission date each year. The changes in the inventory levels influence the costs and constraints of arbitrage. Lower inventory levels after allowance submissions will increase the inventory risk and widen the bid-ask spread, affecting trading behavior. Market makers require additional compensation for inventory risk (Ho and Stoll, 1981; Biais, 1993). In addition, it is harder for market makers to conduct short-selling activities when inventory levels are lower. Hence, the allowance submissions mandate in April can alter the price dynamics in the European carbon spot and futures markets.

Previous evidence for abnormal price changes, increase in volume and volatilities in the futures contracts around the European Commission announcement date of aggregate realized emissions has been documented by recent studies such as Grüll and Kiesel (2012) and Hitzemann, Uhrig-Homburg and Ehrhart (2013). However, unlike previous studies, this paper is the first to analyze the changes in the trading behavior and the joint price dynamics underlying the carbon spot and futures markets, before and after the allowance submissions mandate of April 30. First, we test whether there is a change in the mispricing relationship of the spot and futures markets; that is, we test for changes in the equilibrium level, mean-reverting speed, and no-arbitrage bands of the carbon spot and futures relationship before and after the submission date. The results obtained are important in understanding the arbitrage activities in the European carbon emission markets at market microstructure level. Second, we investigate whether allowance submissions influence the information transmission between spot and futures carbon markets. It is possible that the spot market responds to new information more quickly than the futures market before the submission date due to the active trading in the spot market. Therefore, we test for changes in the short-run price discovery process using Granger causality tests (Granger, 1969), and also examine for changes in the dynamics of the volatility transmission process before and after the submission date. In particular, we use the heterogeneous autoregressive realized volatility (HAR-RV) model of Corsi (2009) for testing changes in the volatility spillover process between the spot and futures markets. For the empirical analysis, we use the intraday Phase II transactions data on the EU ETS from 2009 to 2011.

The empirical results show that the mispricing relationship underlying the spot and futures markets differs significantly before and after the allowance submission date. In particular, we observe a change in the long-run equilibrium level, the speed of adjustment, and the upper and lower bands of the no-arbitrage area after the allowance submission date. The above effects are prominent in 2009 and 2011, but not in 2010. This disparity is primarily driven by the broader market movements observed in the emissions market over these years (explained below). In terms of the information transmission process, the results of Granger causality tests reveal that, although in line with Rittler (2012) there is bidirectional information transmission between carbon spot and futures returns, the spot market leads (or Granger-causes) the futures market much more in the periods before the allowance submission date, while the futures market leads (or Granger-causes) the spot market much more after the submission date. Further, for the volatility transmission process, the results of the bivariate HAR-RV model show that the volatility spillovers between spot and futures markets significantly differ before and after the submission date. More specifically, we find that volatility spillovers from the futures market to the spot market are only significant in the periods after the submission date. Before the allowance submission date, the price discovery happens in the spot market, with informational spillovers in the volatility from the spot to the futures market. This is driven by the fact that the buying and selling of carbon allowances is much more pronounced in the spot market before the submission date as part of unwinding hedge positions and rebalancing books. Hence any new information revealed in the market will be first incorporated into the price dynamics and volatility in the spot market. Our results are in contrast to Rittler (2012), who does not consider the impact of allowance submission and finds unidirectional information spillovers from the futures to the spot market, but not vice versa. Our results also differ from Milunovich and Joyeux (2010), who find minor relevance of information transmission in the volatility process at a lower frequency. As in our previous analyses, we find that the effects of allowance submission on volatility spillovers are more pronounced in the years 2009 and 2011 than in 2010.

Our findings indicate that the dynamics of the EU emissions market during the compliance year 2009 are drastically different from those we observe during the compliance years 2008 and 2010. This is because of the differential market dynamics witnessed during these years. The 2008 compliance year can be overall characterized by a steady growth in the carbon emissions market, reaching double its 2007 value. But late 2008 and early 2009 showed a deteriorating market, with lower oil and energy prices, and a sluggish economic outlook. During 2009, the global financial crisis intensified and industrial production in the EU dropped significantly, causing an unexpected deep decrease in demand for carbon emissions. By February 2009, EUA prices had plummeted to €8, versus €30 nine months earlier. According to the World Bank report, the carbon emission in the EU decreased by 11% from 2008 to 2009, following a 15% reduction in the EU industrial production in the same period (World Bank, 2012). Whilst the amount of carbon allowances allocated to firms is based on the forecast of industrial production, since firms emitted less than expected in 2009, the total amount of carbon allowances surrendered in April 2010 also declined considerably. On the supply side, the financial crisis stimulated financial institutions and private investors to deleverage and redirect their positions away from risky investments and toward safer assets and markets. This meant that the EU ETS project-based mechanisms, where operators implement projects that reduce emissions in emerging regions and use the resulting emission reduction units to help meet their own targets, were hard to implement and effectively came to a standstill. According to the World Bank, the carbon market endured its most challenging year to date in 2009. In contrast and relative to the previous year, 2010 brought tranquillity with EUA prices stabilizing to a new equilibrium level of around €16. The year 2010 can be characterized by a move towards improvement of market mechanisms, implementing robust and transparent regulation, and building market confidence. Hence, we observe that the carbon market dynamics during the 2009 compliance year are distinct from those in 2008 and 2010. This explains the differential and insignificant impact of the allowance submission mandate in April 2010, whilst the impact is pronounced before and after the April 2009 and 2011 submission mandates. All the above findings are also robust when considering order flow transactions sampled at various intraday time frequencies (such as 10 and 30 minutes).

Therefore, we contribute to the existing studies of the EU ETS carbon emission market and show that the April allowance submissions mandate significantly influences the carbon price dynamics. Furthermore, the results in this paper are of interest to investors and operators who manage carbon allowances and its derivatives for compliance, risk management, arbitrage, raising capital and profit-taking purposes. The distinct pricing efficiencies between the EU ETS carbon spot and futures contracts before and after the April submissions date have to be taken in consideration for effective hedging and risk management. The changing lag effects and liquidity changes due to the April submissions will aid arbitragers in understanding the price discovery process and the arbitrage opportunities in the EU ETS market. Additionally, the findings will also aid market makers in their liquidity management. Further, the results will be of special interest to regulators and carbon market designers aiming to improve the trading mechanisms of the EU ETS. To minimize the impact of the submission date on the carbon trading markets, several alternative submission mechanisms (and their implementation costs) should be considered, such as instituting multiple submission dates within the year or allowing operating firms to submit allowances in multiple instalments.

The remainder of this paper is organized as follows. Section 2 gives a brief overview of the EU ETS framework. Section 3 describes the construction of intraday spot and futures prices. Sections 4 and 5 investigate the impact of allowance submissions on carbon market mispricing dynamics and on information transmission between the spot and futures markets, respectively. Section 6 concludes.

2. The EU ETS compliance process and data construction

EU ETS operates an annual compliance process of monitoring, reporting and verification of emissions by operating firms. The central authorities set a “cap” on the total amount of greenhouse gases that a country or region is allowed to emit within a calendar year. By the end of February, they allocate free GHG emission allowances to operating firms covered by the scheme. Firms’ emissions during the year should not exceed the allocated allowance represented by their in-hand allowances; otherwise they must surrender additional allowances in the next calendar year to cover the excess emissions from the previous year and further pay a heavy civil penalty. The scheme involves regular monitoring of operators during the year starting from January to the end of December. Firms that emit more than their allocated allowances are required to undertake measures to reduce their emissions (for example, by investing in more efficient technologies and/or energy sources) or they can buy carbon allowances from another firm that has some emission allowances remaining. As a consequence, the total amount of emissions can be controlled and kept under a target level.

