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Options introduction and volatility in the EU ETS

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To improve risk management in the European Union Emissions Trading Scheme (EU ETS), the European Climate Exchange (ECX) has introduced option instruments in October 2006. The central question we address is: can we identify a potential destabilizing effect of the introduction of options on the underlying market (EUA futures)? Indeed, the literature on commodities futures suggest that the introduction of derivatives may either decrease (due to more market depth) or increase (due to more speculation) volatility. As the identification of these effects ultimately remains an empirical question, we use daily data from April 2005 to April 2008 to document volatility behavior in the EU ETS. By instrumenting various GARCH models, endogenous break tests, and rolling window estimations, our results overall suggest that the introduction of the option market had the effect of decreasing the level of volatility in the EU ETS while impacting its dynamics. These findings are fairly robust to other likely influences linked to energy and commodity markets.

JEL Classification: G13, G18, Q57, Q58.

Keywords: EU ETS, option prices, volatility, GARCH, rolling estimation, endogenous structural break detection.

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1 Introduction

To what extent does the introduction of options tend to destabilize tradable permits markets? Indeed, allowing for option trading may have some consequences on volatility in the underlying market. According to Weaver and Banerjee (1990), the introduction of options may affect the volatility of the underlying market, since they affect producers' decisions through intertemporal arbitrage. Conversely, it may also very well increase the liquidity and the informational efficiency of the underlying market. Back (1993) shows that options may guide producers' decisions based on a mix of true information and speculators' noise signals. Since allowance price stability is an important determinant of the performance of cap-and-trade programs, an analysis of how the introduction of options trading affected volatility in the European Union Emissions Trading Scheme (EU ETS) is worthwhile.

Previous empirical literature provides mixed conclusions concerning the introduction of options. In an exhaustive survey on this topic, Mayhew (2000) shows ambiguous effects of the introduction of derivatives on the volatility of the underlying asset, *i.e.* it may be either positive or negative depending on the market under consideration (equities, bonds, or commodities). Fleming and Ostdiek (1999) have contributed to the analysis of the introduction of derivatives instruments on the underlying crude oil market and derived products. The authors provided evidence of a short-run effect on the level of volatility while the long-run effect may be due to exogenous factors, such as the deregulation of energy markets. Thus, detecting whether the introduction of options has increased or decreased volatility in the EU ETS remains an empirical issue worth of investigation.

The EU ETS is a *compliance* market, which means that each installation of the approximately 10,600 covered installations needs to surrender each year a number of allowances, fixed by each Member State in its National Allocation Plan (NAP), equal to its verified emissions (Ellerman and Buchner (2008), Alberola *et al.* (2009)). To comply with their emissions target, installations may exchange quotas either over-the-counter, or through brokers and market places.[5] *Bluenext*[6] is the market place dedicated to CO_2 allowances based in Paris. It has been created on June 24, 2005 and has become the most liquid platform for spot trading.[7] The *European Climate Exchange* (ECX) is the market place based in London. It has been created on April 22, 2005 and is the most liquid platform for futures and option trading.[8]

Following the rapid development of spot and futures trading on these exchanges[9], more sophisticated carbon products have been progressively introduced, thereby offering to market participants a greater flexibility in the management of their compliance requirements. Option prices have been introduced by ECX on October 13, 2006.[10] The introduction of carbon options naturally raises the

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[5] To guarantee compliance, any reported violation may be associated with a high penalty (Stranlund *et al.* (2005)). The existence of a hedging (option) instrument may facilitate compliance, and as such be viewed as a complement of enforcing policies.

[6] Formerly called *Powernext Carbon*.

[7] 72% of the volume of spot contracts are traded on Bluenext (Reuters).

[8] 96% of the volume of futures contracts are traded on ECX (Reuters).

[9] Other exchanges are worth mentioning: *(i) NordPool*, which represents the market place common to Denmark, Finland, Sweden, Norway, and is based in Oslo; *(ii)* the *European Energy Exchange* (EEX), based in Leipzig, trading spot and derivatives products for emissions allowances rights; and *(iii)* the *New York Mercantile Exchange* (NYMEX), based in the U.S., which is also trading European futures and options emissions rights. The price of products exchanged on these market places are strongly correlated, which is also a feature of stock markets.

[10] Note that options have also been introduced by EEX on March 5, 2008. However, we do not have enough historical data at

question of their utility for market agents. There are mainly two uses of options: *(i)* for *speculation* purpose in order to make a profit from trading, and *(ii)* for *hedging* purpose, in order to reduce or eliminate the risk in a position. The second use obviously allows industrials to lower the economic, political and financial uncertainties attached to market developments in the EU ETS. Böhringer *et al.* (2008) emphasize that overlapping instruments should be avoided to achieve efficiency in global environmental policy. The main "environmental policy"-related risk for industrials would then consist in permits price changes, which could be strongly reduced by using hedging instruments such as options.

Empirical studies of the EU ETS option market remain scarce. Uhrig-Homburg and Wagner (2007) describe extensively derivative instruments in the EU carbon market based on qualitative surveys. Chesney and Taschini (2008) provide an application of CO_2 price dynamics modeling to option pricing. Chevallier *et al.* (2009) provide a case-study of investors' changes in risk aversion around the 2006 compliance event using both futures and options. To our best knowledge, no prior study has investigated the impact of the options introduction in the EU ETS on the characteristics of the underlying carbon price in terms of volatility.

