A Microstructure Analysis of the Carbon Finance Market

Don Bredin
University College Dublin *

Stuart Hyde
University of Manchester†

Cal Muckley
University College Dublin‡

Abstract

The European Union's Emissions Trading Scheme is the key policy instrument of the European Commission's Climate Change Program aimed at reducing greenhouse gas emissions to eight percent below 1990 levels by 2012. The key asset traded under the scheme is the European Union allowance (EUA). This article examines the extent of the development in the futures market of the EU Emissions Trading Scheme. Using ultra high frequency data we find considerable evidence that the market has developed since its establishment in 2005. Our results indicate significant developments consistent with sequential information arrival with a negative contemporaneous relationship between volume and volatility for all contracts. The implication is that liquidity traders dominate any role played by informed traders. Incorporating the duration between trades in our analysis has significant impact suggesting that any empirical investigation of the intra-day volume-volatility relationship needs to actively account for the impact of time elapse between trades.

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*E-mail: don.bredin@ucd.ie

†E-mail: stuart.hyde@mbs.ac.uk

‡E-mail: cal.muckley@ucd.ie. Corresponding author: Cal Muckley, School of Business, University College Dublin, Blackrock, Dublin, Ireland. The authors would like to thank Michael Brennan, John McConnell, Maureen O'Hara and Matthew Spiegel for valuable comments and participants at the 2009 Global Finance Academy Conference at University College Dublin and at the 2009 finsia/MCFS Conference, Melbourne. Ike Johnson provided research assistance.

1 Introduction

In January 2005 the European Union (EU) introduced formally the emissions trading scheme (ETS). The scheme forms a central part of the EU agreement to cut worldwide emissions of carbon dioxide (CO_2) within the Kyoto Protocol.[1] Under the Kyoto agreement, the EU is committed to reduce greenhouse gas (GHG) emissions by eight percent (relative to 1990 levels) by 2012. The aim of the EU to reduce emissions by 2012 through the EU ETS is to be achieved via two phases. The first Phase (Pilot) of trading was 2005-2007 and the second one (Kyoto), which coincides with the first compliance period of the Kyoto Protocol, is 2008-2012. After these two initial phases, the third European trading Phase will commence in 2013.

The emissions trading scheme issues a restricted amount of emission allowances to firms on an annual basis. At the end of each year firms must hold the required amount of emission permits to meet their emissions of CO_2 over that year.[2] The ETS facilitates trades for firms that are either long or short on emission permits. Non-compliance with the commitments will result in a penalty of €40 (€100) per tonne of CO_2 produced during the first (second) commitment period. The aim of the ETS is to generate a price signal that will encourage firms to reduce their emissions. Paolella and Taschini (2008) emphasize that the ultimate aim of this scheme (as well as the US CAAA-Title IV scheme) must be to create an environment where there is scarcity of allowances which will lead to an upward trend in prices. There has been a considerable amount of uncertainty associated with the price of CO_2 emissions over its short life to date.[3]

Convery and Redmond (2007) highlight that while emissions reduction has been the principal aim for the Kyoto Phase, the main objective of the Pilot Phase was to get the scheme up and running and specifically that it would be fully operational by 2008, the start of Phase 2 (Kyoto Phase).[4] Given that markets (both spot and future), registries

[1]Member states of the European Union ratified the Kyoto agreement in May, 2002. The agreement became legally binding on February 16, 2005.

[2]Firms are required to submit a report verifying their emissions in any year by March 31^{st} of the following year. In addition, emission allowances cannot be banked for future periods.

[3]The trading scheme also provides developing business opportunities for intermediaries and service providers. The pricing behavior of CO_2 emissions is particularly important to these players and is examined in detail by Bredin and Muckley (2011).

[4]Ellerman and Buchner (2006) estimate that the Phase 1 ETS has been responsible for reducing CO_2

and monitoring, reporting and verification has been established, one may argue that the principal aim of Phase 1 has been achieved. The volumes (both physical and monetary value) being traded on the European Climate Exchange (ECX) have grown dramatically since 2005. Between 2005 and 2008, physical volume increased from 94 million to 2.8 billion tonnes of CO_2 being traded, while the monetary value increased from €2.1 billion to over €55.9 billion.

This paper examines the performance of the EU ETS from a market microstructure perspective with the aim of understanding the information assimilation process, liquidity and the degree of market efficiency during both the Pilot and the initial period of the Kyoto Phase.[5] An examinination of both the Pilot and the initial period of the Kyoto Phase is important. An understanding of the initial setting up period of the exchange may have relevant and significant implications for future exchanges or trading schemes, as well as subsequent periods of the EU ETS. For example, emissions trading systems are to be established in six regions in China by 2013 and nationwide by 2015 to reduce China's emissions intensity relative to its GDP. The adopted microstructure approach provides the first thorough indication, using volume, volatility and trade duration, of the initial performance of the EU ETS.

Price and volume behavior provide key insights into the structure and running of financial markets. They are particularly informative with respect to the rate of information inflow, how information is being disseminated and the extent to which market prices convey the information. From an empirical research perspective the volume-volatility relationship has implications on the empirical distribution of speculative prices. The mixture of distributions hypothesis (MDH) asserts a joint dependence of volume and volatility on the underlying information flow (see, *inter alia*, Clark, 1973; Tauchen and Pitts, 1983; Anderson, 1996). Alternatively, while the MDH does not allow for serial dependence between volume and volatility – it is a contemporaneous relationship, the sequential information arrival hypothesis (SIAH) (Copeland, 1976) posits that traders both receive information and act on it in a sequential manner, hence a new equilibrium is not established instantaneously and the potential for a lead-lag relationship between volume and volatility exists. Moreover, the role of duration during these periods has hitherto not been explored. Yet

emissions by between 50 and 200 million tonnes.

[5]Our interpretation of efficient markets draws on the work of Dacorogna et al. (2001).

while microstructure models (see Diamond and Verrecchia, 1987; Easley and O′Hara, 1992) suggest trade arrival times convey information neither hypothesis explicitly accounts for the effect of time duration in measuring the information content of trades.[6]

The microstructure literature acknowledges that trading activity in asset markets is induced by both revisions to investor expectations of asset prices, following the arrival of new information, and by their requirements for liquidity (see, O′Hara, 1987 and Blume et al., 1994). Recent research into the analysis of trading volume as a measure and signal of investor information and liquidity needs, raises important issues concerning its interaction with other key variables of the trade process, in particular asset price volatility and trade duration. Duration is considered to reflect the trading strategy of informed traders or be an indicator of liquidity. Market microstructure suggests a relation between trade duration, trade volume and asset price volatility. However, prior empirical research customarily focuses upon the price impact of one or two specific trade process variables in isolation, rather than their combined effects. In order to understand the full dynamic interactions among the three trade process variables they should be modeled simultaneously. We adopt such an approach in this paper to examine the information assimilation process, liquidity and the degree of market efficiency during the Pilot and the Kyoto Phase of the EU ETS. We initially adopt the duration based model proposed by Xu et al (2006) to examine the relationship between time consistent volume and volatility, while controlling for exogenous duration effects. In addition, we adopt an alternative model specification, in the vein of Manganelli (2005), which allows duration to be endogenous and to be modelled simultaneously together with volume and volatility. Our analysis is carried out on Phase 1 and 2 EU ETS futures and we focus on futures data provided by the ECX.[7]

Our key results indicate significant market developments, with reduced frictions indicating evidence of greater levels of efficiency and evidence of sequential information arrival in existence. The evidence of reduced market frictions is reflected in the form of reduced duration, higher volumes traded, lower volatilities and greater levels of bi-directional causality. In particular, taking account of the duration information, we find that trades associ-

[6] Duration is defined as the elapsed time between consecutive trades.

[7] Futures contracts account for 76% of the volume of trades in EUA's. Of these contracts, 96% are traded on ECX which was acquired by the Intercontinental Exchange in July 2010. The remainder are traded on the European Energy Exchange (EEX) and Nordpool (see Mansanet-Bataller and Pardo, 2008).

ated with longer durations have a higher impact on volatility. Our results also indicate a negative contemporaneous relationship between volume and volatility for all contracts examined. The implication is that liquidity traders dominate any role played by informed traders (Easley and O′Hara, 1992). Moreover, the empirical evidence appears consistent with the sequential information arrival hypothesis (Copeland, 1976) rather the predictions of the mixture of distribution hypothesis (Clark, 1973; Tauchen and Pitts, 1983). The evidence in favor of the sequential information arrival hypothesis is consistent with recent results on the EU ETS reported by Conrad et al. (2011).

The remainder of the paper is set out as follows: section 2 discusses the emergent literature in carbon finance with specific reference to the ECX and microstructure issues. Section 3 introduces the empirical methodology, outlining the adopted approach to study market microstructure issues from both a theoretical and empirical perspective. Section 4 presents the data and empirical results and section 5 provides some concluding comments.

2 Recent Developments in Carbon Finance

Futures contracts were introduced on the European Climate Exchange (ECX) in March 2005, with options trading following in October 2006. Trades on the ECX are cleared through the Intercontinental Exchange (ICE), which also hosts the electronic marketplaces for the Chicago Climate Exchange, with delivery of allowances at any national EU registry.[8] Since 2005, the ECX has witnessed dramatic growth in trade volume. In March 2008 it introduced certified emission reduction (CER) futures and options and in October 2008 it introduced an EUA-CER spread trade.[9]

Despite the premature nature of the EUA market there has been a plethora of studies in recent years examining the pricing behavior and developments in both the spot and futures markets. Redmond and Convery (2006) examine EU ETS using daily data over the period 1^{st} December 2004 to 31^{st} July 2006 focussing on the behavior of the price of carbon in relation to energy commodities, meteorological factors and a number of other variables in-

[8] In late April 2010, the Intercontinental Exchange (ICE) agreed to pay over US$600 million in cash to acquire Climate Exchange (owner of the ECX) for which it previously cleared trades.

[9] Mizrach and Otsubo (2011) investigate the price discovery between the EUA and CER futures on the ECX.

cluding dummy variables to take account of policy and regulatory issues. Similarly, Alberola et al. (2008) and Bredin and Muckley (2011) further document the role of fundamentals on daily spot and futures prices respectively. Paolella and Taschini (2008) examine both SO_2 (in the US) and CO_2 (EU) spot price dynamics, Benz and Trück (2009) take account of the non-normality associated with the EU allowance returns on spot contracts finding evidence of regime switching while Daskalakis et al. (2009) examine the price behavior of spot, futures and options contracts across the different phases and in three of the European trading venues. The empirical studies to date have highlighted the difficulties associated with Phase 1 (Pilot Phase). In particular there was considerable uncertainty associated with the market price of EUA's. In April 2006, coincident to the unofficial release of the 2005 emissions data by some of the EU member states the EUA's price collapsed. EU ETS spot prices had reached a high of €30.50 prior to April 2006. Following the official release by the EU commission on the 15^{th} May 2006, showing a larger than expected surplus in the market, the spot price fell to €15.63 on the 17^{th} May 2006. Given that banking EUAs was prohibited between phases, the price eventually converged to close to zero at the end of Phase 1. Overall for Phase 1, it would appear that the cap placed on emissions was far too lax and so downward pressure on the price continued.