By March 31 each year, the EU ETS requires all firms covered by the scheme to submit their verified annual emissions report to the European Commission, in line with the Monitoring and Reporting Regulation (MRR). The aggregate realized emissions data are then published by the Commission in early April. Operating firms are required to surrender the quantity of EUAs or other accepted carbon financial instruments corresponding to their GHG emissions in the previous year by April 30. The GHG emissions not covered by the surrendered carbon allowances incurred fines of €40 per CO_2 ton in Phase I and €100 per CO_2 ton in Phases II and III, which is significantly higher than the prices of carbon allowances. In addition, the uncovered carbon emissions are also deducted in the next compliance year. In Phase III, the EU ETS has introduced an enforcement regime whereby the civil penalty is enforced by the court of law if firms do not meet the legal requirement set by the EU ETS. Hence, the operating firms have a strong incentive to avoid the civil penalty. In this case, firms that do not have sufficient carbon allowances to surrender have to purchase the allowances for the uncovered emissions in the spot market before the submission date. For firms with spare carbon allowances, they have the incentive to sell these allowances for cash, especially in the current financial crisis when the costs of borrowing are high. For the above reasons, it is expected that trading in the carbon spot market will be more active in the periods before the submission date than thereafter. This implies that the transmission of information may be different before and after the submission date. Further, since allowances surrendered are no longer traded, the changes in inventory resulting from April submissions each year can affect the trading behavior in carbon markets, especially on the spot market.

To examine the effects of allowance submission on the EU ETS, the spot and futures price series are constructed based on order flow data from those markets. The spot market tick-by-tick data is provided by BlueNext Exchange, while futures markets data is obtained from the Intercontinental Exchange (ICE). For the empirical investigation, we use the Phase II transactions data on the EU ETS, which runs from 2008 to 2011. Since the allowance submission date for the previous year's emission falls on April 30 in the following year, the first submission date in EU ETS Phase II is on April 30, 2009, and our sample period ends in December 31, 2011. For each year, we consider the futures contract expiring in December, which is the most liquid contract. The trading hours in the ICE and BlueNext exchange are 0700 to 1700 GMT. However, trading in the spot market is not active at the beginning and end of the trading day. To avoid illiquid trading, we only use the transactions occurring between 0900 and 1600 GMT. In order to convert irregular transaction data to equidistant price data at frequencies of h-minutes, for each h-minute interval we compute the mean of the log prices of the immediate preceding and following transactions as the log price at the h-minute mark. For our analysis, we report the results for h=15-minute intervals.[1] To avoid the intraday effects, the log price of the first trade immediately following 0900 is used as the price at the 0900 time interval each day, and the log price of the last trade immediately preceding 1600 is adopted as the price at the 1600 time interval each day.

[Insert Figure 1 here]

As preliminary evidence of the impact of allowance submissions, Figure 1 displays the mispricing pattern (i.e., the logarithmic difference between the observed and theoretical futures prices) in the carbon futures markets at the intraday frequency of 15-minute intervals.[2] We observe that the time series behavior of mispricing before the allowance submission date of April 30 is distinct from that after the submission date,

[1] We also consider 10-minute and 30-minute intraday frequencies for our tests. The empirical results are qualitatively identical to those for 15 minutes and hence not reported in the paper but are available upon request.

[2] A similar mispricing pattern is observed in order-flow data for intraday 10- and 30-minute frequencies.

especially for the years 2009 and 2011. In particular, we see that in 2011, before May 04, which is the first trading day after the submission date, the observed futures prices are persistently higher than the theoretical futures prices by around 2–8%. By contrast, after the submission date the futures mispricing hovers just above and below zero. This phenomenon may be driven by the fact that there is more trading activity before the submission date than afterwards, as market participants and operating firms unwind their hedge positions and rebalance their books. This is also reflected in the average value of daily futures open interest we observe before and after the submission date. More specifically, we compare the three-month average daily futures open interest before and after April 30. We find that the average size of the outstanding (long/short) futures trade positions systematically increases by 45%, 26% and 16% after the April submissions date for the years 2009 to 2011 respectively. Hence, we see the demand for hedging in the futures market revives once the compliance date has passed.

3. Impact of allowance submission on the spot-futures dynamics

3.1 Estimating mispricing in carbon markets

Most studies use Brennan's (1958) cost-of-carry pricing relationship to estimate mispricing, where the theoretical futures is expressed as:

$$F_{t,T}^{*} = S_t e^{(r_t + u_t - c_t)(T-t)}, \qquad (1)$$

where $F_{t,T}^{*}$ is the theoretical price of the futures contract at time t, maturing at time T; S_t is the spot price at time t; r_t is the annualised risk-free rate; u_t is the annualized cost of storage at time t; and c_t is the annualised convenience yield. Mispricing at any time point t, Z_t, is computed as:

$$Z_t = \ln(F_{t,T}) - \ln(F_{t,T}^{*}) = \ln(F_{t,T}) - \ln(S_t e^{r_t + u_t - c_t)(T-t)}), \qquad (2)$$

where $F_{t,T}$ is the observed futures price at time t. A number of previous studies use the cost-of-carry relationship for carbon markets (see, for example, Joyeux and Milunovich (2010), Rittler (2012), among others). Since carbon assets in the EU ETS are electronically registered and incur little cost, as in previous studies we assume the cost of storage (u_t) for carbon allowances to be zero. For the risk-free rate (r_t), following Rittler (2012), we use the monthly EURIBOR on a daily basis.

We allow for non-zero convenience yield for holding carbon allowances and employ the option-implied methodology recently developed by Hochradl and Rammerstorfer (2012) to estimate the convenience yield. This method is based on the original economic idea of convenience yield, where the convenience yield is defined as the benefit of holding spot assets rather than futures assets. The convenience yield is estimated as the difference between a put option on a spot contract and another put option on a futures contract. Previous studies debate the existence of convenience yield in carbon emission markets. Uhrig-Homburg and Wagner (2009) and Joyeux and Milunovich (2010) argue that firms only require carbon allowances annually to meet the regulatory requirements and thus the convenience yield in carbon markets should be insignificant. Conversely, Trück, Borak, Härdle and Weron (2007), Chevallier (2009) and Daskalakis, Psychoyios and Markellos (2009) observe that carbon futures markets have a significant convenience yield. Since the GHG emissions are uncertain during the year, and due to the high transaction costs and illiquidity in carbon markets compared to major stock exchanges, there can be significant benefit to be gained from possessing spot carbon allowances, and thus the convenience yield in carbon markets is not zero. Furthermore, Rittler (2012) shows that the theoretical carbon futures prices with zero convenience yield are persistently higher than the observed futures prices, which could constitute evidence for the existence of convenience yield. Hence we account for convenience yield in the cost-of-carry relationship.

[Insert Table 1 here]

The summary statistics for mispricing observed at the intraday frequency of 15 minutes are reported in Table 1. The statistics for the various sample periods display non-zero skewness and excess kurtosis, and the results of Jarque-Bera tests show significant deviation from Gaussianity. We find that in 2009 and 2011 the average mispricing and its standard deviation are significantly larger before the submission date than after. In addition, in 2009 and 2011, we observe a negative skewness in the mispricing distribution before the submission date, in contrast to a positive skewness after the submission date. This indicates large negative movements in mispricing before the April submission date. Further, we observe that the values of kurtosis before the submission date are almost double those afterward. Overall, this cursory investigation reveals clear changes in the distribution of mispricing before and after the submission date. For the year 2010, we do not observe such distinctive variations in the distribution.

[Insert Figure 2 here]

To provide a further examination of the distributional characteristics of mispricing, we present in Figure 2 kernel density estimates pre- and post-submission date. The figure demonstrates a shift in the distribution of mispricing further to the left following the submission date in 2009, while in 2011 we observe a clear shift in the distribution of mispricing further to the right. The steep density curve before the submission date in 2009 widens and is higher post-submission date. Similar but more pronounced change is seen in 2011, where we observe the density curve distinctly higher and much more concentrated around the average after the submission date. We see no noticeable change in the kernel density estimations in 2010. This is consistent with the summary statistics reported above.