When introducing option trading in October 2006, the ECX may have indirectly increased the volatility of the underlying futures market. Indeed, the higher the leverage effect associated with option trading, the higher speculation about fuel substitution develops, which translates into rising volatility. This effect has been observed in some other markets and is generally viewed as a negative externality. More specifically, we examine the following central questions: what is the impact of the option market on the carbon price in terms of volatility? Is the introduction of the option market the only cause behind volatility changes? The latter question leads us to consider other factors such as institutional decisions, energy and global commodity markets to which volatility changes could be attributed as well.

Our empirical study departs from previous literature on several aspects. First, we develop a GARCH model with a dummy variable to study the impact of the introduction of the option market (Antoniou and Foster (1992), Antoniou and Holmes (1995), Gulen and Mayhew (2000)). As in Antoniou and Foster (1992), we decompose our sample into two sub-periods to identify any impact on the nature (the dynamics) of the volatility through changes in GARCH coefficients. This econometric analysis is finally taken one step further by using rolling estimations with a window of 200 observations. Then, we proceed with an endogenous structural break test (Inclán and Tiao (1994), Sansó, Aragó and Carrion (2004)) to detect more precisely the influence of options introduction. To the best of our knowledge, this kind of test has not been used for such a purpose yet.

After taking into account the volatilities of several energy- and commodity-related variables, we do observe an impact of the introduction of the option market on the level of the volatility of carbon futures prices. The results are fairly robust to various specifications of the conditional volatility including different combinations of exogenous variables. These findings therefore suggest that the observed changes in the unconditional component of volatility for EUA futures returns and the introduction of options are linked. In addition, we show a significant change in the dynamics of volatility which might be related to the introduction of options (while this latter effect needs to be

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hand for this product and liquidity was known to be very low. So, we decide to focus on ECX option prices only. The study of discrepancies between ECX and EEX option prices is left for further research.

interpreted cautiously). Overall, our article brings a better understanding of the role played by the option market on the volatility of the carbon price in the EU ETS.

The remainder of the paper is organized as follows. Section 2 presents the carbon futures and option markets. Section 3 summarizes the data used. Section 4 details the econometric methodology, along with estimation results. Section 5 concludes.

2 Overview of the futures and option markets in the EU ETS

In what follows, we detail first the structure and main features of EU ETS derivatives, and second we provide a liquidity analysis with a specific focus on the daily liquidity in option contracts.

2.1 Structure and main features of EU ETS derivatives

The EU ETS has been created by the Directive 2003/87/CE. Across its 27 Member States, it covers large plants from CO_2-intensive emitting industrial sectors with a rated thermal input exceeding 20 MW. One allowance exchanged on the EU ETS corresponds to one ton of CO_2 released in the atmosphere, and is called a European Union Allowance (EUA). 2.2 billion allowances per year have been distributed during Phase I (2005-2007). 2.08 billion allowances per year will be distributed during Phase II (2008-2012). With a value of around €20 per allowance, the launch of the EU ETS thus corresponds to a net creation of wealth of around €40 billion per year. On January 2008, the European Commission has extended the scope of the EU trading system to other sectors such as aviation and petro-chemicals by 2013, and confirmed its functioning Phase III until 2020. As for many commodities markets, carbon allowances may be traded through on-exchange markets and through over-the-counter derivatives markets (see Daskalakis et al. (2009), Benz and Hengelbrock (2008) and Rotfuss (2009) for exhaustive descriptions of the EUA derivatives markets). We present below the main features of futures and options contracts written on EUAs.

We choose to model the behavior of the ECX futures prices for the carbon time-series in this article. One reason is that, due to the banking restrictions implemented between 2007 and 2008 (Alberola and Chevallier, 2009), spot prices show a non-reliable behavior during Phase I.[11] The futures contract is a deliverable contract where each member with a position open at cessation of trading for a contract month is obliged to make or take delivery of emission allowances to or from national registries. The unit of trading is one lot of 1,000 emission allowances. Each emission allowance represents an entitlement to emit one ton of carbon dioxide equivalent gas. Market participants may purchase consecutive contract months to March 2008, and then December contract months from December 2008 to December 2012.[12] Delivery occurs by mid-month of the expiration contract date. Trading occurs from 07.00AM to 05.00PM GMT.

Besides, we introduce ECX options into our econometric analysis. ECX option trading started on October 13, 2006. The underlying security for option trading is the ECX futures contract of corre-

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[11] Besides, in the EU ETS, allowances need to be surrendered only on a yearly basis during the compliance event by mid-May, which makes the distinction between spot and forward prices less relevant than on other commodity markets such as the crude oil or the electricity market where storage costs are important. Note by contrast that storage costs are zero for CO_2 allowances.

[12] Note *spreads* between two futures contracts may also be traded.

Table 1
Expiration dates for ECX options contracts
Source: Bloomberg

Month	Last Trade	Expiration
November 2006	11/22/06	11/22/06
December 2006	12/19/06	12/19/06
December 2007	12/24/07	12/24/07
December 2008	12/10/08	12/10/08
January 2009	1/21/09	1/21/09
February 2009	2/18/09	2/18/09
December 2009	12/9/09	12/9/09
December 2010	12/15/10	12/15/10
December 2011	12/14/11	12/14/11
December 2012	12/14/12	12/14/12

sponding maturity. Options have been introduced on ECX as *European*-style options, *i.e.* options convey the right, but not the obligation to buy (call) or sell (put) the underlying asset at a specified strike price and expiration date.[13] Similarly, the contract size is 1,000 emissions allowances. Expiration dates for ECX options contracts are summarized in Table 1.