While this literature examines daily price behavior, a relatively small number of studies investigate microstructure issues, e.g., price discovery and liquidity issues, using high frequency data. The first such study, Benz and Hengelbrock (2009) finds evidence of increased liquidity during Phase 1 for both the ECX and Nord pool, with particularly strong evidence for the considerably larger ECX market.[10] Further in terms of price impact and price discovery, the ECX represents a price leader especially for recently traded contracts (December 2007 and 2008). Extending the research on price discovery, Mizrach and Otsubo (2011) examine a number of issues relating to trading volumes, transactions costs (spreads), price impact and return predictability for EUA and CER contracts during 2009 (Phase 2). Consistent with Benz and Hengelbrock (2009), Mizrach and Otsubo (2011) find evidence that the ECX futures market provides 90% of the price discovery. This research establishes the primacy of the ECX platform for investigating the behavior of EUA futures.

[10] Both spot and futures contracts are traded on the Norwegian platform Nord Pool, which has a market share of 12.5% on the futures market. In 2010 NASDAQ QMX acquired all the shares in Nord Pool International, Nord Pool clearing ASA and Nord Pool Consulting, (see, Mizrach, 2010).

An alternative emergent literature empirically examines the extent of intra-day volatility. Rotfuß (2009) provides an analysis of volatility characteristics for the first and second trading period while Chevalier and Sevi (2011) document the superior ability of realized variance measures at forecasting volatility for EUA futures.[11] Focussing on the initial period of Phase 2, Conrad et al. (2011) demonstrate that regulatory announcements have statistically significant effects on intra-day volatility, while there is a marginal influence from scheduled macro economic announcements. Conrad et al. (2011) also show that regulatory announcements and lagged volume have a positive and statistically significant impact on the volatility of EUA returns. Finally, Rittler (2009) shows evidence of volatility transmission from the futures market to the spot market and confirms that futures provide the leading role in price discovery.

In this article, we extend the outlined microstructure related findings with regard to market liquidity, volumes and intra-day volatility on the EU's ETS. Specifically, we further examine the information assimilation process and the degree of market efficiency, in the ETS, during both the Pilot and the initial period of the Kyoto Phase of the Scheme. Unlike the previously discussed studies, we simultaneously model the three key trade process variables: duration (i.e. the time elapsed between trades), trade volume and asset price volatility with a view to accounting for the dynamic interactions involved and identifying the class of traders principally present in the market, whether informed or liquidity traders. In addition, we examine the empirical evidence in regard to the sequential information arrival hypothesis (Copeland, 1976) and the mixture of distributions hypothesis (Clark, 1973; Tauchen and Pitts, 1983). Finally, we conduct a range of sensitivity tests, across model specifications and samples of data, and we compare our Pilot Phase findings with those of the initial period of Phase 2.

[11] Chevallier and Sevi (2011) also find the distribution of standardized returns to be non-normal, contrary to the Mixture of Distributions Hypothesis (MDH).

3 Econometric Methodology

3.1 Empirical Issues

Market microstructure research must confront the problems generated by the fact that transactions data arrives at irregularly spaced intervals in time. Many studies simply ignore the time variation between successive trades, and analyze the data utilizing econometric techniques more appropriate for equally spaced observations. We maintain that this approach may result in a significant loss of information, since the elapsed time between consecutive trades (duration) may convey important information about the state of the market. Two approaches have been proposed to accommodate this concern. First, Engle (2000) argues that variables in empirical microstructure models should be adjusted for duration in order to obtain time-consistent parameter estimates. In this vein, Xu et al. (2006) incorporate a time factor by standardizing both volume and volatility with respect to elapsed time (trade duration) thereby creating time consistent measures for empirical tests. The hypothesis is that the longer the interval over which a return is measured, the higher the probability of pertinent news arrival and the greater the ensuing trade size and volatility. In this spirit, we begin our analysis by utilizing a time consistent structural vector autoregression (VAR) model to characterize the dynamic relationship between our duration-based volatility and volume measures.

Second, Engle and Russell (1998) and Dufour and Engle (2000) explicitly incorporate the duration between trades as an endogenous variable in a microstructure model. The inclusion of a duration variable not only addresses the estimation problems associated with irregularly occurring observations, but more importantly it also permits the information conveyed by duration to be explicitly incorporated in the modeling framework. In order to better understand the dynamic relationship between duration, volume, and volatility, we further extend the analysis by specifying a trivariate VAR framework in which we explicitly model duration. Specifically, we will examine whether the mixed distribution hypothesis (MDH) applies in the case of EUA futures and how do variations in the pattern of informed and liquidity trading influence price volatility as well as the observed volatility-volume relationship.

3.2 The VAR models

Initially, we formulate a bivariate VAR model where volume and volatility are standardized per unit of time, thereby accommodating the scale effect of duration on trade volume and volatility.

$$\begin{aligned} z_{d,t} &= \mu_z + \sum_{i=1}^{p} a_{zi} z_{d,t-i} + \sum_{i=0}^{q} (b_{zi} + c_{zi}\tau_{t-i}) v_{d,t-i} + u_t \\ v_{d,t} &= \mu_v + \sum_{i=1}^{p} a_{vi} z_{d,t-i} + \sum_{i=1}^{q} (b_{vi} + c_{vi}\tau_{t-i}) v_{d,t-i} + \epsilon_t \end{aligned} \tag{1}$$

where $z_{d,t}$ and $v_{d,t}$ are duration-based volatility and volume, respectively.[12] Specifically, if $d_t = T_t - T_{t-1}$ is duration, the elapsed time between consecutive trades at T_t and T_{t-1}, then $z_{d,t} = ln[\frac{Z_t}{d_t}]$ is the log volatility per unit of time, and $v_{d,t} = ln[\frac{V_t}{d_t}]$ is the log volume per unit of time. Here, we measure volatility, Z_t , by the absolute value of returns, $|r_t|$ and the volume variable, V_t , by the trade size at calendar time t. The order of the lag length for the duration-based volatility and volume variables, (p, q), are determined on the basis of the Akaike information criterion (AIC). Following Xu et al. (2006) we include an interaction term $\tau_{t-i}(\tau_t = ln(d_t))$, that allows the volume to vary with duration in both equations.[13] As can be seen from equation 1, $z_{d,t}$ and $v_{d,t}$ are driven by two uncorrelated random shocks; an informed traded shock, u_t and an uninformed traded shock, ϵ_t. Easley and O′Hara (1992) argue more informed traders tend to trade at short durations, thus we expect larger volumes to be traded at shorter durations. Informed traders are defined as traders that use the fundamentals to form reliable opinions as to whether an instrument is under or over valued and then act on these opinions. Uninformed traders (liquidity traders) do not know the fundamental value of the instrument when forming their trading decisions (see, Harris, 2003). Liquidity traders are motivated by consumption needs and portfolio strategies or their trading is a reflection of their particular price sensitivities or particular

[12]Both duration-based volatility and volume are per unit time and in log terms to ensure that the variables are positive.

[13]It is then possible to examine whether duration between trades affects price adjustment to trades in the volatility equation. In the volume equation, the interaction term allows us to observe the correlation between current and past volume.

trading rules (see Easley and O′Hara, 1992). Hence, the impact of volume on absolute price changes, as a result of the trading activity of informed traders, should be greater at shorter durations.

The ordering of the variables is based on the assumption that a shock to duration would be transmitted to trading volume and price volatility. The intuition is that, as suggested by market microstructure theory, with the arrival of new information (time dependent), informed traders choose to trade various volumes of futures contracts. Depending on the nature of the information (good or bad news), as well as the demand/supply nexus, agents execute either large numbers of trades over a short time frame (high trading activity) or fewer trades over a longer time interval (low intensity).[14] Although one could argue that a trader, a priori, decides on her trading volume given her demand needs, we conjecture that this notion ignores the effect that news has on *a priori* beliefs and the timing of trades. Hence, the ordering of the variables in above (and in the extended VAR later) is theoretically informed.[15]

Easley and O′Hara (1992) argue that the timing of an order placement also conveys relevant information to the market maker, and will be internalized by an informed trader when deciding their order placement strategy. Hence, volume and duration interact to influence price (volatility) at time *t*. Further, Manganelli (2005) highlights that although an informed trader may prefer to exploit their informational advantage by trading a larger amount of the asset, initiating this strategy would immediately reveal their inherent informational advantage and the market maker would adjust quotes accordingly. Thus, in order to disguise their investor type, an informed trader may segment their order flow into a sequence of smaller trades separated in time. The subsequent market trading intensity then determines the amount of shares exchanged at each price. Consequently, given informed traders always trade to exploit their informational advantage, subsequent to the arrival of price relevant information, expected duration will fall and expected volumes will rise, making trade more likely. Thus we adopt a causal ordering such that causality runs

[14]The underlying assumption is that liquidity (noise) agents, trade with constant intensity.

[15]In Kyle (1985), insider (informed) traders act strategically. They rationally anticipate the impact of orders on prices, by conditioning on the behavior of other market participants (namely, the market maker and uninformed traders). As new private information arrives, informed traders review the existing price quotes of a specialist market maker and select the amount of shares which maximizes their informational advantage to trade.

from duration to volume, and from both duration and volume to volatility.[16] In addition, based on both the MDH and sequential arrival of information specifications, we expect a positive relationship between volatility and volume. However, while the MDH suggests a positive contemporaneous causal relationship between volume and volatility, the sequential arrival of information model implies a lead-lag relationship in both directions (bidirectional causality) between these two variables.