3.2 Analysis of carbon market mispricing

In order to examine the effects of allowance submissions, we model the carbon mispricing dynamics (Z_t) using non-linear equilibrium correction models. In a frictionless market, Z_t will fluctuate around zero, with an immediate adjustment process when prices deviate from the equilibrium. However, market imperfections such as transaction costs, illiquidity, trading behavior and regulations act as limits to equilibrium correction within a certain upper and lower bound. It is increasingly documented that the spot-futures mispricing relationship is nonlinear, due to the presence of such constraints, and market regulations significantly alter this relationship (see, for example, McMillan and Philip (2012)). Since the allowance submissions affect the trading activities in the emission allowance spot market much more than the futures, one might expect the mispricing dynamics to be altered pre- and post-submission date.

We first examine changes in the carbon mispricing relationship using the threshold autoregressive (TAR) model of Tong (1978, 1990), as defined in the following equation:

$$\Delta Z_t = \alpha + \delta D_t + \rho_1 Z_{t-1} I_t D_t + \rho_2 Z_{t-1} I_t (1 - D_t) + \rho_3 Z_{t-1} (1 - I_t) D_t$$
$$+ \rho_4 Z_{t-1} (1 - I_t)(1 - D_t) + \sum_{i=1}^{k} \lambda_i \Delta Z_{t-i} + \varepsilon_t \quad (3)$$

where I_t is a heaviside indicator function that is equal to one if Z_{t-1} is above the threshold and zero otherwise, and D_t is a dummy variable that is equal to one during the period before the submission date (April 30) and zero thereafter. We include k lags of the dependent variable (ΔZ) in the regressions to account for autocorrelation. We use the SIC information criteria as well as the significance of the autoregressive lags in order to obtain the optimal lag length k. For the various regression time periods considered, an optimal lag length of around 6 is obtained. The coefficient δ captures the difference in equilibrium levels between the two periods, with ρ_1, ρ_2, ρ_3 and ρ_4 parameters determining the speed of mean reversion. In particular, ρ_1 and ρ_2 govern the speed of adjustment in the upper regimes, while ρ_3 and ρ_4 are related to the speed of adjustment in the lower regimes. Symmetric adjustment holds if $-2<\rho_1=\rho_2<0$ or if $-2<\rho_3=\rho_4<0$ in each subperiod, and the evidence of asymmetric adjustment can be seen when $\rho_1 \neq \rho_3$ or $\rho_2 \neq \rho_4$ and both lie between -2 and 0.

Several approaches are adopted in order to determine the value of the threshold. The simplest method is to set the threshold at zero. This is an economically meaningful value and in this case, the underlying cointegrating vector derived from the TAR model would correspond to the attractor. However, in order to allow the value of the threshold to differ from the attractor and, more importantly, time-vary, we adopt two alternative methods. The first approach involves a recursive estimation based on Chan's (1993) procedure, whereby the above regression is run over a number of possible threshold values (discarding the largest and smallest 10 percent values) and the optimal threshold value is determined based on the conditional least squares (CLS) methodology. Chan (1993) shows that the estimated threshold value is in fact super-consistent and is much more precise than other alternative methods. For comparison, we also implement time-varying thresholds by using a simple moving average methodology. In this case, the threshold values are the simple 10-day moving average of mispricing values (Z_t). The results reported in Table 2 are based on Chan's (1993) procedure, with the results obtained by using the moving average being qualitatively very similar (and reported in the online appendix).

[Insert Table 2 here]

We observe several interesting points. First, the Wald test results for $\rho_1=\rho_3$ and $\rho_2=\rho_4$ are rejected in most cases, showing that the speed of adjustment is different in the two regimes. This supports the use of the TAR model instead of the linear adjustment process for the mispricing dynamics. Second, all the intercept terms are positive and significant, suggesting a positive long-run equilibrium. The coefficient δ is significant and positive in 2009 and 2011, showing that the equilibrium level decreases after the allowance submissions in April. In 2010 we observe δ to be negative and significant during the period February to July (at the 1% level) and February to August (at the 10% level), but insignificant in the period running from February to October. The results suggest a temporal increase in the equilibrium level after the submission of allowances, with the effect decaying as time passes.

Examining the parameters associated with the speed of mean-reversion, ρ_1, ρ_2, ρ_3 and ρ_4 are all negative and significant, showing that the futures mispricing, Z_t, is stationary in all the subperiods. This implies that the spot and futures returns are cointegrated with each other before and after the submission date. Since the main concern of this paper is with the effects of allowance submissions, we test whether the speed of adjustment is statistically similar before and after the April submission date, for both the upper and lower regimes, using Wald tests. The null hypotheses of $\rho_1=\rho_2$ and $\rho_3=\rho_4$ are rejected for all the subperiods in 2009, which suggests the speed of mean-reversion in both the upper and lower regimes significantly changes after the submission date in 2009. $\rho_1=\rho_2$ and $\rho_3=\rho_4$ are also rejected in the period running from February to July 2010, but cannot be rejected for the other subperiods in 2010. This shows that the impact of allowance submission on mean-reverting speeds lessens over time in 2010. For 2011, we only reject the null of $\rho_3=\rho_4$ for the all subperiods, indicating that the submission of allowances in 2011 significantly affects the speed of adjustment in the lower regime.[3] Overall, the above results suggest that allowance submissions significantly impact the mispricing relationship, with significant changes to the equilibrium level as well as the speed of adjustment in all three years. The effects are persistent in 2009 and 2011 but weaker in 2010.

[3] It can be observed from Figure 1 that there are some extreme observations in the intraday mispricing series in 2011. These observations are normally at the beginning of a trading day, perhaps because of illiquidity. We also examine the impact of allowance submissions after removing these observations, with the results qualitatively very similar.

The above estimated TAR model imposes abrupt regime switches, which requires a number of unrealistic assumptions, such as all the agents holding homogeneous expectations, and incurs the same interest rates and transaction costs (Monoyios and Sarno, 2002). Consequently, smooth-transition models have been preferred over TAR models. In order to allow for a smooth change of regimes, we employ the quadratic-logistic smooth-transition (QLSTR) model developed by Jansen and Teräsvirta (1996), where the adjustment of small deviations from the equilibrium is allowed to differ from that of large deviations, and which takes into account smooth shifts between regimes. In addition, unlike the single threshold for each side in the TAR model, the QLSTR model allows for different threshold points to be set for both sides of the attractor. This enables us to examine how the allowance submission influences the no-arbitrage boundaries as well as the speed of transition between the two regimes. We estimate the following QLSTR model:

$$\Delta Z_t = \left[\alpha_{0,1} + \alpha_{1,1} Z_{t-1} + (\beta_{0,1} + \beta_{1,1} Z_{t-1})(1 + \exp(-\gamma_1 (Z_{t-1} - c_{1,1})(Z_{t-1} - c_{2,1})))^{-1} \right] D_t$$
$$+ \left[\alpha_{0,2} + \alpha_{1,2} Z_{t-1} + (\beta_{0,2} + \beta_{1,2} Z_{t-1})(1 + \exp(-\gamma_2 (Z_{t-1} - c_{1,2})(Z_{t-1} - c_{2,2})))^{-1} \right] (1 - D_t) + \sum_{i=1}^{k} \lambda_i \Delta Z_{t-i} + \varepsilon_t \quad (4)$$

where γ_i is the parameter for the speed of transition between the two regimes; $c_{1,i}$ and $c_{2,i}$ are the lower and upper threshold boundaries of the inner regime, which determines the locations where the adjustment process switches regimes; and $\alpha_{1,i}$ and $\beta_{1,i}$ govern the speed of adjustment in the inner and outer regimes respectively. More precisely, the speed of mean-reversion in the outer regime is determined by the sum of $\alpha_{1,i}$ and $\beta_{1,i}$, where $i=1$ represents the period before the submission date (April 30) each year, and $i=2$ for the periods thereafter. If $\gamma_i \rightarrow 0$, we get a linear ADF model, while if $\gamma_i \rightarrow \infty$, the function becomes zero for $c_{1,i} < Z_t < c_{2,i}$ and is equal to one for $Z_t < c_{1,i}$ and $Z_t > c_{2,i}$. At the point of transition, the model allows different adjustment behaviors for positive and negative deviations. Hence the model nests the Balke and Fomby (1997) three-regime threshold model. The optimal lag length for the autoregressive component, k, is determined by the SIC information criteria as well as the significance of the autoregressive coefficients. We report the main results of the QLSTR model in Table 3.