2.2 Liquidity analysis

During Phase I (2005-2007), the total volume of allowances exchanged in the EU ETS has been steadily increasing. The number of transactions has been multiplied by a factor four between 2005 and 2006, going from 262 to 809 million tons. This increasing liquidity of the market has been confirmed in 2007, where the volume of transactions recorded equals 1.5 billion tons. This peak of transactions may be explained by the growth of the number of contracts valid during Phase II, with delivery dates going from December 2008 to December 2012, which amount for 4% of total exchanges in 2005, and 85% in 2007. These transactions reached €5.97 billion in 2005, €15.2 billion in 2006, and €24.1 billion in 2007, thereby confirming the fact that the EU ETS represents the largest emissions trading scheme to date in terms of transactions. In 2008, the carbon market was worth between €89-94 billion, up more than 80% year-on-year (Reuters). The launch of secondary certified emission reduction (CER)[14] contracts on ECX certainly fostered this growth rate of transactions.

The trading of ECX futures started on April 22, 2005 with varying delivery dates going from De-

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[13] An *American* option is like an European option, except it can be exercised *at any time* prior to maturity.

[14] According to the article 12 of the Kyoto Protocol, Credit Development Mechanisms (CDM) projects consist in achieving GHG emissions reduction in non-Annex B countries. After validation, the UNFCCC delivers credits called Certified Emissions Reductions (CERs) that may be used by Annex B countries for use towards their compliance position. CERs are fungible with EU ETS allowances with a maximum limit of around 13.4% on average.

cember 2005 to December 2012. Futures contracts with vintages December 2013 and 2014 were introduced on April 8, 2008. For the December 2009 futures contract, futures trade at €13.32/ton of CO_2 as of January 15, 2009, and have reached a maximum price of €32.90/ton of CO_2 in 2008.[15] From April 2005 to January 2009, the total volume of ECX futures exchanged for all vintages is equal to 40.67 billion.

The volume of options contracts traded from October 13, 2006 to January 16 2009 for the futures contracts of maturity December 2008 and December 2009 are presented in Table 2, along with the average volume contract for each strike. The total volume of options contracts traded is equal to 235Mton of CO_2 for the December 2008 contract, and to 73 Mton of CO_2 for the December 2009 contract (as of January 16, 2009). Calls are more actively traded than puts with an average volume of, respectively, 163 Mton and 72 Mton of CO_2 for the December 2008 contract. This pattern is reversed for the December 2009 contract with a total volume of calls and puts traded equal to, respectively, 31 Mton and 42 Mton of CO_2. This latter result may be explained by anticipations of carbon price decreases due to economic uncertainties by market participants. We may notice that the volume of call prices exchanged is clustered around the strikes ranging between €25 and €28. Conversely, the volume of put prices exchanged is clustered around the strikes ranging from €15 to €24. These asymmetries reflect the hedging strategies constructed by market agents to reduce the risk of their position with regard to high/low carbon price changes. They also reflect the uncertainties affecting the allowance market concerning the possible range of price changes in a moving institutional context.

Compared to 1.9 billion CO_2 futures traded in 2008, the size of the option market (235 Mton) during the same year provides evidence that options are actively traded despite it remains an emerging market. This is of central importance for our empirical analysis, since we want to assess whether options have an effect on the carbon price volatility. Since it is possible that the liquidity in options contracts was not instantaneously effective at the date of the introduction of the options market, we focus next on the *daily* liquidity in options contracts[16].

Figure 1 shows the daily liquidity in options contracts during our study period. This figure confirms that, on average, calls are more traded than puts in the EU ETS. More importantly, we notice that the liquidity in options contracts seemed to increase from 500,000 tons to 1Mton for the first time on May 18, 2007 for calls and on June 27, 2007 for puts. Besides, we may observe the very high degree of concentration of options trading during January 2008. During that period, the daily volume of calls traded is often superior to 1Mton, with a maximum of 4.450Mton on January 28, 2008. Similarly, for puts we have a peak at 3.8Mton on January 04, 2008. Figure 1 therefore reveals that the options market becomes increasingly liquid through time, as one can expect, and that the highest volumes of options exchanged seem to coincide with anticipations of yearly compliance events.

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[15] In the longer term, analysts forecast EUA prices of €20-25/ton of CO_2 over Phase II and €25-30/ton of CO_2 over Phase III (Reuters).

[16] We wish to thank an anonymous reviewer for highlighting this point.

Table 2
Volume of options contracts traded on ECX from October 13, 2006 to January 16 2009 for the futures contracts of maturity December 2008 and December 2009 (in 1,000 tons)
Source: European Climate Exchange

	Strikes in €	**07**	**08**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
December 2008	**Call prices**	N/A	N/A	N/A	N/A	N/A	N/A	200	350	700	300	500	2,060	5,575	1,650	5,150	6,785	5,370
	Put prices	N/A	400	3,690	1,145	2,425	1,290	4,218	11,380	2,173	2,010	3,875	3,015	8,440	4,820	2,600	4,500	9,650
	Total	N/A	400	3,690	1,145	2,425	1,290	4,418	11,730	2,873	2,310	4,375	5,075	14,415	6,470	7,750	11,285	15,020
December 2009	**Call prices**	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1,000	500	2,100	3,550	500	3,700	N/A	1,000	250	N/A
	Put prices	642	600	4,305	1,242	2,300	2,300	5,450	8,250	4,500	2,000	900	15	1,350	300	4,700	N/A	1,450
	Total	642	600	4,305	1,242	2,300	2,300	5,450	9,250	5,000	4,100	4,450	515	5,050	300	5,700	250	1,450