Given duration is informative about an assets true value (Diamond and Verrecchia, 1987; Easley and O′Hara, 1992), it follows that duration should interact with volume to influence the characteristics of asset prices. To capture these interactions, we extend the VAR analysis to include time as an endogenous variable.[17] The VAR for duration, d_t, volume, V_t , and volatility, Z_t , is:

$$\begin{aligned} d_t &= \mu_d + \sum_{i=1}^{p1} \gamma_{id} d_{t-i} + \sum_{i=1}^{q1} \rho_{id} V_{t-i} + \sum_{i=1}^{r1} \delta_{id} Z_{t-i} + \varepsilon_t \\ V_t &= \mu_v + \sum_{i=0}^{p2} \gamma_{iV} d_{t-i} + \sum_{i=1}^{q2} \rho_{iV} V_{t-i} + \sum_{i=0}^{r2} \delta_{iV} Z_{t-i} + \eta_t \\ Z_t &= \mu_z + \sum_{i=0}^{p3} \gamma_{iZ} d_{t-i} + \sum_{i=0}^{q3} \rho_{iZ} V_{t-i} + \sum_{i=1}^{r3} \delta_{iZ} Z_{t-i} + \zeta_t \end{aligned} \tag{2}$$

where the lag orders are determined by the Akaike information criterion (AIC). The return volatility processes in equations (1) and (2) are a generalization of the return process in the traditional MDH model, which postulates that return volatility depends on the flow of information and a random disturbance term. The return volatility process in the MDH framework can be written as:

[16] This is consistent with Manganelli (2005, p.382) who highlights '(i) the duration between trades can affect prices, (ii) duration should be correlated with volume, and (iii) both duration and volume should be correlated with transaction price variances.'

[17] The bivariate VAR specification provides a base from which to analyse our trivariate findings, allowing for the possible exogeneity of duration effects. The inclusion of the bivariate VAR model, which specifies an interaction term between volume and duration in the determination of future volumes and volatility, serves to investigate, in a preliminary manner, the importance of accounting for duration effects. In the trivariate model, the constraint of exogenous duration variation is relaxed and duration is included as an endogenous term. This allows for interaction effects from duration to volume and to volatility and *vice versa*. The inclusion of both model specifications, disallowing and allowing for endogenous duration effects, is of particular interest.

$$Z_t = K_t + \upsilon_t \tag{3}$$

where $K_t = \ln k_t^{1/2}$, k_t is the latent information flow and υ_t is the disturbance term. In the traditional MDH model, return volatility is related to the latent information flow k_t concurrently, and the disturbance term is serially independent. The volatility process in equation (2) generalizes the MDH volatility process in equation (3) in several ways. First, it permits a lagged dependence in Z_t. This generalization is quite appropriate given that empirical evidence suggests strong volatility persistence, even after controlling for the effect of information flow. The cause of volatility persistence is usually attributed to one or a combination of microstructure imperfections including, inventory control, exchange-mandated price smoothing, and/or lagged adjustment to information among others. The present model accommodates a process of dynamic adjustment or a learning effect in relation to the new information, so that return volatility is affected by lagged information.

In the extreme case, where the serial dependence is absent, the values of the lagged coefficients in equation (2) will be insignificantly different from zero and the model simply degenerates to the traditional MDH volatility process.[18] Second, in this three variable formulation, the latent information is linked to trading volume and duration which is consistent with the argument that information induces trades, which in turn, move prices. Third, the VAR model permits lagged information effects on volatility, thereby removing the stringent restriction imposed by the MDH model that information must be instantaneously impounded into prices. Finally, empirical tests of the MDH model at the intraday level typically use transaction data aggregated up to fixed intraday intervals. Naturally, there is a loss of information in this aggregation. This loss occurs partly due to the large number of zeros, making econometric analysis extremely complex if the intervals are small. In contrast, the three variable VAR model is directly based on irregularly spaced transaction data, which is free from the problem of temporal aggregation. At the same time it accounts for transaction time, by the inclusion of duration.

[18] It follows that the specification is more general in that it can accommodate serial dependence in volatility.

4 Data and Empirical Results

4.1 Data and Contractual Issues

We adopt intra-day transaction data for Phase 1 and 2 EUA futures contracts with a December 2005, 2006, 2007 and 2008 expiry.[19] One futures contract corresponds to 1,000 EUA's, which represent the right to emit 1,000 tonnes of CO_2 equivalent greenhouse gases. The sample size for our four contracts are as followings; December 2005 (22^{nd} April 2005 to 19^{th} December 2005), December 2006 (16^{th} June 2005 to 18^{th} December 2006), December 2007 (3^{rd} June 2005 to 17^{th} December 2007) and December 2008 (28^{th} September 2005 to 15^{th} December 2008). The contracts expire on the last Monday of December, while settlement is three days after the last trading day. The data is taken from the continuous trading session, which runs from 7am to 5pm (UK local time). The ECX has currently over 100 members trading EUA's.[20] Incoming orders on the ECX are binding until the end of the trading day if they have not been executed, changed or canceled. The minimum tick size is €0.01 per tonne of CO_2, while a range of order types are available including limit, market and stop orders.[21] The annual fee for ECX members is €2,500, while the trading and clearing fee per contract is currently €3.50. There are currently (introduced in December 2008) three market makers for the ECX (Five Rings Capital (formerly Jane Street Global Trading), Saxon Finance and RNK Capital). The market maker is required to provide bid and ask quotes for at least 85% of the trading time between 8am and 5pm (UK local time) and are required to respond to quote requests within five minutes.

The data includes comprehensive information relating to all transactions, maturities, trade prices, opening prices and trading volume for four different futures instruments traded on Phase 1 and 2 of the EU ETS. To prepare the data for the analysis, we first sum the trading volumes when we detect a series of equal recorded prices for the same contract maturity which occur at the same time. The summation of trading volumes can be motivated by the practice in the management of the electronic book. This consists of utilizing

[19] Contracts with a quarterly expiry exist (March, June, September and December), however the December expiry contracts are far more liquid and hence we focus on these instruments.

[20] See www.ecx.eu for details.

[21] A dummy variable to take account of the change in the tick size, from €0.05 to €0.01, on the 27^{th} March 2007 has been included.

the existing liquidity that is available in the sense that a trader can choose to split a large transaction into a series of smaller transactions and trading with different counter parties. We then compute the duration between trades, treating the overnight period as if it did not exist.[22]

In table 1 we report the relevant summary statistics. The available data for each contract varies considerable; with roughly 9, 19, 31 and 40 months available for the December 2005, 2006, 2007 and 2008 respectively.[23] The first consideration is the relatively small number of observations, which is representative of the number we would observe for relatively infrequently traded stocks on major exchanges (such as the NYSE). As is the norm there is a fair degree of consistency across the instruments for the case of volume. There is a steady upward trend in relation to volume, until it falls back for the December 2008 contract. However, the duration figures tell a very different story and one which is consistent with events in the market. The December 2005 expiry has a very small number of observations and reports quite a large duration (time between consecutive trades). There was a significant increase in trading for the 2006 contracts and this is reflected in the fall in mean duration to approximately 10 minutes. The over allocation of allowances, along with the restrictions on inter Phase banking is reflected in the duration figures for 2007, with a doubling of the time between trades compared to 2006. Finally, the 2008 figures represent trading behavior for Phase 2 of the EU ETS and there is a considerable drop in duration for these contracts. The summary statistics on duration do highlight the market development in particular for Phase 2 expiring contracts. The last four columns of table 1

[22]As our futures contracts are quite thinly traded, following Manganelli (2005), we prefer to retain the overnight return. In respect to duration, we treat the overnight period as if it didnt exist. By way of contrast, eliminating absolute returns during the overnight period, *e.g.*, by adopting a dummy variable, would have possibly caused the loss of important data for these quite illiquid futures contracts. In fact, less frequently traded securities, in general, do not exhibit any regular pattern during the day. Following Engle (2000), regressions were conducted on the time series of absolute returns using a piece-wise linear spline with time related knots specified during the trading day. With respect to our futures contracts, we found an absence of significant diurnal effects across the December '05, '06, '07 and '08 contracts as well as during the period of the robustness test (September 29 through to December 15 for the December 2008 contract), presented in section 4.3. These findings, of a thinly traded EUA futures market, are indicative of the merit of retaining the overnight return to avoid the possibility of losing important data.

[23]The contracts examined expire in December in all cases; 2005, 2006, 2007 and 2008. For the remainder of the paper the contracts will be referred to by the year of expiration.

report volatility and volume per unit of time. Of particular note is that volume per unit of time has grown steadily from 2005 to 2008 expiry, while the volatility per unit of time has stabilized for the 2008 contract.

Table 2 reports the summary statistics for duration and volume for all December expiring contracts for each calendar year. The statistics indicate that the vast majority of trading takes place in the final year of the contract, with a considerable rise in volumes traded for all contracts in the final trading year. The fall in duration is quite dramatic, in particular for the December 2008 contract. In order to reflect the dispersion of the duration and the volume variables, their statistical moments are presented. The trends over time, across contracts, with respect to declines in the mean and variance of duration and increases in the skewness and kurtosis of the duration measurement are consistent with the considerable rise in trading activity. Concerning the volume measurement, there is an irregular pattern across the statistical moments over time reflecting the development of the market from the set-up Phase to Phase 2.

4.2 Empirical Results

The theoretical justification for the ordering of the variables in the VAR is provided in section 3, here we examine whether this justification can be rejected empirically by examining simple Granger causality tests, reported in table 3. The distinction between the December 2005 contract and all other other contracts (either Phase 1 or 2) is evident. We fail to reject a number of hypotheses for the December 2005 contract, for instance that volatility does not Granger cause duration and that either duration or volume do not Granger cause volatility, at the standard 5% level of significance.[24] However, for the remaining contracts the results indicate strong inter-relationships between the three variables and hence we conclude that there is some evidence of a bi-directional "causation" between the variables. Such strong evidence of inter-relationships and bi-directional causality between all variables does not provide evidence to counter our theoretical basis for ordering the VAR. Furthermore, the

[24]Notwithstanding, it is worthwhile highlighting that, despite a relatively small sample size as detailed in table 1, the Dec 05 contract is associated with granger causality in three of the six bivariate relations studied [at the 5% level] and in four of the bivariate relations studied [at the 10% level]. Albeit this evidence isn't as convincing as the causality evidence found in respect to the Dec 06, 07 and 08 contracts, it nevertheless is, in our view, quite persuasive.

bi-directional causality points to evidence in favor of sequential information arrival, and is inconsistent with the MDH, for the EU ETS futures market.

The estimates of the bivariate, duration standardized VAR, represented in equation (1) are reported in tables 4 to 7 for the December 2005, 2006, 2007 and 2008 contracts respectively. Following Alberola et al. (2008) we take account of recognized structural breaks in the data, e.g., the compliance break in April 2006 and the break associated with the announcement of stricter validations of National Allocation Plans in October 2006, by including dummy variables to capture the potential shifts due to these breaks in the estimation of the 2006, 2007 and 2008 contracts. In addition, following Rotfuß (2009), we adopt a dummy variable to take account of a structural break March 27^{th} 2007 when the Intercontinental Exchange (ICE) reduced the minimum tick size for all EUA futures contracts from €0.05 to €0.01. It has been included in the model for the December 2007 and the December 2008 contract. This dummy variable is statistically significant in all cases for the 2008 contract and there are mixed levels of significance for the 2007 contract. However, our results show that the impact of the breaks on volume and volatility are mainly confined to the 2006 contract. In each case the VAR is estimated up to the optimal lag length identified by the AIC. The tables report significant coefficients only. The results (coefficient b_0) indicate that there is a negative contemporaneous relationship between volume and volatility for all contracts. Moreover, the coefficient is highly significant in each case. The implication here is that liquidity traders are dominating any informed trading behavior. A similar finding has been reported by Karpoff (1988) for the case of financial futures contracts, bonds and commercial paper. There is also some evidence to indicate that lagged volume increases volatility (for the December 2006 and 2008 contract) and so evidence in favor of sequential information arrival. Thus, our results would appear to be inconsistent with the MDH.