[Insert Table 3 here]

We find that the absolute value of β_1 is increasing each year, implying that the market is becoming more mature and therefore can correct the mispricing more quickly.

The parameters of interest in Equation (4) are those that determine the speed of regime transition, the speed of mean-reversion, and the upper and lower threshold boundaries of the no-arbitrage space. Five Wald-tests are conducted to examine whether the speed of adjustment in the inner and outer regimes, the speed of transition, and the location of the upper and lower no-arbitrage boundaries are statistically similar before and after the submission date. The test for the null hypotheses of $\alpha_{1,1}=\alpha_{1,2}$ and $\beta_{1,1}=\beta_{1,2}$ shows that the allowance submission date significantly affects the speed of mean-reversion in the inner and outer regimes in 2009 and 2011, but not in 2010. Further, we notice that the parameter related to the speed of regime transition, γ, does not significantly alter due to the submission date, since we cannot reject the null of $\gamma_1=\gamma_2$ in all years. This shows that the allowance submissions do not have a significant impact on the speed of transition within the inner and outer regimes.

The most interesting parameters in the model are the upper and lower threshold parameters, c_1 and c_2. Although we observe long-run equilibrium level shifts after the submission date in all three years, if c_1 and c_2 do not significantly alter, the movement of the equilibrium level does not necessarily induce the significant change in arbitrage behavior. The Wald test results for $c_{1,1}=c_{1,2}$ and $c_{2,1}=c_{2,2}$ indicate that both the upper and lower threshold boundaries of the no-arbitrage space alter after the submission date in 2009 and 2011. For 2010, we observe a significant change in the lower boundary just after the submission date in April; however the effects do not persist in the subsequent periods.

To summarize, the results so far show significant changes in the mean-reverting process, with equilibrium level and speed of mean-reversion within regimes, as well as the no-arbitrage bands, significantly different pre- and post-submission date. These findings suggest that the submission of carbon allowances in April affects the mispricing relationship and arbitrage activities in carbon markets.

4. Impact of allowance submission on information transmission

In this section, we examine whether allowance submissions affect the transmission of information between carbon spot and futures markets. Hence, we first test for changes to the short-term price discovery process underlying the two markets using

Granger causality analysis and also investigate for any changes in the joint volatility dynamics between markets using volatility spillover analysis.

4.1 Price discovery analysis

Operating firms with insufficient carbon allowances in hand have to purchase the additional allowances in the secondary market before the submission date in order to avoid severe financial punishment. Thus, trading activities in the carbon spot and futures markets will be more pronounced in the lead up to the submission date than afterward. Further, firms holding EUA futures to hedge against anticipated compliance exposure will unwind their positions with physical settlement. As market participants rebalance their books, there will be more active trading in the spot before the submissions date.

The analysis of price discovery serves to determine how the newly arrived information is incorporated into the price dynamics of the two interlinked markets. Previous studies such as Uhrig-Homburg and Wagner (2009) and Chevallier (2010) document the leadership of carbon futures market in the price discovery process, when analyzed on a daily frequency. However, Rittler (2012) observes a bidirectional feedback mechanism between the spot and futures carbon markets when using price information on an intraday frequency. The central question that we ask is whether the price discovery process is influenced by allowance submissions.

[Insert Table 4 here]

We adopt Granger causality tests, developed by Granger (1969), to study the lead-lag relationship between the spot and futures carbon markets before and after the submission date. The test is based on a vector autoregressive (VAR) model that examines the joint significance in the lagged returns of one market in the equation of the other market within the VAR system.[4] We report the *F*-test results from Granger causality tests in Table 4. For all sample periods considered from 2009 to 2011, we strongly reject the null hypothesis (at the 1% level) that the spot market does not Granger-cause the futures market, while also strongly rejecting the null hypothesis (at the 1% level) that the futures market does not Granger-cause the spot market (except in

[4] The optimal lags for the VAR specifications are determined using the Schwarz information criterion, although using the Hannan-Quinn information criterion provides a very similar lag selection.

the period February-April 2009). For the years 2009 and 2011, when we consider the value of the *F*-test statistics, we find a stronger Granger causality from the spot to the futures market in the periods before the submission date (indicated by larger *F*-test statistics) than after the submission date, where we find a stronger Granger causality from the futures market to the spot market. The results indicate that, although in line with Rittler (2012) there is bidirectional information transmission between carbon spot and futures returns, the spot market is the predominant contributor to the price discovery process before the allowance submission date, while the futures market provides price leadership after the allowance submissions. We observe that spot trading becomes more important and informationally relevant over the first quarter of each year due to the buying and selling of spot contracts as part of the compliance process. That is, firms buy allowances for compliance purposes on the spot market when in deficit, while firms sell their allowances on the spot market when an excess supply exists. For 2010, we find that the spot market provides a stronger price leadership than the futures market before as well as after the allowance submissions. This result may be driven by the fact that the EUA market experienced a large sell-off of allowances, mostly in the spot market, as operators as well as trading and financial companies monetized allowances to raise funds in the midst of the financial credit crunch. Overall, the findings suggest that the submission of carbon allowances impacts the price discovery process in carbon markets.

4.2 Volatility spillovers

We now examine whether allowance submissions affect the dynamics of volatility transmission between carbon spot and futures. Ritter (2012) documents a close relationship between the volatility dynamics of carbon spot and futures markets, with spillovers observed from the volatility and shocks in the futures market into the spot market. Hence, we analyze volatility spillovers among the two markets and the extent to which the volatility transmission process is influenced by emission allowance submissions.

We formulate a bivariate case of the heterogeneous autoregressive realized volatility (HAR-RV) model proposed by Corsi (2009) to capture the joint volatility dynamics of the two markets. Chevallier and Sevi (2011) observe that that the HAR-RV model outperforms several GARCH specifications in terms of dynamic modeling and forecasting accuracy for carbon emission futures. We augment the model with a dummy variable that represents the period before the allowance submissions date. In particular, we estimate the following equation:

$$\mathbf{v}_t = (\boldsymbol{\alpha} + \boldsymbol{\beta}_1 \mathbf{v}_{t-1} + \boldsymbol{\beta}_5 \mathbf{v}_{(t-1|t-5)} + \boldsymbol{\beta}_{22} \mathbf{v}_{(t-1|t-22)})\mathbf{D}_t + \boldsymbol{\varepsilon}_t \text{ ,} \tag{5}$$

where $\mathbf{v}_t = (RVF_t \;\; RVS_t)'$ is the vector of realized volatilities at time t; RVF_t and RVS_t are the daily realized volatility in the futures and the spot market at time t respectively, where daily realized volatility is estimated as the summation of the intraday squared returns (see Andersen, Bollerslev, Diebold and Labys, 2003 for details); $\mathbf{D}_t = (D_t \;\; 1\text{-}D_t)'$, where D_t is the dummy variable that represents the period before the submissions date; and $\mathbf{v}_{t-1|t-k} = (RVF_{t-1|t-k} \;\; RVS_{t-1|t-k})'$ is the vector of the lagged realized volatilities from the spot and futures market, where $RVF_{(t-1|t-k)} = \frac{1}{k}\sum_{j=1}^{k} RVF_{t-j}$ and $RVS_{(t-1|t-k)} = \frac{1}{k}\sum_{j=1}^{k} RVS_{t-j}$ for $k = 5$ and 22 corresponding to 5-day and 22-day realized volatility. Hence, this framework consists of three volatility components, including daily, weekly and monthly realized volatilities. Each of the components corresponds to various response times of different groups of investors to the arrival of new information. An intuitive interpretation of the HAR-RV framework is that it allows for volatility patterns over longer intervals to associate with those over shorter intervals (Corsi, 2009). Hence, using this framework, we are able to study the impact of allowance submissions on the short-term as well as long-term volatility spillover effects between the carbon spot and futures markets. The parameters of interest are the coefficients of the slope ($\boldsymbol{\beta}$) matrix, $\beta_{i,S,k}$ and $\beta_{i,F,k}$, corresponding to the spot and futures markets respectively, where $i=1$ for the period before the submissions date (April 30) each year and $i=2$ for the periods thereafter.