	Strikes in €	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**37**	**38**	**40**	**45**	**46**	**50**
December 2008	**Call prices**	27,495	10,106	14,273	10,013	1,780	18,300	1,400	3,250	625	3,050	25,200	100	200	14,900	500	400	3,200
	Put prices	1,700	1,100	2,100	1,000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Total	29,195	11,206	16,373	11,013	1,780	18,300	1,400	3,250	625	3,050	25,200	100	200	14,900	500	400	3,200
December 2009	**Call prices**	3,055	550	2,850	700	10	1,300	500	N/A	N/A	300	2,410	100	500	1,500	1,000	400	2,950
	Put prices	N/A	1,500	N/A	150	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Total	3,055	2,050	2,850	850	10	1,300	500	N/A	N/A	300	2,410	100	500	1,500	1,000	400	2,950

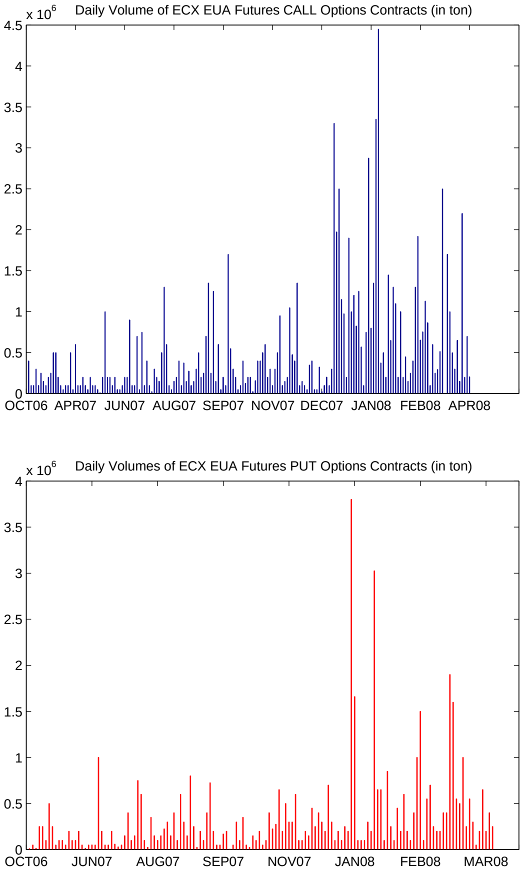

Figure 1

Daily volumes (in ton) of options contracts for ECX EUA Futures Calls (top) and Puts (bottom) from October 13, 2006 to April 03, 2008

<u>Source</u>: European Climate Exchange

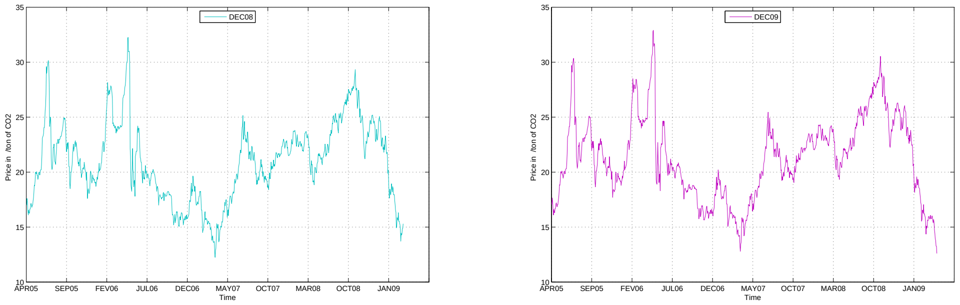

Figure 2
Carbon futures prices of maturities December 2008 (left) and 2009 (right) from April 22, 2005 to January 16, 2009
Source: European Climate Exchange

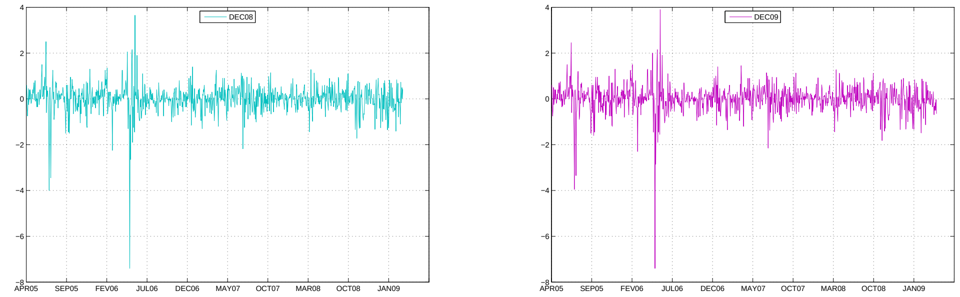

Figure 3
Returns on ECX Carbon Futures Prices of maturities December 2008 (left) and 2009 (right) from April 22, 2005 to January 16, 2009

3 Data

Our sample period goes from April 22, 2005 to April 04, 2008. We gather a full sample of 756 daily observations. The source of the data is ECX, Bloomberg and Reuters.

3.1 Carbon Price

For carbon allowances, we use daily futures and options for the December 2008-2009 contracts traded in €/ton of CO_2 on ECX. Figure 2 shows the futures price development for contracts of maturities December 2008 and 2009 from April 22, 2005 to January 16, 2009. We may observe that futures prices for delivery during Phase II (2008-2012) proved to be much more reliable than futures prices for delivery during Phase I (2005-2007) due to the banking restrictions enforced between the two Phases (Alberola and Chevallier, 2009). Besides, we note that post-2007 futures convey a coherent price signal - around 20 €/ton of CO_2 - throughout the historical available data for the second phase of the scheme. The futures price development features a lower bound around 15€/ton of CO_2 in April 2007, and an upper bound around 35€/ton of CO_2 in November 2008.