The volatility is quite persistent, as evidenced by the positive significant coefficients of lagged volatility, especially for the later 2008 contract. There is also consistent evidence for all contracts of positive correlation in lagged volume. This strong dynamic relationship between volume and volatility is also contingent on the time duration between trades. The negative volume-volatility relationship is further strengthened as the duration between trades increases since the contemporaneous interaction term between duration and volume (coefficient c_0) is negative and significant. Moreover for the 2008 contract lagged interaction terms are also negative and significant consistent with Xu et al. (2006), suggesting trades with a longer duration have a lower impact on volatility.[25] This suggests that any empirical investigation of the intra-day volume-volatility relationship needs to actively account for the impact of time elapse between trades. Overall our results are consistent across all contracts, with considerable evidence of market development in line with sequential information arrival. Of particular importance is the finding that this development continues for the Kyoto Phase (Phase 2) contract (Dec.08) and further highlights operational improvements.

In table 8 we report the results of the trivariate structural VAR specified in equation (2) for the Kyoto Phase (Phase 2).[26] By treating duration as an endogenous variable, we are able to obtain a clearer understanding of the interaction between time, volume and volatility. We adopt an identical set of dummy variables as specified in the exogenous duration bivariate models detailed above. Our results further highlight the level of consistency relative to the duration based bivariate VAR results. Volume continues to have a significantly negative impact on volatility contemporaneously, with some evidence that lagged volume increases volatility.

The positive relationship between volatility and lagged volume is consistent with the sequential information arrival hypothesis and has also been reported by Conrad et al. (2011). The contemporaneous duration has a statistically significant positive impact on volatility. The positive relationship is also economically significant as it indicates that liquidity traders prevail in the current EU ETS market rather than informed traders. The dominance of uninformed/liquidity traders in the market is supported by findings in a recent study by

[25]The identified positive contemporaneous relation between duration and volatility, when controlling for volume, is indicative of the prevalence of liquidity traders in the market (Easley and O'Hara, 1992). The Easley and O'Hara (1992) hypothesis indicates that informed traders, to benefit from their informational advantage, execute a trade in several consecutive relatively small transactions so that the liquidity trader does not recognize the new information and alter the quotes to nullify the informed trader's informational advantage. As a result, large volumes and price impact are expected to be associated with short durations due to the presence of informed traders. Our findings are inconsistent with this latter hypothesis as they indicate that liquidity traders prevail in the market rather than informed traders.

[26]We conduct similar analysis for each of the first Phase contracts. The results are qualitatively similar to those obtained from the bi-variate VAR and to those we report for the trivariate VAR using the 2008 contract data. Hence to conserve space we refrain from reporting the results here. The results are available from the authors on request.

Iordanis and Maher (2011). Given significant evidence of lagged relationships, our results are at odds with the predictions of the MDH and are better characterized by the SIAH. Again, consistent with the bivariate results, lagged duration has a negative and significant impact on current volatility.[27] The duration of the current and previous two trades have a positive impact on volume with the duration of earlier trades having a negative impact.

The results for the impulse response functions for 25 lags (trades), including standard errors, are reported in figures 1 to 4.[28] The diagonal graphs indicate the effect of the shock on duration, volatility and volume on each of the respective terms. While there is some persistence, this is consistent with results on more developed asset markets. The standard error bands are relatively larger for the early contracts given the relatively smaller number of observations. For the off-diagonal entries, we find evidence that duration does have an impact on volume and volatility, and vice versa, but generally over short intervals. As a further robustness test of the model we estimate (2) using data taken only from the nearby contracts. Nearby contracts are defined in this market context as those trading in the month prior to their maturity. We do not include observations on contracts trading in the maturity month, simply to avoid biases caused by unusual market activity characteristic of times approaching maturity as traders unwind or rollover positions. Given the fact that most trading activity generally takes place in the contract specified on the nearby month, the analysis of data taken only from this contract data may be useful to further substantiate our findings, as it confines the data analysis to the most actively traded contracts. In figure 5 we report the impulse response function for the Kyoto Phase (Phase 2) contract and the results are consistent with those reported for the full sample.[29]

[27] Trade arrival times or duration convey private information hence duration is linked to the latent variable information flow in a similar manner to volume. A rational market maker will interpret high volumes in combination with short durations as evidence of trading by informed agents and will adjust quoted prices accordingly (Easley and O'Hara, 1992). As a result, within the SIAH framework, the lagged information variable, duration, is expected to be economically and statistically significant in the volatility equation of the trivariate VAR system.

[28] The triangular decomposition (Cholesky) is adopted to achieve orthogonalization.

[29] The results of the estimates from the nearby contracts are consistent with the results of the full sample for all contracts, both Pilot and Kyoto Phase, and so justifies our conclusion that the MDH does not hold for EU ETS Futures.

4.3 Robustness Testing and Signed Volume Effects

In tables 9 and 10 we report the findings of the trivariate structural VAR specified in equation (2) for the December 2008 contract in the Kyoto Phase (Phase 2) during the period September 29 2008 through to December 15 2008. The findings reported in table 9 relate to the trivariate duration-volatility-volume VAR while the findings reported in table 10 relate to this VAR specification with signed volume substituted for volume figures. The signed volume indicates whether the corresponding trade is a buyer initiated (+) or a seller initiated (-) trade while the conventional volume measurement which we adopt in the other specifications is always non-negative and does not convey this information.

The findings reported in table 9 for the latter months of the December 2008 contract corroborate those findings presented in table 8 for the full period of the December 2008 contract as well as the duration based bivariate VAR results. In particular, volume continues to have a significantly negative impact on volatility contemporaneously, with some evidence that lagged volume increases volatility. The contemporaneous duration has a statistically significant positive impact on volatility. Given significant evidence of lagged relationships, our results are at odds with the predictions of the MDH and are better characterized by sequential information arrival. Again, consistent with the bivariate results and the full blown trivariate results, lagged duration has a negative and significant impact on current volatility. As discussed above, taking these findings together they support the sequential information arrival hypothesis and they indicate that liquidity traders prevail in the current EU ETS market rather than informed traders.

Turning to the findings reported in table 10 which reflect the presence of signed volume rather than volume in the trivariate specification, it is evident that while there is some scant evidence of lagged volume increasing volatility. The contemporaneous negative relation between volume and volatility is no longer present. Notwithstanding, the contemporaneous duration has a statistically significant positive impact on volatility. The positive contemporaneous relation between duration and volatility is economically significant as it indicates that liquidity traders prevail in the current EU ETS market rather than informed traders. In addition, consistent with the bivariate results and the full blown trivariate VAR results, lagged duration has a negative and significant impact on current volatility. Given significant evidence of lagged relationships, our results are once again at odds with the predictions of the MDH and are better characterized by sequential information arrival. Finally, as is established by, *inter alia*, Lyons (1997) and Berger *et al.* (2006) for high frequency exchange rate data, pronounced positive signed autocorrelations of signed volume (*i.e.* order flow) results are evident at the tick-by-tick level in our study. This high level of autocorrelation may indicate the passing of a large trade among traders or it may reflect order splitting, whereby a large trade is executed sequentially. Taking the findings in table 10 together, they do not support MDH and they indicate the prevalence of liquidity traders rather than informed traders in the EU ETS market.

4.4 Carbon Finance Market Implications

Our detailed high frequency examination of the EU ETS extends the large number of recent studies examining carbon finance market developments using low frequency data. Exchange traded market activity, and EUA futures in particular, have grown dramatically with the move from Pilot to the Kyoto Phase. Besides the spike in 2006, mean duration and volumes for the contracts examined have been reflective of a market that is developing year on year.[30] Although our transaction level data does not include a trade indicator variable for the December 05, 06 and 07 maturity contracts, the market for EUAs is viewed as being driven by buyer initiated trades rather than seller initiated trades. Our conclusion is supported by findings in a recent study by Iordanis and Maher (2011). The authors highlight that the EU ETS can be viewed as a buyer orientated market, where a greater proportion (in terms of volume) of trades are buyer rather seller initiated. Our empirical results for duration and its relation with both volume and volatility are consistent with this view. Another consistent finding across contracts is the negative contemporaneous relationship between volume and volatility. The implications are that liquidity trades are dominating any informed trader behavior. Informed traders, as is often the case, may have a preference to trade on the over the counter (OTC) market.

[30] Two important structural breaks occurred in 2006, the compliance break in April 2006 and the break associated with the announcement of stricter validations of National Allocation Plans in October 2006. See Alberola et al. (2008).

5 Conclusions

This paper investigates the initial stages of the European Union (EU) emissions trading scheme (ETS) introduced formally in January 2005 from a market microstructure perspective. The scheme instigated as part of the EU agreement to cut worldwide emissions of carbon dioxide (CO_2) within the Kyoto Protocol issues a restricted amount of emission allowances to firms on an annual basis and subsequently allows firms to trade the emission permits they hold. This study covers the first phase of trading from 2005 to 2007 and the initial year of the second phase, which coincides with the first compliance period of the Kyoto Protocol, from 2008 to 2012. The main motivations for selecting such a sample period is to make inferences in respect to prospective pilot emissions trading schemes and subsequent periods of the EU ETS as well as to assess the main objective of the Pilot Phase, as indicated by Convery and Redmond (2007), to get the scheme up and running such that it would be fully operational by 2008. We examine the microstructure and trading behavior in the context of these objectives.

Much of the prior literature investigates the time series properties of various different EU ETS instruments (spot, futures, options) under the scheme usually sampling data at a daily frequency, e.g., Bredin and Muckley (2011), Paolella and Taschini (2008), Daskalakis et al. (2009) and Benz and Trück (2009). Using ultra high frequency tick by tick trade data offers new insights on trading behavior, price formation and information arrival. A small number of recent papers have started to examine the performance of carbon finance markets from a microstructure perspective, most notably Benz and Hengelbrock (2009), Conrad et al. (2011) and Mizrach and Otsubo (2011). However these studies follow a standard approach to investigating price formation and price impact and neglect to consider the potential impact of the time that expires between trade events. We address this issue and rather than adopting the standard approach of examining the price impact of one or two specific trade process variables in isolation, we focus on their combined effects to examine the information assimilation process, liquidity and the degree of market efficiency during the Pilot and the initial period of the Kyoto Phase of the EU ETS.