[Insert Table 5 here]

Table 5 presents the results of the bivariate HAR-RV model in Equation (8). For the period before the submission date, we find that the short-term variance component of the spot market ($\beta_{1,S,1}$) significantly affects the current volatility of the futures market in all years (2009-2011), while the long-term variance component of the spot market ($\beta_{1,S,22}$) is significant for 2009 and 2011. We also observe that the medium-term variance component is significant, with negative impact, in 2011. However, the spillover coefficients from the spot to the futures market become mostly insignificant after the submissions date. In the case of the spot market, we observe that there are no volatility spillover effects from the futures market before the submission date; however, this evidence is reversed in the period after the submission date. In particular, we find marginal significance for the futures market long-term variance component in 2009 and 2010, while in 2011, we observe a strong significance for the short-term and medium-term variance components underlying the futures market. The results indicate that the futures market volatility has a significant impact on the spot market volatility only in the period after the submission date.

The Likelihood Ratio tests for the joint significance of the short-, medium- and long-term variance components in the periods before and after the submission date confirm that the volatility spillovers from the spot to the futures market are statistically significant in the periods before the submission date. After the allowance submission date, price discovery happens mainly in the futures market, with informational spillovers strongly significant only in 2011. The results are driven by the fact that the transactions in the spot market are much more active before the submission date and hence any new information released will be first incorporated into the volatility dynamics of the spot market, subsequently spilling over to the futures market volatility. Our results differ from those of Rittler (2012), who does not take into account the allowance submissions effect and observes volatility spillovers only from the carbon futures to the spot market, but not vice versa.

5. Conclusion

This paper investigates the effects of allowance submissions on the relationship between the spot and futures markets using the intraday order flow transactions data in the Phase II commitment period of the EU ETS. By April 30 each year, operating firms are required by law to disclose their emissions from the preceding year and surrender sufficient carbon allowances to cover their emissions. It is expected that the buying and selling of the carbon allowances in the spot and futures markets will be much more active before the submission date than after. Also, the surrender of carbon allowances in April will reduce the inventory level of carbon assets impacting trading behavior after the submission date. Hence we investigate whether the price dynamics between the European carbon spot and futures markets are affected by the allowance submission mandate in April.

First, we test for changes in the cross-market efficiency of the spot-futures dynamics and find that nature of the mispricing before the submission date differs significantly from that after the April submission date. More specifically, we find that the mispricing equilibrium level and the adjustment speed, as well as the no-arbitrage boundaries, shift subsequent to the submission date. This shows that the behavior of arbitrage activities is influenced by allowance submissions. Second, we test whether the transmission of information between the spot and futures markets is affected by allowance submissions. For this, we investigate the changes in the short-term causality structure between the spot and futures markets using Granger causality tests. Further, using the bivariate heterogeneous autoregressive realized volatility (HAR-RV) model, we test for changes in the dynamics of volatility transmission between carbon spot and futures markets. The results show that, although in line with previous studies spot and futures markets Granger-cause each other, the spot market is the leading market before the submission date, while the futures market takes the leading role after the submission date. This indicates that the spot market plays a dominant role in the price discovery process before the April submissions, after which the futures market subsumes this dominant informational role. In terms of the joint volatility dynamics, we find a change in the volatility spillovers mechanism between the spot and futures markets, with volatility spillovers from the spot market to the futures market before the submission date and volatility spillovers from the futures to the spot market thereafter. This is driven by the fact that trading activities in the spot market are much more active in the periods before the submission date as market participants unwind their compliance hedge positions with physical settlement and balance their books. Thus, any new information revealed in the market is swiftly incorporated into the price dynamics and volatility of the spot market. These results contrast with previous studies, which do not take into account the impact of the allowance submissions, and find unidirectional spillovers from the futures to the spot market. The results are much more prominent in 2009 and 2011 than in 2010, due to decline of GHG emissions in the EU during the 2009 compliance year, caused by the significant drop in output (industrial production) and intensified global financial crisis.

In conclusion, this paper finds that the submission of allowances has a significant impact on the efficiency of the spot-futures dynamics as well as on the transmission of information between the spot and futures markets. The above findings are robust to order flow transactions sampled at different intraday time frequencies. The results indicate that in modeling the relationship between carbon spot and futures prices, the impact of the submissions date should be taken into consideration. The findings of this paper are of interest to investors and market makers operating in the carbon emissions market. The distinct pricing efficiencies between the EU ETS carbon spot and futures contracts before and after the April submissions date have to be taken in consideration for effective hedging and risk management. The changing lag effects and liquidity changes due to the April submissions will aid arbitragers in understanding the price discovery process and the arbitrage opportunities in the EU ETS market. Additionally, the findings will also aid market makers in their liquidity management. Further, our results will be of special interest to regulators and market designers who ensure the well-functioning of the emissions trading program. To minimize the impact of the submission date on the carbon trading markets, several alternative submission mechanisms (and their implementation costs) should be considered, such as instituting multiple submission dates within the year or allowing operating firms to submit allowances in multiple instalments.