Table 3
Descriptive Statistics of ECX EUA Futures Returns and Energy and Global Commodity Markets Returns from April 22, 2005 to January 16, 2009
Source: European Climate Exchange, Reuters

Full Period	Mean	Median	Max	Min	Std. Dev.	Skew.	Kurt.	N
Carbon Futures Returns								
EUA_{DEC08}	-0.0018	0.0200	3.6500	-7.4000	0.6149	-2.2450	29.7930	936
EUA_{DEC09}	-0.0047	0.0200	3.9000	-7.4000	0.6169	-2.1299	29.1426	957
Energy and Global Commodity Markets Returns								
$Brent$	-0.0135	0.0381	11.0876	-15.6324	1.6227	-0.8159	19.0411	830
$Coal$	0.0034	0.0100	8.2900	-5.5600	0.6566	1.1207	46.3338	830
CRB	0.0619	0.4000	30.5700	-38.8100	5.3023	-0.8334	12.9586	830
$CleanDark$	0.0151	-0.0250	50.1700	-40.1400	4.2297	1.4064	50.5866	830
$Ngas$	0.0009	-0.0700	42.4500	-20.5200	3.2438	3.3141	49.2934	830
$Power$	0.0121	-0.0200	43.7100	-39.7800	4.1482	0.5050	44.8046	830
$CleanSpark$	0.0137	-0.0300	45.5000	-42.2200	4.8714	0.0109	33.3175	830
$Switch$	0.0001	0.0001	0.0500	-0.0300	0.0053	1.3380	18.8594	830

Note: EUA_{DEC08} and EUA_{DEC09} refer respectively to the carbon futures returns of maturity December 2008 and December 2009, CRB to the Reuters/Commodity Research Bureau Futures Index, $StdDev.$ refers to the standard deviation, $Skew.$ refers to the skewness, $Kurt.$ refers to the kurtosis, and N refers to the number of observations.

Descriptive statistics of ECX futures contracts of maturity December 2008 and 2009 are presented in Table 3. We may observe that ECX futures of all maturities present negative skewness and excess kurtosis[17]. These summary statistics therefore reveal an asymmetric and leptokurtic distribution.[18]

We also present in Figure 4 the empirical autocorrelation function of EUA returns and squared returns for the futures contracts of maturity December 2008 and December 2009. For both series, although the returns themselves are largely uncorrelated, the variance process exhibits some correlation. This is consistent with the earlier discussion on the necessity to use GARCH modeling for CO_2 price series[19].

3.2 Energy Prices

According to previous literature, energy prices are the most important drivers of carbon prices due to the ability of power generators to switch between their fuel inputs (Delarue *et al.* (2008), Ellerman and Feilhauer (2008)). This option to switch from natural gas to coal in their inputs represents an abatement opportunity to reduce CO_2 emissions in the short term. High (low) energy prices contribute to an increase (decrease) of carbon prices. This logic is described by Kanen (2006) who identifies brent prices as the main driver of natural gas prices which, in turn, affect power prices and ultimately carbon prices. Bunn and Fezzi (2009) also identify econometrically that carbon prices react significantly to a shock on gas prices in the short term. Descriptive statistics for energy and

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[17] Note for a normally distributed random variable skewness is zero, and kurtosis is three.

[18] Such a fat-tailed distribution may suggest a GARCH modeling as GARCH models better accommodate excess kurtosis in the data.

[19] Note however that it appears difficult to motivate other type of models, for example processes that are able to account for long memory, given the relatively short time horizon at hand since the creation of the EU ETS.

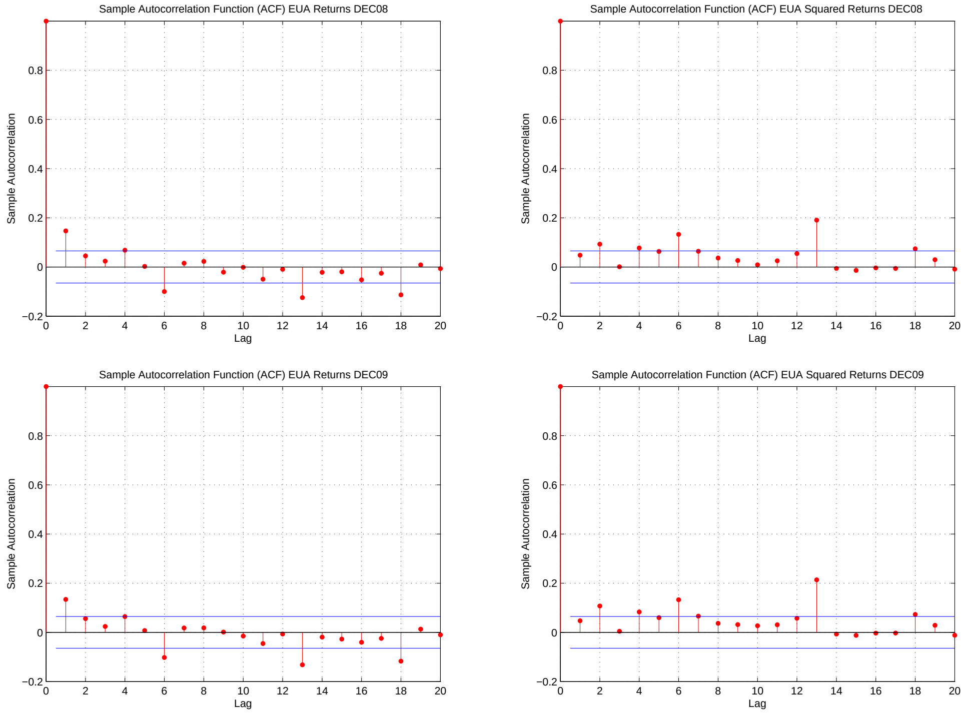

Figure 4
Empirical autocorrelation function of EUA returns (left) and squared returns (right) for the ECX futures contracts of maturity December 2008 (top) and December 2009 (bottom)

global commodity markets returns may also be found in Table 3.