Given that 3 of the 4 contracts examined are from the Pilot Phase, the first consideration is the relatively small number of observations, which are representative of the number we would observe for relatively infrequently traded stocks on major exchanges (such as the

NYSE). However, with the exception of the structural breaks in 2006, there is a considerable degree of consistency, in our findings, across the instruments which we examine. There is clear evidence of market development in the Pilot Phase and in particular in the Kyoto Phase. The reduced frictions in the market, in particular for our Phase 2 contract highlight the greater levels of efficiency in the EU ETS. In particular the reduced duration, higher volumes traded, higher volatility and greater levels of bi-directional causality consistently point towards reduced market frictions and a more efficient market (see Dacorogna et al. 2001). Our results are generally consistent with the progression illustrated in studies by Benz and Hengelbrock (2009), Conrad et al. (2011) and Mizrach and Otsubo (2011). Our empirical results based on Granger-Causality tests as well as two and three variable VARs all indicate evidence in favor of sequential information arrival and are inconsistent with the mixed distribution hypothesis, complementing the finding of Chevalier and Sevi (2011). In all estimations duration is found to have significant contemporaneous and lagged effects on volatility and volume and have a key impact on the volume-volatility relationship. This suggests that any empirical investigation of this relationship using intra-day data needs to actively account for the impact of time duration between trades.

A common finding from the VAR models indicates that there is a negative contemporaneous relationship between volume and volatility for all contracts. The implication here is that liquidity traders are dominating any informed trading behavior. This result is consistent with the market view that informed traders, as is often the case, may have a preference to trade on the OTC market. If informed traders are active in the OTC market, is this due to greater levels of depth, breadth and overall market liquidity? We leave this question to be examined by future research.

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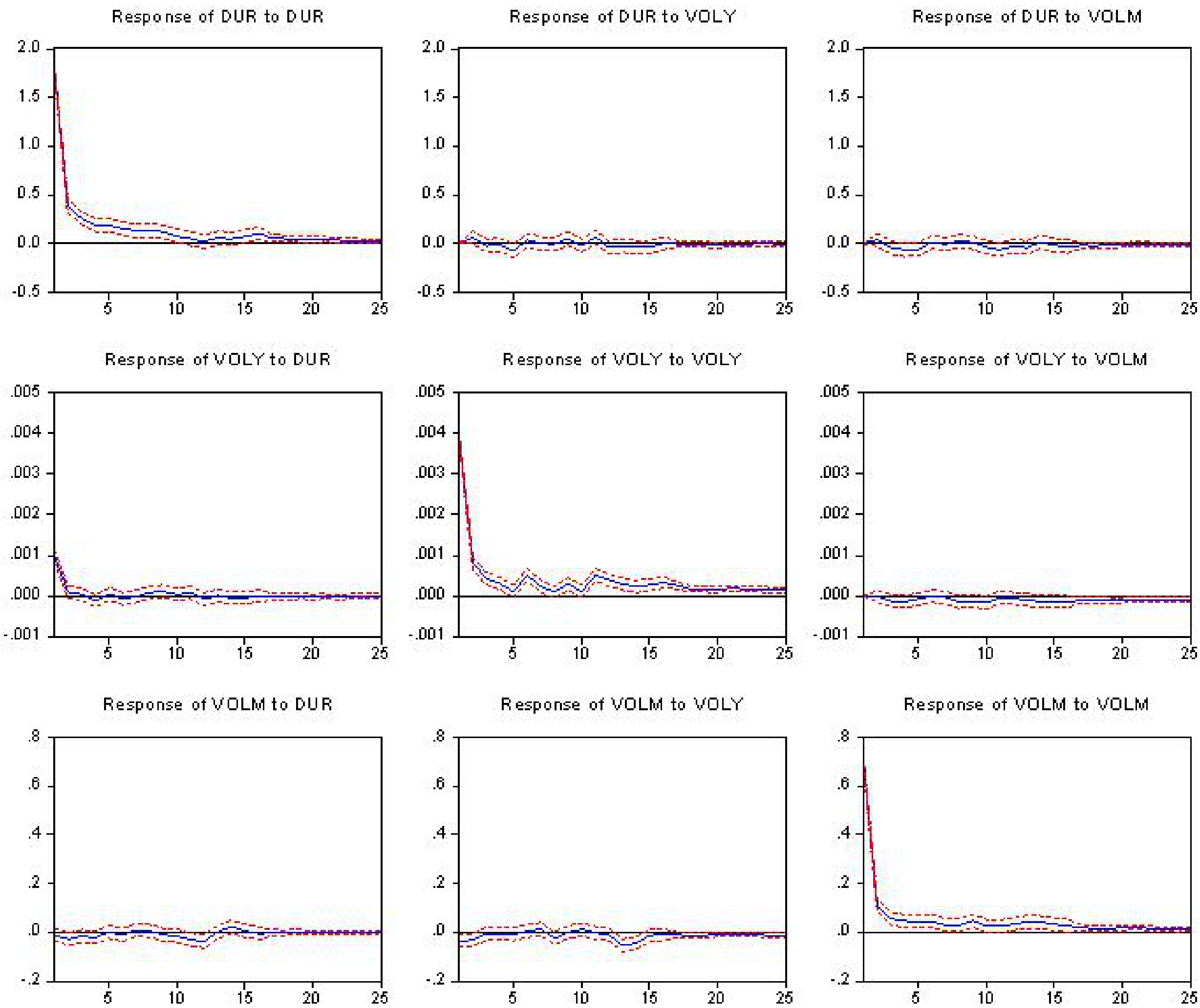
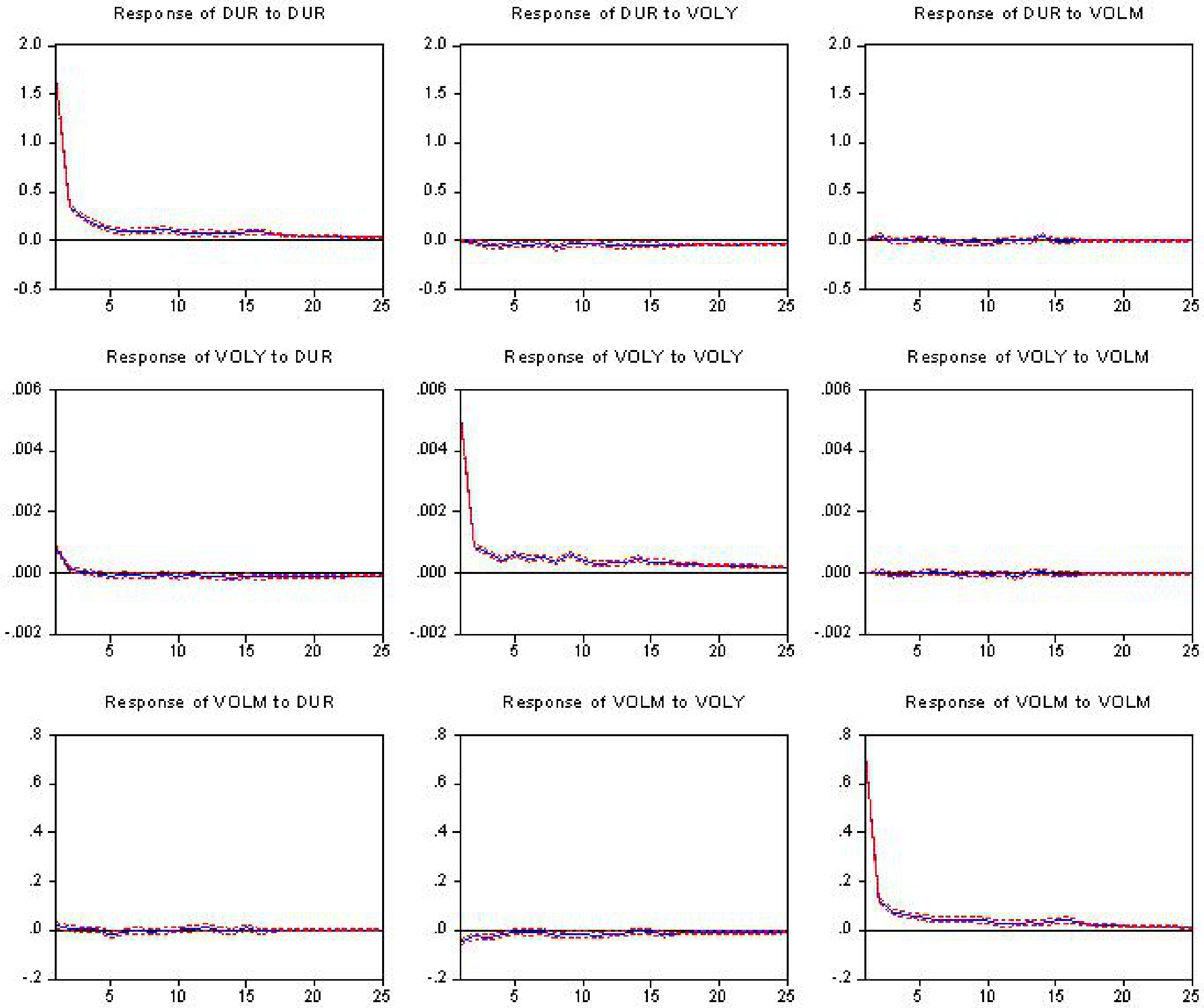
Figure 1: Impulse Response Functions of the December 2005 Contract