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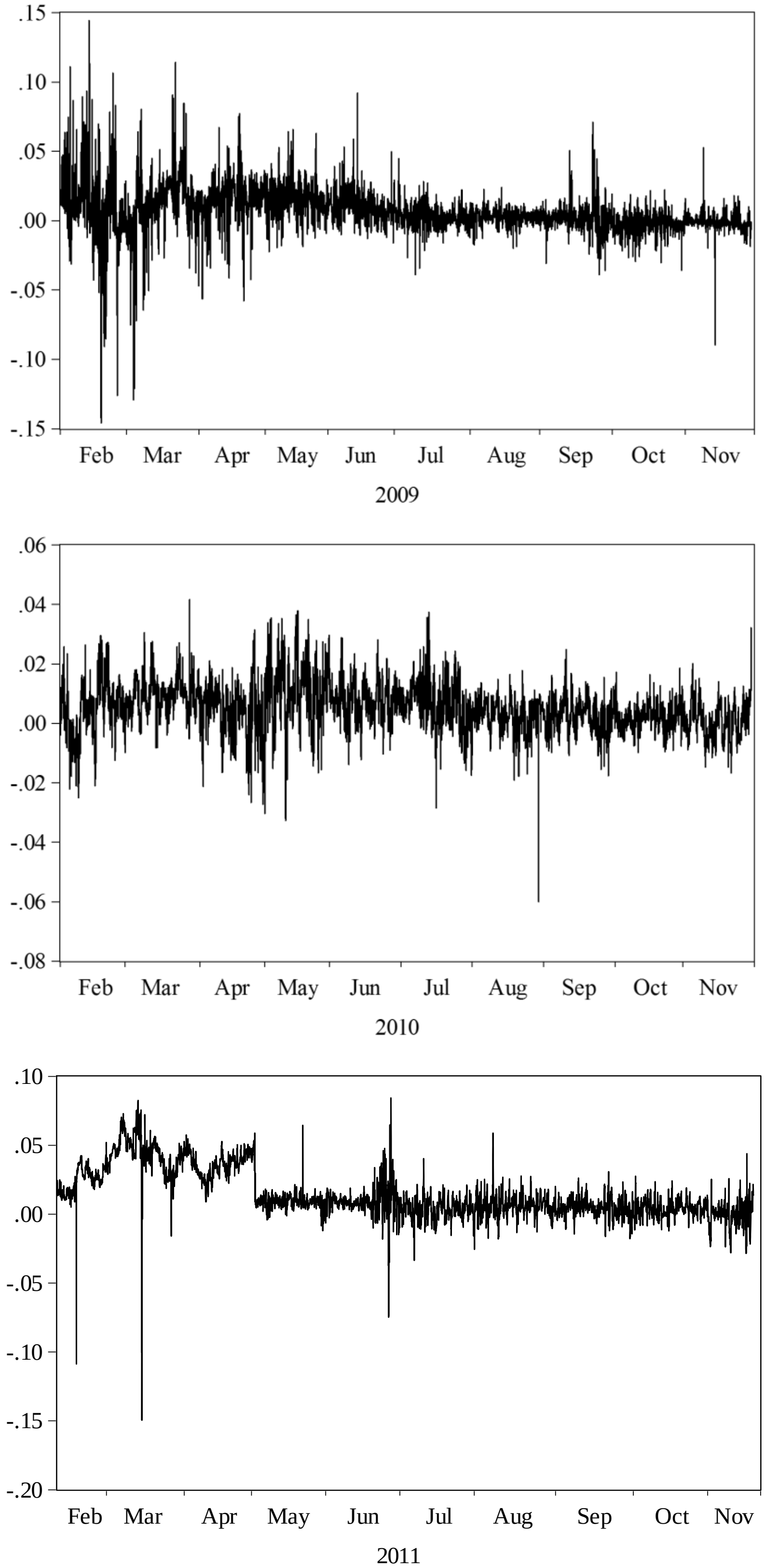
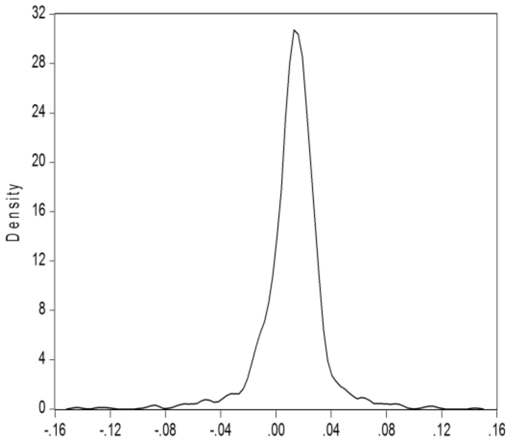
Figure 1: Intraday mispricing of carbon markets

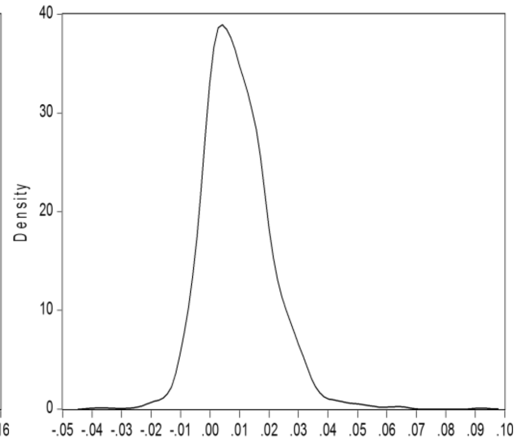


Note: The figure shows the intraday mispricing of carbon futures from February to November each year (2009-2011), using 15-minute order flow transactions data. The carbon futures mispricing is computed as the difference between the observed futures prices and the theoretical futures prices.

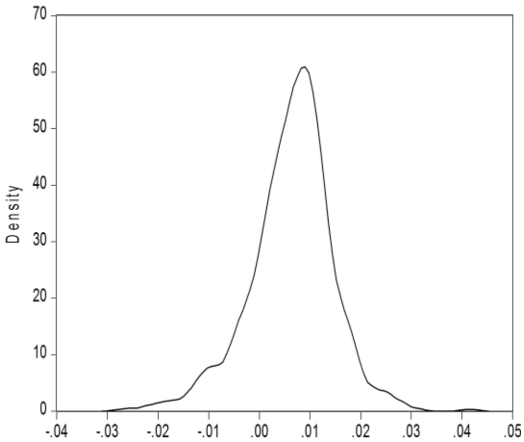
Figure 2: Kernel density estimation of carbon market mispricing

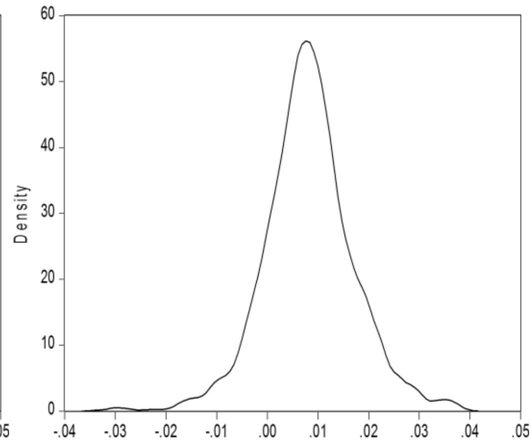
Panel A. 2009 February to April | 2009 May to July



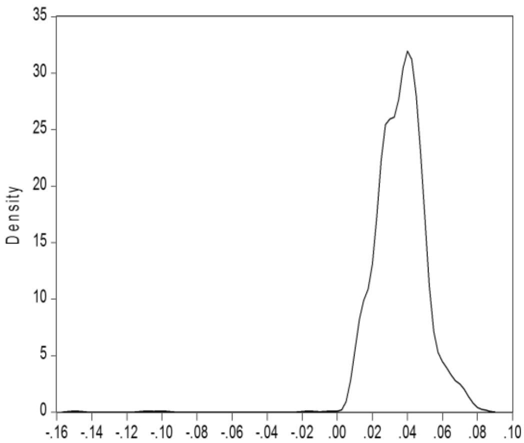


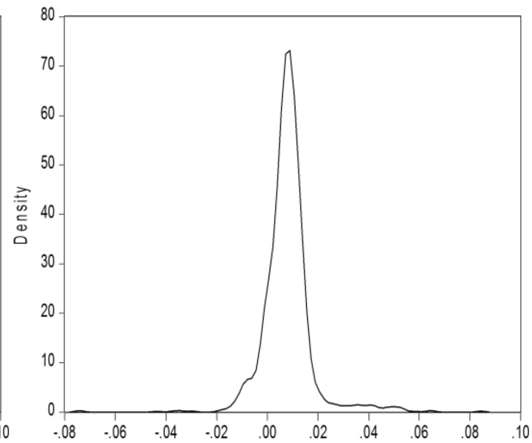
Panel B. 2010 February to April | 2010 May to July





Panel C. 2011 February to April | 2011 May to July





Note: The figure shows kernel density estimates of carbon futures mispricing before and after the submission date each year. The results in 2009, 2010 and 2011 are shown in Panels A, B and C, respectively.

Table 1: Summary statistics for mispricing

	2009 02-04	2009 05-07	2010 02-04	2010 05-07	2011 02-04	2011 05-07
Mean	0.0124	0.0094	0.0063	0.0083	0.0362	0.0080
Std. Dev.	0.0223	0.0114	0.0082	0.0088	0.0148	0.0098
Skewness	-0.918	0.847	-0.433	-0.029	-2.114	0.701
Kurtosis	11.980	6.174	4.383	4.471	28.086	16.276
Jarque-Bera	6294.107***	969.689***	202.835***	167.672***	43011.170***	13352.160***

Note: The table provides the summary statistics for mispricing, observed at the intraday frequency of 15 minutes, for the various sample periods. '2009 02-04' indicates the sample period covering February 2009 to April 2009, and by analogy for the rest of the sample periods. ***, ** and * denote significance at the 1%, 5% and 10% levels respectively.