3.2.1 Brent, Natural Gas, and Coal Prices

For energy prices, we use the daily Intercontinental Exchange (ICE) Crude Oil Brent Free-of-Board in $/barrel, the daily ICE Natural Gas 1-Month Forward contract traded in UK pence/Therm, and the daily coal futures Month Ahead price CIF ARA[20] traded in €/ton. Price series are converted to € using the daily exchange rate provided by the European Central Bank.

Figure 5 presents the price development for the Zeebrugge natural gas next month, Rotterdam coal futures, and NYMEX crude oil futures price series from April 22, 2005 to January 16, 2009. Natural gas prices exhibit a strong volatility compared to coal prices. In November 2005 and September 2008, natural gas prices soared to 90€/MWh, and steadily decreased afterwards to 40€/MWh in February 2008 and December 2008. The competitiveness of natural gas compared to coal may be more specifically captured during the period going from December 2006 to July 2007. The brent price series peaked over 80€/barrel from May to August 2008.

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[20] CIF ARA defines the price of coal inclusive of freight and insurance delivered to the large North West European ports, *e.g.* Amsterdam, Rotterdam or Antwerp.

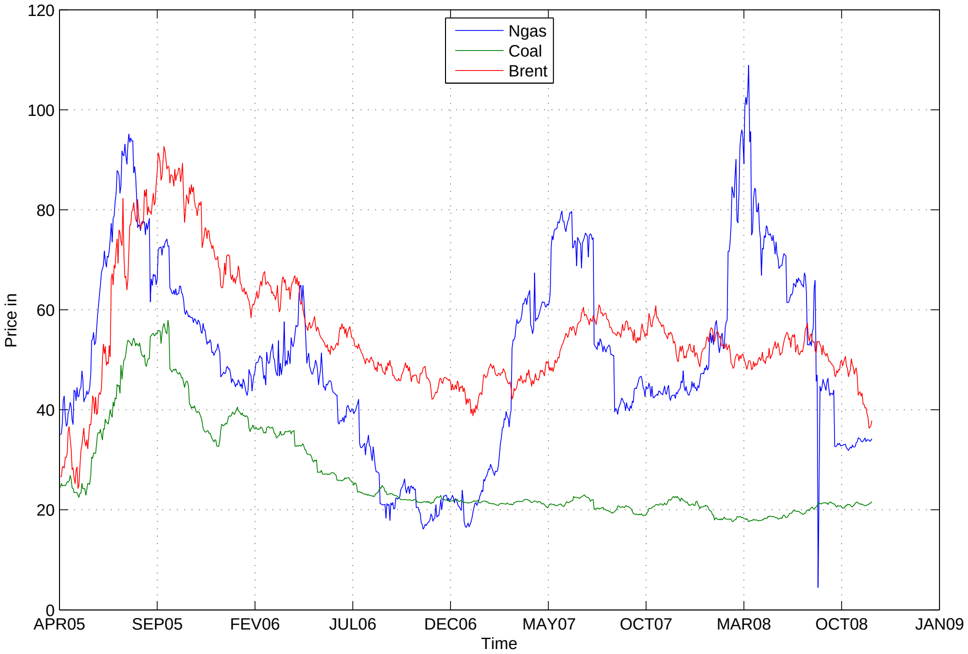

Figure 5
Zeebrugge natural gas, Rotterdam coal futures, and NYMEX crude oil futures prices from April 22, 2005 to January 16, 2009
Source: Reuters

3.2.2 Power, *Clean Spark*, *Clean Dark*, and *Switch* Prices

The price of electricity Powernext (*elec* in €/MWh) is the contract of futures Month Ahead Base. To take account of abatement options for energy industrials and relative fuel prices, three specific spreads are included.

First, the Clean Dark Spread (*clean dark spread* expressed in €/MWh) represents the difference between the price of electricity at peak hours and the price of coal used to generate that electricity, corrected for the energy output of the coal plant and the costs of CO_2:

$$clean\ dark\ spread = elec - (coal * \frac{1}{\rho_{coal}} + p_t * EF_{coal}) \tag{1}$$

with ρ_{coal} the net thermal efficiency of a conventional coal-fired plant.[21], and EF_{coal} the CO_2 emissions factor of a conventional coal-fired power plant[22].

Second, the Clean Spark Spread (*clean spark spread* expressed in €/MWh) represents the difference between the price of electricity at peak hours and the price of natural gas used to generate that electricity, corrected for the energy output of the gas-fired plant and the costs of CO_2:

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[21] *i.e.* 35% according to Reuters.

[22] *i.e.* 0.95 tCO_2/MWh according to Reuters.