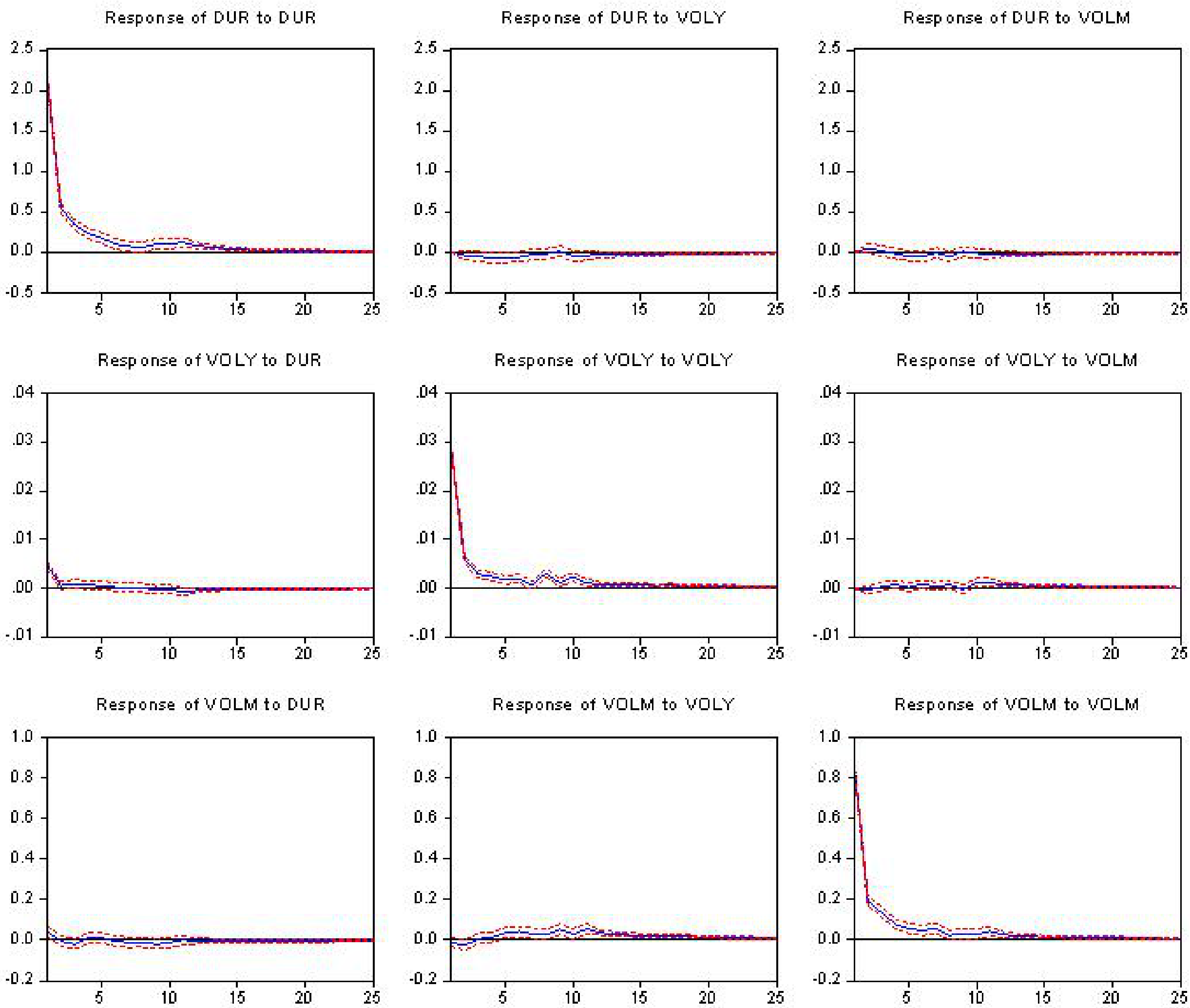
Notes. The figure presents impulse response functions, as well as the corresponding standard errors, for up to 25 lags for the December 2005 maturity futures contract. The graphs presented on the top left to bottom right diagonal of the figure trace out the time path of the effect of the shocks on duration, volatility and volume on each of the respective terms. The off-diagonal graphs trace out the time path of the effect of shocks across duration, volatility and volume.

Figure 2: Impulse Response Functions of the December 2006 Contract



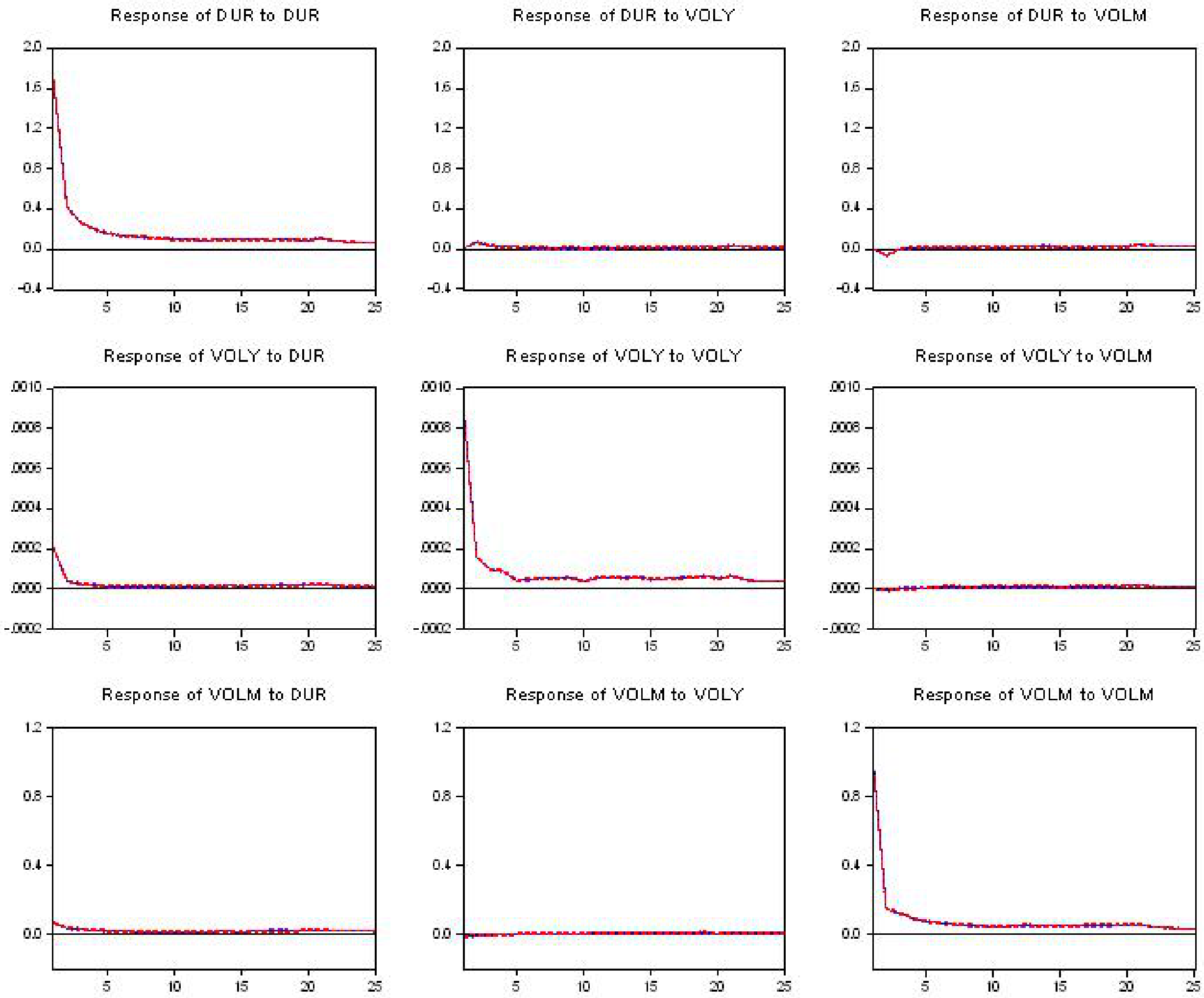
Notes. The figure presents impulse response functions, as well as the corresponding standard errors, for up to 25 lags for the December 2006 maturity futures contract. The graphs presented on the top left to bottom right diagonal of the figure trace out the time path of the effect of the shocks on duration, volatility and volume on each of the respective terms. The off-diagonal graphs trace out the time path of the effect of shocks across duration, volatility and volume.

Figure 3: Impulse Response Functions of the December 2007 Contract



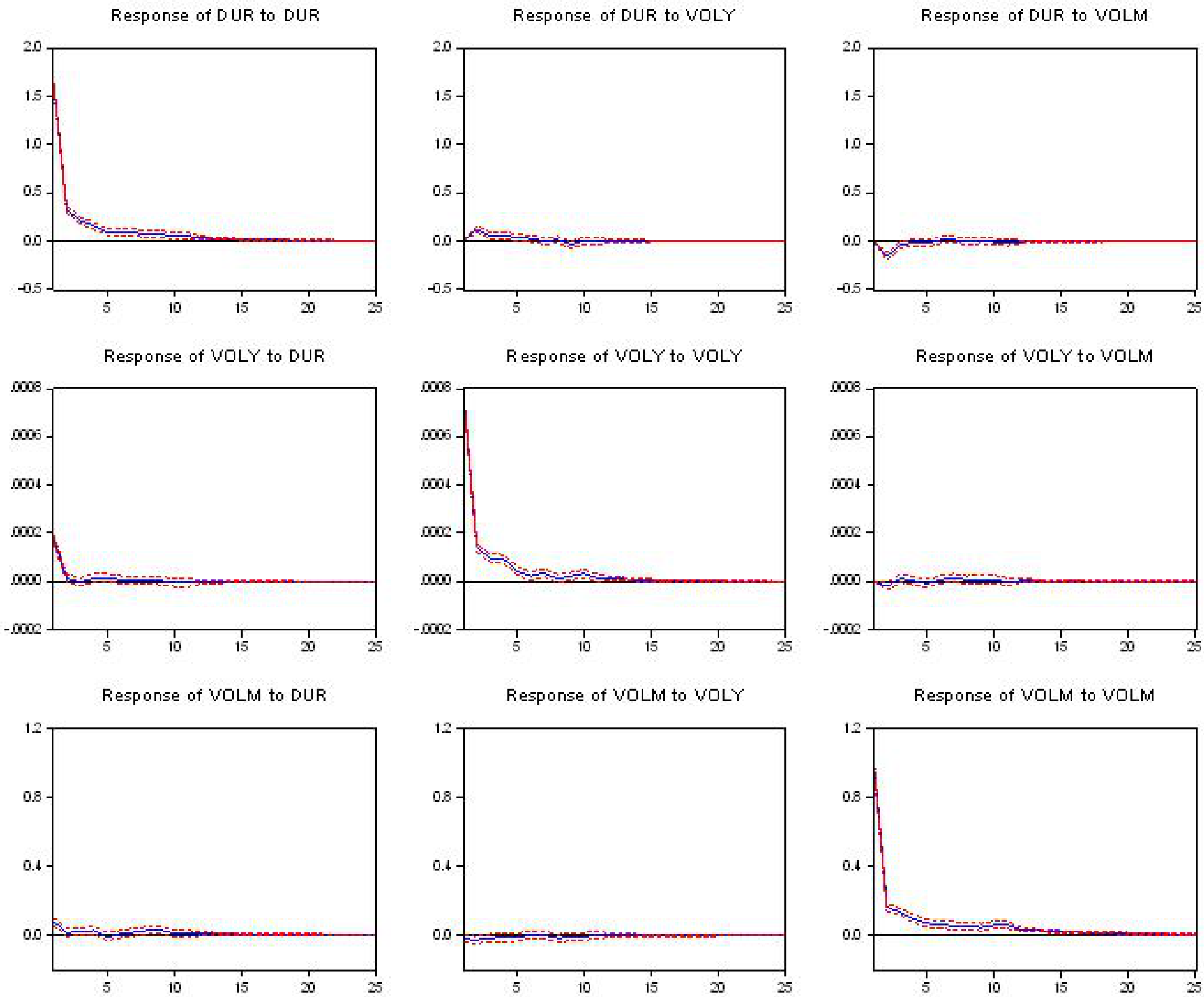
Notes. The figure presents impulse response functions, as well as the corresponding standard errors, for up to 25 lags for the December 2007 maturity futures contract. The graphs presented on the top left to bottom right diagonal of the figure trace out the time path of the effect of the shocks on duration, volatility and volume on each of the respective terms. The off-diagonal graphs trace out the time path of the effect of shocks across duration, volatility and volume.