Table 2: Estimation results of the threshold autoregressive (TAR) model

	α	δ	ρ_1	ρ_2	ρ_3	ρ_4	$\rho_1=\rho_2$	$\rho_3=\rho_4$	$\rho_1=\rho_3$	$\rho_2=\rho_4$
Panel A: Year 2009										
Feb-Jul	0.0016***	0.0023***	-0.3631***	-0.2357***	-0.2696***	-0.1551***	6.245**	6.983***	10.654***	2.177
	(3.120)	(3.561)	(-12.370)	(-4.882)	(-10.814)	(-3.805)				
Feb-Aug	0.0012***	0.0026***	-0.3363***	-0.2127***	-0.2796***	-0.1400***	8.270***	12.190***	12.311***	2.919*
	(3.105)	(4.869)	(-12.835)	(-5.308)	(-11.787)	(-3.786)				
Feb-Oct	0.0009***	0.0028***	-0.3027***	-0.1720***	-0.2918***	-0.1877***	17.140***	8.666***	14.265***	4.919**
	(3.628)	(6.357)	(-13.682)	(-6.158)	(-12.322)	(-6.071)				
Panel B: Year 2010										
Feb-Jul	0.0011***	-0.0011***	-0.0617***	-0.1402***	-0.3385***	-0.1955***	7.149***	5.080**	25.142***	1.025
	(4.904)	(-3.270)	(-2.593)	(-7.186)	(-7.898)	(-4.085)				
Feb-Aug	0.0005***	-0.0005*	-0.0616***	-0.1040***	-0.3386***	-0.3053***	2.360	0.357	26.443***	19.766***
	(3.039)	(-1.672)	(-2.663)	(-6.090)	(-8.108)	(-7.967)				
Feb-Oct	0.0004***	-0.0004	-0.0598***	-0.0967***	-0.3408***	-0.3408***	2.393	0.519	29.973***	29.967***
	(3.040)	(-1.283)	(-2.893)	(-7.019)	(-8.888)	(-9.523)				
Panel C: Year 2011										
Feb-Jul	0.0009***	0.0057***	-0.1357***	-0.1721***	-0.2035***	-0.1122***	1.151	11.099***	31.404***	3.261*
	(3.637)	(8.682)	(-9.845)	(-5.370)	(-10.752)	(-5.157)				
Feb-Aug	0.0009***	0.0064***	-0.1497***	-0.1804***	-0.2248***	-0.1264***	0.933	15.771***	38.852***	3.561*
	(4.632)	(10.147)	(-11.215)	(-6.063)	(-12.284)	(-6.731)				
Feb-Oct	0.0012***	0.0074***	-0.2080***	-0.2028***	-0.5952***	-0.1872***	0.057	184.840***	52.425***	5.053**
	(7.977)	(14.661)	(-16.867)	(-10.650)	(-22.167)	(-10.620)				

Note: The table reports the estimation results of the threshold autoregressive (TAR) model in Equation (3). The thresholds are determined by using Chan's (1993) procedure. $\alpha+\delta$ and α are the intercept terms during the period before and after the submission date (April 30) each year, respectively. The values in parentheses are the *t*-statistics. Columns $\rho_1=\rho_2$, $\rho_3=\rho_4$, $\rho_1=\rho_3$ and $\rho_2=\rho_4$ present the Wald statistic results testing for equality of regression coefficients. ***, ** and * denote significance at the 1%, 5% and 10% levels respectively.

Table 3: Estimation results of the quadratic-logistic smooth transition (QLSTR) model

	$\alpha_{0,i}$	$\alpha_{1,i}$	$\beta_{0,i}$	$\beta_{1,i}$	γ_i	$c_{1,i}$	$c_{2,i}$	$\alpha_{1,1}=\alpha_{1,2}$	$\beta_{1,1}=\beta_{1,2}$	$\gamma_1=\gamma_2$	$c_{1,1}=c_{1,2}$	$c_{2,1}=c_{2,2}$
Panel A: Year 2009												
Feb-Jul: *i=1*	0.0036***	-0.2514***	-0.0052***	-0.2096***	108246.900	-0.0014***	0.0668***	7.938***	3.753*	0.102	11.853***	58.389***
	(4.769)	(-6.693)	(-4.520)	(-5.137)	(0.258)	(-2.587)	(91.915)					
i=2	0.0008	-0.1009**	0.0035	-0.3866***	17284.640	-0.0088***	0.0453***					
	(1.430)	(-2.374)	(1.357)	(-4.711)	(0.810)	(-4.567)	(17.682)					
Feb-Aug: *i=1*	0.0036***	-0.2530***	-0.0053***	-0.2093***	108246.900	-0.0014***	0.0668***	10.858***	4.460**	0.117	14.394***	69.530***
	(5.157)	(-7.242)	(-4.870)	(-5.503)	(0.277)	(-2.780)	(96.892)					
i=2	0.0006	-0.0964***	0.0031	-0.3822***	17284.640	-0.0087***	0.0452***					
	(1.453)	(-2.650)	(1.453)	(-5.248)	(0.915)	(-5.108)	(19.191)					
Feb-Oct: *i=1*	0.0036***	-0.2482***	-0.0052***	-0.2089***	108246.900	-0.0014***	0.0668***	15.230***	6.726***	0.135	0.300	134.840***
	(5.534)	(-7.816)	(-5.252)	(-5.983)	(0.298)	(-2.992)	(107.114)					
i=2	0.0001	-0.0856***	-0.0006	-0.3754***	17284.51	-0.0042	0.0453***					
	(0.393)	(-2.822)	(-0.621)	(-6.923)	(0.917)	(-0.948)	(27.943)					
Panel B: Year 2010												
Feb-Jul: *i=1*	-0.0014	-0.0897	0.0121	-0.4747*	5421.904	-0.0219***	0.0156***	0.527	1.543	0.002	7.345***	0.008
	(-0.572)	(-0.713)	(1.626)	(-1.713)	(1.300)	(-5.200)	(2.586)					
i=2	0.0081	-0.4406	-0.0070	0.2177	9277.955	0.0142	0.0499					
	(0.570)	(-0.944)	(-0.499)	(0.450)	(0.115)	(1.125)	(0.127)					
Feb-Aug: *i=1*	-0.0014	-0.0912	0.0122*	-0.4814*	5419.885	-0.0219***	0.0157***	0.025	0.263	1.402	0.127	0.003
	(-0.589)	(-0.745)	(1.697)	(-1.788)	(1.354)	(-5.420)	(2.669)					
i=2	0.0198	0.4571	-0.0330	-1.3828	668.347**	0.0221	0.0221					
	(0.084)	(0.131)	(-0.093)	(-0.796)	(2.544)	(0.179)	(0.179)					
Feb-Oct: *i=1*	-0.0014	-0.0910	0.0121*	-0.4796*	5418.831	-0.0219***	0.0157***	0.008	0.005	0.884	0.011	0.000
	(-0.626)	(-0.790)	(1.801)	(-1.897)	(1.436)	(-5.752)	(2.837)					
i=2	0.2700	-4.8778	-0.3143	3.5576	4.0154	0.0411	10.8871					
	(0.073)	(-0.098)	(-0.098)	(0.062)	(0.001)	(0.069)	(0.001)					
Panel C: Year 2011												
Feb-Jul: *i=1*	0.0018	-0.0437	0.0100***	-0.8005***	3263.053	0.0136***	0.0917***	2.470	10.993***	0.087	2.648	19.691***
	(1.117)	(-1.438)	(3.982)	(-17.025)	(1.447)	(10.886)	(10.886)					
i=2	-0.0095**	0.1324	0.0115***	-0.4060***	111991.900	0.0229***	0.0539***					
	(-2.317)	(1.226)	(2.805)	(-3.673)	(0.305)	(8.662)	(29.435)					
Feb-Aug: *i=1*	0.0018	-0.0449	0.0106***	-0.8393***	3260.655	0.0917***	0.0131***	5.487**	12.360***	0.124	3.824*	21.827***
	(1.192)	(-1.543)	(4.205)	(-18.850)	(1.507)	(11.501)	(2.634)					
i=2	-0.0126***	0.1943**	0.0145***	-0.4592***	111991.900	0.0233***	0.0539***					
	(-3.432)	(1.984)	(3.937)	(-4.588)	(0.382)	(22.694)	(33.575)					
Feb-Oct: *i=1*	0.0019	-0.0481*	0.0108***	-0.8721***	3260.623*	0.0131***	0.0918***	6.368**	19.254***	0.196	4.725**	26.721***
	(1.368)	(-1.778)	(4.680)	(-21.245)	(1.678)	(2.971)	(12.684)					
i=2	-0.0124***	0.1836**	0.0140***	-0.4463***	11991.900	0.0231***	0.0539***					
	(-3.804)	(2.091)	(4.301)	(-4.996)	(0.447)	(26.014)	(38.232)					