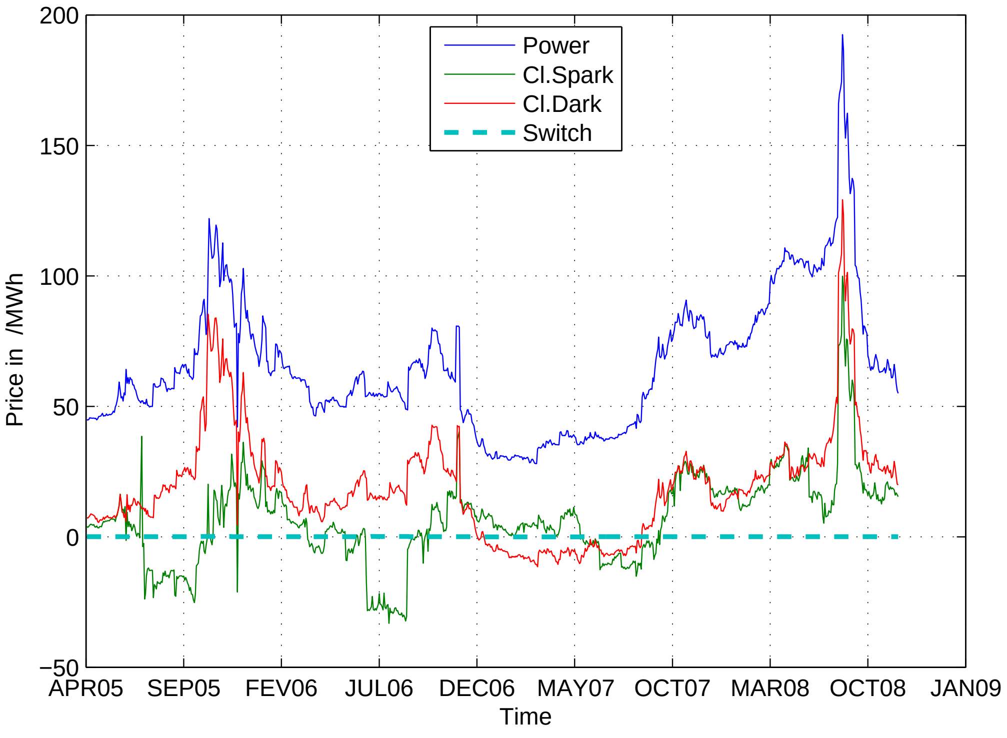

Figure 6
Powernext electricity futures, $Clean\ Spark\ Spread$, $Clean\ Dark\ Spread$, and $Switch$ prices from April 22, 2005 to January 16, 2009
Source: Reuters

$$clean\ spark\ spread = elec - (ngas * \frac{1}{\rho_{ngas}} + p_t * EF_{ngas}) \tag{2}$$

with ρ_{ngas} the net thermal efficiency of a conventional gas-fired plant.[23], and EF_{ngas} the CO_2 emissions factor of a conventional gas-fired power plant[24].

Third, the *switch* price of CO_2, expressed in €/MWh, is used as a proxy of the abatement cost:

$$switch = \frac{cost_{ngas}/MWh - cost_{coal}/MWh}{tCO2_{coal}/MWh - tCO2_{ngas}/MWh} \tag{3}$$

with $cost_{ngas}$ the production cost of one MWh of electricity on base of net CO_2 emissions of gas in €/MWh, $cost_{coal}$ the production cost of one MWh of electricity on base of net CO_2 emissions of coal in €/MWh, $tCO2_{coal}$ the emissions factor in CO_2/MWh of a conventional coal-fired plant, and $tCO2_{ngas}$ the emissions factor in CO_2/MWh of a conventional gas-fired plant as detailed above.

The *Switch* price represents the fictional daily price of CO_2 that establishes the equilibrium between the *Clean Dark* and *Clean Spark* spreads. It is advantageous in the short term to switch from coal to natural gas, when the daily CO_2 price is *above* the *Switch* price, and conversely.

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[23] *i.e.* 49.13% according to Reuters.
[24] *i.e.* 0.41 tCO_2/MWh according to Reuters.

As shown in Figure 6, the use of coal appeared more profitable than natural gas during 2005-2006. Since the beginning of 2007, the difference between both spreads has been narrowing. This situation therefore provides incentives for power operators to switch the use of natural gas instead of coal, as represented by the $Switch$ price series. Besides, we may note a peak in the price of electricity from September to November 2008.

3.3 Global commodity markets

Several indices may be used to capture the influence of risk factors linked to global commodity markets. The main index which is used as the barometer of commodity prices is the Reuters/Commodity Research Bureau (CRB) Futures Index. This index is composed of 17 commodities in different sectors such as energy, grains, industrials, livestock, precious metals and softs. It may be viewed as a broad measure of overall commodity products.[25]

The constituent commodities and the economic weighting of these indices aim at minimizing the idiosyncratic effects of some individual commodity markets.[26] As a commodity, the dynamics of futures allowance prices are very likely to be impacted by the price volatility on global commodity markets, and thus we include the Reuters/CRB Futures Index as an exogenous factor in our estimates.

Energy and global commodity markets returns are presented in Figure 7.

3.4 Correlation between energy and global commodity markets

We are able to alleviate correlation concerns among energy and global commodity markets by looking at the correlation matrix between the returns of potential explanatory variables in Table 4.

The correlation levels remain reasonable, *i.e.* strictly inferior to 60%. We thus may use the returns on energy and global commodity markets as potential factors affecting changes in volatility without only limited collinearities. Since it is possible to have low correlations together with collinearity, we have investigated the presence of multicolinearity by computing the inflation of variance between explanatory variables. These calculations did not reveal serious problematic multicolinearities.[27]

In the next section, we present the econometric methodology used along with our estimation results.