Figure 4: Impulse Response Functions of the December 2008 Contract



Notes. The figure presents impulse response functions, as well as the corresponding standard errors, for up to 25 lags for the December 2008 maturity futures contract. The graphs presented on the top left to bottom right diagonal of the figure trace out the time path of the effect of the shocks on duration, volatility and volume on each of the respective terms. The off-diagonal graphs trace out the time path of the effect of shocks across duration, volatility and volume.

Figure 5: Impulse Response Functions of the Nearby December 2008 Contract



Notes. The figure presents impulse response functions, as well as the corresponding standard errors, for up to 25 lags for the nearby December 2008 maturity futures contract. The graphs presented on the top left to bottom right diagonal of the figure trace out the time path of the effect of the shocks on duration, volatility and volume on each of the respective terms. The off-diagonal graphs trace out the time path of the effect of shocks across duration, volatility and volume.

Table 1: **Summary Statistics for EU ETS Futures**

	Duration			**Volume**		**Volatility(t)**		**Volume(t)**	
Instrument	No. Obs	Mean	Median	Mean	Median	Mean	Median	Mean	Median
Dec. 05	3,135	21.631	421.761	10.318	10	0.229	0.005	0.227	0.019
Dec. 06	15,831	9.988	191.000	12.072	10	0.506	0.000	0.367	0.052
Dec. 07	5,118	23.146	392.000	13.216	10	2.695	0.000	0.600	0.026
Dec. 08	126,722	2.317	27.470	7.038	10	0.331	0.000	0.776	0.053

Notes. The summary statistics are reported for the full sample of data. The duration is defined as time elapsed between consecutive trades and the mean and median figures above are measured in minutes. Volatility(t) refers to volatility per unit of time and volume(t) represents volume per unit of time.

Table 2: **Annual Summary Statistics**

		2005 Contract					2006 Contract				
Sample Year	Name	No. Obs	Mean	Variance	Skewness	Kurtosis	No. Obs	Mean	Variance	Skewness	Kurtosis
2005	Duration	2,975	21.794	1,472.351	3.862*	22.023*	1,072	18.914	1,089.875	4.090*	23.107*
2005	Volume	2,975	10.392	220.289	12.063*	216.930*	1,072	13.536	192.757	5.208*	36.562*
2006	Duration						14,349	9.121	258.649	4.225*	27.732*
2006	Volume						14,349	12.038	231.568	12.735*	304.463*
		2007 Contract					**2008 Contract**				
Sample Year	Name	No. Obs	Mean	Variance	Skewness	Kurtosis	No. Obs	Mean	Variance	Skewness	Kurtosis
2005	Duration	130	44.617	3,377.413	1.976*	3.538*	12	44.617	2,526.016	1.295	0.605
2005	Volume	130	19.700	581.266	5.008*	30.384*	12	19.700	268.750	1.770	2.951
2006	Duration	2,204	28.599	1,777.974	2.778*	11.145*	1,371	25.078	1,599.353	2.966*	11.044*
2006	Volume	2,204	14.715	361.337	6.642*	67.765*	1,371	17.028	596.980	9.992*	151.723*
2007	Duration	2,784	17.500	1,314.360	4.070*	22.360*	28,142	4.130	77.850	5.992*	63.808*
2007	Volume	2,784	14.200	351.266	5.651*	47.735*	28,142	8.957	77.793	3.793*	29.382*
2008	Duration						97,197	1.484	10.397	7.139*	111.579*
2008	Volume						97,197	6.341	63.059	4.281*	40.035*

Notes. The summary statistics for duration and volume for each calendar year are reported for the 2005, 2006, 2007 and the 2008 futures contract. The duration is defined as time elapsed between consecutive trades and is measured in minutes. A * indicates statistical significance at the 5% level.

Table 3: **Causality Tests**

Null Hypothesis	**Dec. 05**	**Dec. 06**	**Dec. 07**	**Dec. 08**
Volume does not Granger Cause duration	2.528	11.767	4.309	62.923
	(0.000)	(0.000)	(0.000)	(0.000)
Duration does not Granger Cause volume	3.088	9.138	4.122	88.127
	(0.000)	(0.000)	(0.000)	(0.000)
Volatility does not Granger Cause duration	1.496	1.753	1.745	9.964
	(0.072)	(0.020)	(0.021)	(0.000)
Duration does not Granger Cause volatility	0.943	1.869	1.674	2.803
	(0.531)	(0.011)	(0.030)	(0.000)
Volatility does not Granger Cause volume	1.657	2.526	3.132	1.831
	(0.033)	(0.000)	(0.000)	(0.013)
Volume does not Granger Cause volatility	0.756	3.076	2.678	9.889
	(0.769)	(0.000)	(0.000)	(0.000)

Notes: This table reports Granger causality tests on duration, volume and volatility derived from the tick by tick data for the December 2005, 2006, 2007, and 2008 contracts. F statistics are reported, with levels of significance in brackets.

Table 4: **Bivariate Volume-Volatility VAR (December 2005 Contract)**

		Volatility Equation		**Volume Equation**	
		$R^2 = 0.162$		$R^2 = 0.121$	
		Coefficient	t-stats	Coefficient	t-stats
Lagged volatility	a_1	0.206	11.133	-0.009	1.952
	a_2	0.051	2.715	-0.017	3.661
	a_3	0.044	2.314		
	a_4	0.074	3.909		
	a_5	0.052	2.767		
	a_6	0.072	3.803		
	a_{10}	0.037	2.001		
Current volume	b_0	-0.346	4.446		
Lagged volume	b_1			0.191	9.858
	b_2			0.113	5.750
	b_3			0.074	3.755
	b_4			0.058	2.933
Current dur.*volume	c_0	-0.111	4.247		
Lagged dur.*volume	c_1			-0.017	2.681

Notes: This table reports the results of the bivariate volume-volatility VAR. The variables are standardized with respect to duration and are in log-form to ensure that they remain positive. Estimation is based on the tick-by-tick data for the December 2005 expiry EUA futures contract traded on the ECX. The sample is 22^{nd} April 2005 to 19^{th} December 2005. Only coefficients statistically significant at a significance level of 5% are reported along with absolute t-statistics.

Table 5: **Bivariate Volume-Volatility VAR (December 2006 Contract)**

		Volatility Equation		**Volume Equation**	
		$R^2 = 0.113$		$R^2 = 0.107$	
		Coefficient	t-stats	Coefficient	t-stats
Lagged volatility	a_1	0.147	18.239		
	a_2	0.088	10.777		
	a_3	0.052	6.338	0.004	2.010
	a_4	0.050	6.091		
	a_5	0.034	4.142		
	a_6	0.030	3.669		
	a_7	0.027	3.275	0.007	3.936
	a_8	0.018	2.165		
	a_9	0.028	3.469		
Current volume	b_0	-0.368	9.818		
Lagged volume	b_1			0.180	21.048
	b_2			0.100	11.496
	b_3			0.050	5.695
	b_4	0.082	2.138	0.033	3.752
	b_5			0.020	2.289
	b_6	0.138	3.591	0.043	4.930
	b_7			0.044	5.025
	b_8			0.040	4.610
	b_9			0.025	2.915
	b_{10}	0.091	2.414		
Current dur.*volume	c_0	-0.216	17.318		
Lagged dur.*volume	c_1			-0.014	4.903
	c_{10}	0.038	3.000		
April 2006 dummy		0.347	2.452		
October 2006 dummy		0.960	3.513	-0.157	2.550

Notes: This table reports the results of the bivariate volume-volatility VAR. The variables are standardized with respect to duration and are in log-form to ensure that they remain positive. Estimation is based on the tick-by-tick data for the December 2006 expiry EUA futures contract traded on the ECX. The sample is 16^{th} June 2005 to 18^{th} December 2006. Only coefficients statistically significant at a significance level of 5% are reported along with absolute t-statistics.

Table 6: **Bivariate Volume-Volatility VAR (December 2007 Contract)**

		Volatility Equation $R^2 = 0.063$		**Volume Equation** $R^2 = 0.139$	
		Coefficient	t-stats	Coefficient	t-stats
Lagged volatility	a_1	0.122	7.953		
	a_2	0.045	2.915		
	a_3	0.055	3.604		
	a_5	0.048	3.139		
Current volume	b_0	-0.493	7.638		
Lagged volume	b_1			0.208	12.588
	b_2			0.103	6.144
	b_3			0.047	2.766
	b_4			0.040	2.403
	b_5			0.039	2.369
Current dur.*volume	c_0	-0.147	7.340		
Lagged dur.*volume	c_1			-0.014	2.754
October 2006 dummy				0.533	5.607

Notes: This table reports the results of the bivariate volume-volatility VAR. The variables are standardized with respect to duration and are in log-form to ensure that they remain positive. Estimation is based on the tick-by-tick data for the December 2007 expiry EUA futures contract traded on the ECX. The sample is 3^{rd} June 2005 to 17^{th} December 2007. Only coefficients statistically significant at a significance level of 5% are reported along with absolute t-statistics.