Note: The table reports the estimation results of the quadratic-logistic smooth transition (QLSTR) model in Equation (4). $\alpha_{1,i}$ and $\beta_{1,I}$ are the speed of mean reversion parameters; γ_i is the speed of regime transition parameter; $c_{1,i}$ is the lower and $c_{2,i}$ is the upper threshold boundary of the regimes in the i^{th} subperiod. $i=1$ corresponds to the periods before the submission date (April 30) each year, and $i=2$ corresponds to the periods thereafter. The values in parentheses are the *t*-statistics. Columns $\alpha_{1,1}=\alpha_{1,2}$, $\beta_{1,1}=\beta_{1,2}$, $\gamma_1=\gamma_2$, $c_{1,1}=c_{1,2}$ and $c_{2,1}=c_{2,2}$ present the Wald statistic results testing for equality of regression coefficients. ***, ** and * denote significance at the 1%, 5% and 10% levels respectively.

Table 4: Estimation results of Granger causality tests

	Spot≠>Futures	Futures≠>Spot
Panel A: Year 2009		
Feb-Apr	23.845***	0.476
	(0.000)	(0.874)
May-Jul	3.328***	21.854***
	(0.002)	(0.000)
May-Aug	5.540***	26.348***
	(0.000)	(0.000)
May-Oct	11.440***	30.561***
	(0.000)	(0.000)
Panel B: Year 2010		
Feb-Apr	13.201***	5.717***
	(0.000)	(0.000)
May-Jul	14.799***	14.263***
	(0.000)	(0.000)
May-Aug	24.167***	4.290***
	(0.000)	(0.000)
May-Oct	32.190***	5.109***
	(0.000)	(0.000)
Panel C: Year 2011		
Feb-Apr	9.731***	7.340***
	(0.000)	(0.001)
May-Jul	3.487***	32.638***
	(0.001)	(0.000)
May-Aug	2.881***	47.397***
	(0.003)	(0.000)
May-Oct	3.834***	57.652***
	(0.000)	(0.000)

Note: The table reports the *F*-statistic results of Granger causality tests. The optimal lags are selected based on the Schwarz information criterion. The column Spot≠>Futures presents the results for the null hypothesis that the spot market does not Granger cause the futures market and the column Futures≠>Spot presents the results for the null hypothesis that the futures market does not Granger-cause the spot market. Robust *p*-values are presented in parentheses. ***, ** and * denote significance at the 1%, 5% and 10% levels respectively.

Table 5: Estimation results of heterogeneous autoregressive realized volatility (HAR-RV) model

	2009		2010		2011	
	RVF	RVS	RVF	RVS	RVF	RVS
α_1	-1.0949***	0.1953	-0.0026	0.2991*	-9.5363***	-2.5576
	(-5.643)	(1.056)	(-0.014)	(1.656)	(-6.191)	(-1.127)
$\beta_{1,F,1}$	-0.0710	-0.0289	0.0647	0.1194	-0.5961***	-0.0035
	(-0.870)	(-0.372)	(0.396)	(0.774)	(-6.859)	(-0.275)
$\beta_{1,F,5}$	-0.2795	-0.2319	-0.1457	0.6555	0.3503	0.0012
	(-1.419)	(-1.234)	(-0.245)	(1.167)	(1.012)	(0.002)
$\beta_{1,F,22}$	-2.8771***	0.7101	-1.6741	0.0521	2.7737***	0.6079
	(-5.180)	(1.341)	(-1.025)	(0.034)	(4.446)	(0.661)
$\beta_{1,S,1}$	0.3464***	0.0124	0.8022***	-0.3860	9.0916***	0.6070
	(3.024)	(0.113)	(2.955)	(-1.506)	(13.679)	(0.620)
$\beta_{1,S,5}$	0.2734	0.2123	0.4904	0.9343	-6.2839**	-0.7180
	(1.016)	(0.828)	(0.560)	(1.130)	(-2.500)	(-0.194)
$\beta_{1,S,22}$	3.7563***	-0.4255	0.3556	1.2957	-31.4012***	-6.5017
	(6.006)	(-0.714)	(0.174)	(0.673)	(-6.384)	(-0.897)
α_2	-0.2191*	0.0867	-0.0294	-0.0584	-0.0429	0.0356
	(-1.806)	(0.750)	(-0.367)	(-0.770)	(-0.608)	(0.343)
$\beta_{2,F,1}$	0.1333	0.2069	-0.0086	-0.0050	0.3995*	1.4700***
	(0.684)	(1.114)	(-0.090)	(-0.056)	(1.690)	(4.218)
$\beta_{2,F,5}$	-0.4089	-0.1842	0.3245	0.2850	0.0969	-1.7692***
	(-0.870)	(-0.411)	(1.534)	(1.428)	(0.222)	(-2.748)
$\beta_{2,F,22}$	0.5380	1.0264*	-0.5553	0.9145*	0.1589	0.1046
	(0.905)	(1.811)	(-0.985)	(1.718)	(0.238)	(0.106)
$\beta_{2,S,1}$	-0.0435	0.0921	0.1647*	-0.0035	0.1008	0.3759***
	(-0.282)	(0.627)	(1.683)	(-0.038)	(1.610)	(4.074)
$\beta_{2,S,5}$	0.3181	0.4671*	0.2164	0.2008	-0.0383	0.4049*
	(1.127)	(1.736)	(0.997)	(0.980)	(-0.254)	(1.822)
$\beta_{2,S,22}$	-0.1826	-0.1609	0.2596	-0.2853	-0.1901	-0.2367
	(-0.567)	(-0.524)	(0.695)	(-0.810)	(-0.610)	(-0.544)
LR	41.517***	2.064	6.977*	1.377	269.044***	17.155***

Note: The table reports the estimation results of the heterogeneous autoregressive realized volatility (HAR-RV) model in Equation (5). The sample period runs from February to November each year. The values in parentheses are the *t*-statistics. The row *LR* presents the Likelihood Ratio joint test results for the null hypotheses of $\beta_{1,S,1}=\beta_{2,S,1}$, $\beta_{1,S,5}=\beta_{2,,S,5}$, $\beta_{1,S,22}=\beta_{2,S,22}$ in the columns RVF concerning volatility spillovers from the spot to the futures market and the results testing the null hypotheses of $\beta_{1,F,1}=\beta_{2,F,1}$, $\beta_{1,F,5}=\beta_{2,F,5}$, $\beta_{1,F,22}=\beta_{2,F,22}$ in columns RVS concerning volatility spillovers from the futures to the spot market. ***, ** and * denote significance at the 1%, 5% and 10% levels respectively.