Table 7: **Bivariate Volume-Volatility VAR (December 2008 Contract)**

		Volatility Equation		Volume Equation	
		$R^2 = 0.070$		$R^2 = 0.119$	
		Coefficient	t-stats	Coefficient	t-stats
Lagged volatility	a_1	0.169	59.869	-0.015	20.622
	a_2	0.052	18.332		
	a_3	0.031	10.797	0.002	2.111
	a_4	0.023	7.899		
	a_5	0.020	7.067	0.004	5.350
	a_6	0.016	5.446		
	a_7	0.011	3.932	0.002	2.572
	a_8	0.017	6.101	0.002	2.457
	a_9	0.009	3.214	0.003	4.003
	a_{10}	0.012	4.027		
	a_{11}	0.008	2.722		
	a_{12}			0.002	2.104
	a_{13}	0.012	4.239		
	a_{14}				
	a_{15}	0.012	4.088	0.002	2.640
	a_{16}			0.002	2.878
	a_{17}	0.009	3.087		
	a_{19}	0.012	4.060		
	a_{20}	0.007	2.354		
Current volume	b_0	-0.340	31.753		
Lagged volume	b_1	0.043	3.839	0.224	79.234
	b_2	0.022	1.983	0.082	28.379
	b_3	0.034	3.028	0.044	14.944
	b_4	0.037	3.314	0.034	11.669
	b_5			0.024	8.217
	b_6			0.024	8.335
	b_7			0.020	6.867
	b_8			0.013	4.527
	b_9			0.015	5.132
	b_{10}			0.012	4.192
	b_{11}			0.012	4.139
	b_{12}			0.014	4.632
	b_{13}			0.011	3.791
	b_{14}			0.017	5.897
	b_{15}			0.011	3.603
	b_{16}			0.011	3.779
	b_{17}			0.013	4.350
	b_{18}			0.009	3.000
	b_{19}			0.007	2.567
	b_{20}			0.010	3.374
Current dur.*volume	c_0	-0.033	7.511		
Lagged dur.*volume	c_1	-0.033	7.457	-0.008	6.711
	c_2	-0.026	5.910	-0.003	2.315
	c_3	-0.018	4.024		
	c_4	-0.012	2.748		
	c_5	-0.011	2.530		
	c_6			-0.002	2.084
	c_7	-0.012	2.811		
	c_8	-0.010	2.224		
	c_{10}	-0.012	2.776		
	c_{13}			-0.003	2.173
	c_{14}	-0.012	2.271		
	c_{15}	-0.012	2.713		
	c_{18}	-0.013	2.834		
	c_{20}	-0.012	2.753	-0.004	3.172

Notes: This table reports the results of the bivariate volume-volatility VAR. The variables are standardized with respect to duration and are in log-form to ensure that they remain positive. Estimation is based on the tick-by-tick data for the December 2008 expiry EUA futures contract traded on the ECX. The sample is 28^{th} September 2005 to 15^{th} December 2008. Only coefficients statistically significant at a significance level of 5% are reported along with absolute t-statistics.

Table 8: **Trivariate Duration Volume Volatility VAR (December 2008 Contract)**

		Duration Equation		Volume Equation		Volatility Equation	
		Coefficient	t-stats	Coefficient	t-stats	Coefficient	t-stats
Current duration	γ_0			0.095	35.626	0.399	111.329
Lagged duration	γ_1	0.196	64.603	0.034	12.504	-0.084	22.032
	γ_2	0.103	33.383	0.016	5.735	-0.039	10.046
	γ_3	0.060	19.247			-0.027	6.877
	γ_4	0.039	12.347			-0.018	4.653
	γ_5	0.032	10.112	-0.010	3.442	-0.013	3.409
	γ_6	0.024	7.696			-0.017	4.523
	γ_7	0.016	5.053	-0.007	2.379	-0.009	2.235
	γ_8	0.020	6.515			-0.019	4.888
	γ_9	0.019	6.064			-0.010	2.445
	γ_{10}	0.013	4.289	-0.007	2.430	-0.015	3.914
	γ_{11}	0.014	4.588			-0.013	3.396
	γ_{12}	0.011	3.571			-0.009	2.232
	γ_{13}	0.013	4.043				
	γ_{14}	0.012	3.827				
	γ_{15}	0.015	4.807				
	γ_{16}	0.016	5.357				
Current volume	ρ_0					-0.106	26.411
Lagged volume	ρ_1	0.010	2.945	0.179	62.059	0.022	5.488
	ρ_2	0.039	11.905	0.109	37.247	0.014	3.474
	ρ_3	0.017	5.033	0.060	20.392	0.009	2.296
	ρ_4	0.008	2.521	0.040	13.484		
	ρ_5			0.025	8.585		
	ρ_6			0.018	6.190		
	ρ_7			0.018	5.932		
	ρ_8			0.018	6.082	0.009	2.067
	ρ_9			0.009	3.039		
	ρ_{10}			0.015	5.030		
	ρ_{11}			0.017	5.707		
	ρ_{12}			0.010	3.537		
	ρ_{13}			0.013	4.478		
	ρ_{14}			0.013	4.481		
	ρ_{15}			0.015	5.117		
	ρ_{16}			0.020	6.956		
Current volatility	δ_0			-0.054	26.411		
Lagged volatility	δ_1	0.049	20.961	0.021	10.125	0.195	67.535
	δ_2	0.012	5.133			0.067	22.880
	δ_3					0.041	14.057
	δ_4					0.028	9.357
	δ_5					0.027	9.236
	δ_6					0.019	6.569
	δ_7	-0.006	-2.378			0.019	6.513
	δ_8					0.020	6.650
	δ_9					0.025	8.545
	δ_{10}	-0.005	-2.169			0.016	5.559
	δ_{11}					0.015	4.918
	δ_{12}					0.015	5.004
	δ_{13}					0.014	4.726
	δ_{14}					0.016	5.366
	δ_{15}					0.012	4.081
	δ_{16}	-0.006*	2.620			0.021	7.268

Notes: This table reports the results of the trivariate duration-volume-volatility VAR with 16 lags. Estimation is based on the tick-by-tick data for the December 2008 expiry EUA futures contract traded on the ECX. The sample is 28^{th} September 2005 to 15^{th} December 2008. Only coefficients statistically significant at a significance level of 5% are reported along with absolute t-statistics.

Table 9: **Trivariate Duration Volume Volatility VAR (December 2008 Contract - last 4 Months)**

		Duration Equation		Volume Equation		Volatility Equation	
		Coefficient	t-stats	Coefficient	t-stats	Coefficient	t-stats
Current duration	γ_0			0.022	15.494	0.011	70.189
Lagged duration	γ_1	0.176	32.174	0.004	2.457	-0.002	11.763
	γ_2	0.087	15.668	0.005	3.462	-0.001	3.827
	γ_3	0.053	9.529			-0.001	5.615
	γ_4	0.036	6.441				
	γ_5	0.036	6.534				
	γ_6	0.017	3.027			-0.001	2.495
	γ_7	0.016	2.858	-0.003	2.044		
	γ_8	0.017	2.975				
	γ_9	0.015	2.637			-0.001	2.390
	γ_{10}	0.012	2.131				
	γ_{11}	0.019	3.397			-0.001	2.802
	γ_{12}						
	γ_{13}	0.022	4.028	0.005	3.092		
	γ_{14}						
	γ_{15}						
Current volume	ρ_0					-0.016	-25.615
Lagged volume	ρ_1	0.055	2.839	0.219	42.705	0.005	7.212
	ρ_2	0.141	7.117	0.110	20.893		
	ρ_3	0.060	2.998	0.060	11.446	0.001	2.315
	ρ_4			0.047	8.890		
	ρ_5			0.017	3.123		
	ρ_6			0.028	5.293		
	ρ_7			0.016	3.014		
	ρ_8			0.018	3.422		
	ρ_9						
	ρ_{10}			0.012	2.326		
	ρ_{11}			0.021	4.020		
	ρ_{12}			0.013	2.444		
	ρ_{13}			0.011	2.066		
	ρ_{14}			0.018	3.351		
	ρ_{15}			0.015	2.812		
	ρ_{16}			0.011	2.111		
Current volatility	δ_0			-1.091	25.615		
Lagged volatility	δ_1	2.001	12.365	0.300	6.809	0.200	38.914
	δ_2					0.050	9.902
	δ_3					0.048	9.160
	δ_4			0.091	2.085	0.025	4.804
	δ_5					0.018	3.521
	δ_6			0.105	2.417	0.027	5.122
	δ_7					0.012	2.325
	δ_8						
	δ_9					0.016	3.102
	δ_{10}					0.010	1.960
	δ_{11}			0.099	2.308	0.030	5.900
	δ_{12}					0.011	2.235
	δ_{13}	-0.448	2.791				
	δ_{14}					0.020	3.954
	δ_{15}					0.015	2.926
	δ_{16}						

Notes: This table reports the results of the trivariate duration-volume-volatility VAR with 16 lags. Estimation is based on the tick-by-tick data for the December 2008 expiry EUA futures contract traded on the ECX. The sample is XXth September 2008 to 15th December 2008. Only coefficients statistically significant at a significance level of 5% are reported along with absolute t-statistics.

Table 10: **Trivariate Duration Signed-Volume Volatility VAR (December 2008 Contract - last 4 Months)**

		Duration Equation		Volume Equation		Volatility Equation	
		Coefficient	t-stats	Coefficient	t-stats	Coefficient	t-stats
Current duration	γ_0					0.011	68.669
Lagged duration	γ_1	0.179	32.907			-0.002	12.092
	γ_2	0.091	16.522			-0.001	4.429
	γ_3	0.056	10.157			-0.001	5.676
	γ_4	0.038	6.851				
	γ_5	0.038	6.745				
	γ_6	0.017	3.075			-0.001	2.345
	γ_7	0.016	2.930				
	γ_8	0.017	3.028				
	γ_9	0.015	2.703			-0.001	2.431
	γ_{10}	0.012	2.111				
	γ_{11}	0.020	3.521			-0.001	2.779
	γ_{12}						
	γ_{13}	0.023	4.140				
	γ_{14}						
	γ_{15}						
Current volume	ρ_0						
Lagged volume	ρ_1	-0.078	5.195	0.306	59.626		
	ρ_2			0.105	19.622		
	ρ_3			0.057	10.481		
	ρ_4			0.044	8.087		
	ρ_5			0.025	4.633	0.001	1.930
	ρ_6			0.024	4.492		
	ρ_7			0.018	3.280		
	ρ_8			0.022	4.005		
	ρ_9						
	ρ_{10}						
	ρ_{11}			0.019	3.528		
	ρ_{12}						
	ρ_{13}						
	ρ_{14}						
	ρ_{15}			0.014	2.693		
	ρ_{16}			0.013	2.474		
Current volatility	δ_0						
Lagged volatility	δ_1	1.935	12.054			0.197	38.413
	δ_2					0.052	9.902
	δ_3					0.048	9.131
	δ_4					0.026	4.933
	δ_5					0.019	3.664
	δ_6					0.019	3.664
	δ_7					0.013	2.434
	δ_8						
	δ_9					0.018	3.500
	δ_{10}					0.010	1.969
	δ_{11}					0.029	5.756
	δ_{12}					0.010	2.059
	δ_{13}						
	δ_{14}					0.020	3.877
	δ_{15}					0.014	2.911
	δ_{16}						

Notes: This table reports the results of the trivariate duration-volume-volatility VAR with 16 lags. Estimation is based on the tick-by-tick data for the December 2008 expiry EUA futures contract traded on the ECX. The sample is 28^{th} September 2005 to 15^{th} December 2008. Only coefficients statistically significant at a significance level of 5% are reported along with absolute t-statistics.