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[25] Other indices coming from brokers in the banking industry may also be used for sensitivity tests purposes. The Dow Jones-American International Group Commodity Index (DJ-AIGCI) is a benchmark for commodity investments composed of 20 commodities within the energy, petroleum, precious metals, industrial metals, grains, livestock and softs sectors. The Standard & Poor's Commodity Index (SPCI) is a cross section of 17 agricultural and industrial commodities traded in the energy, fibers, grains, meat and livestocks, metals and softs sectors. The Deutsche Bank Commodity Index (DBCI) is composed of six commodities in the crude oil, heating oil, aluminium, gold, wheat and corn industries, and is designed to track the performance of investments in a small set of commodities in a variety of currencies.

[26] See Geman (2005) for a more detailed analysis of the construction, the coverage, the liquidity, and the weighting of each index.

[27] To conserve space, those results are not presented here, and may be obtained upon request to the authors.

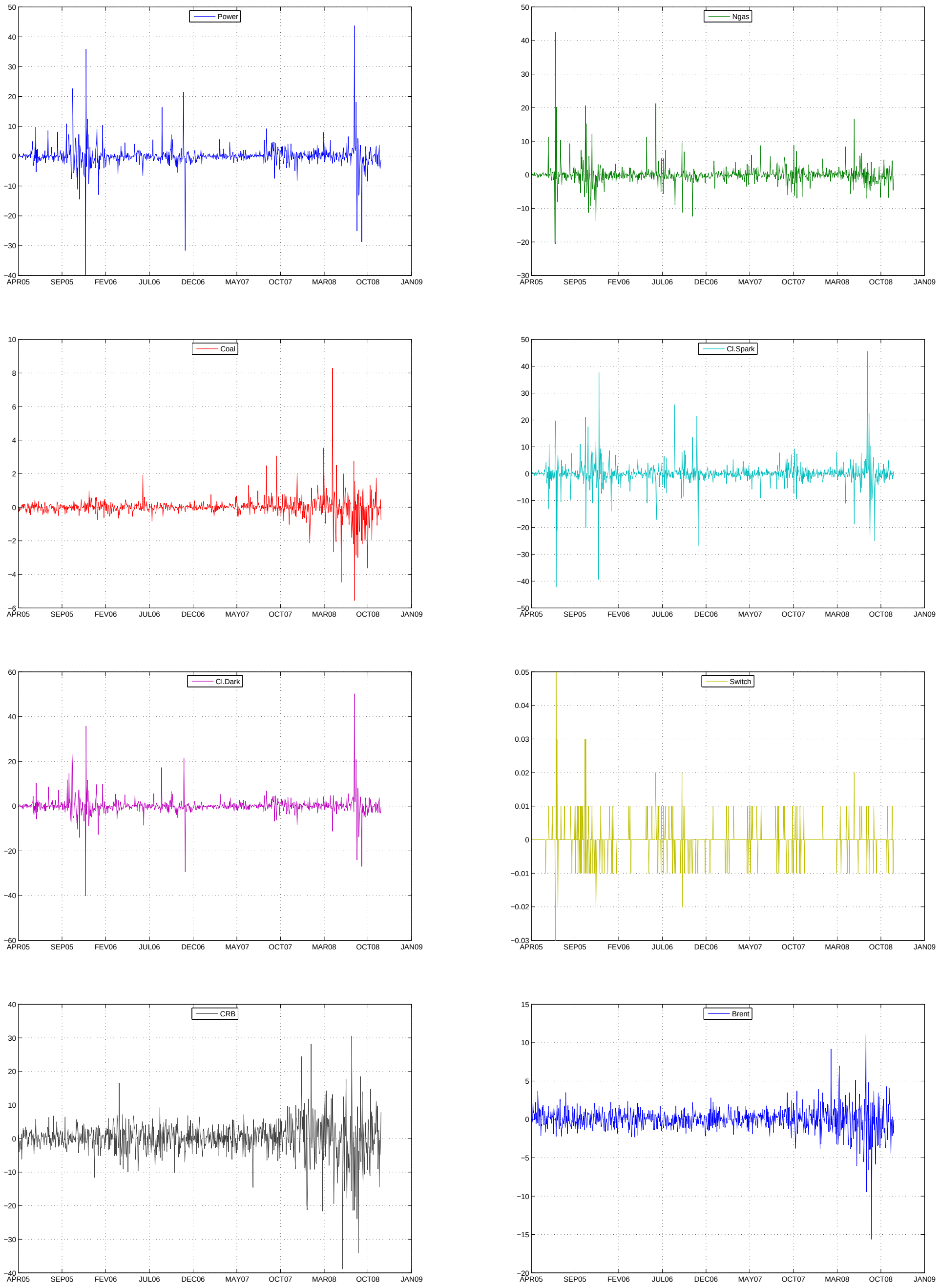

Figure 7
Returns on Energy and Global Commodity Markets Variables from April 22, 2005 to January 16, 2009

Table 4
Matrix of Cross-Correlations Between Energy and Commodity Variables

	CRB	$CleanSpark$	$CleanDark$	$Switch$	$Ngas$	$Brent$	$Power$	$Coal$
CRB	1							
$CleanSpark$	0.053	1						
$CleanDark$	0.128	0.596	1					
$Switch$	0.223	0.714	0.513	1				
$Ngas$	0.214	0.028	0.234	0.314	1			
$Brent$	0.008	0.066	0.219	0.112	0.086	1		
$Power$	0.020	0.274	0.260	0.361	0.125	0.159	1	
$Coal$	0.313	0.037	0.091	0.014	0.214	0.085	0.333	1

Note: CRB refers to the return on the Reuters CRB global commodity index, $CleanSpark$ refers to the return on the *Clean Spark Spread*, $CleanDark$ refers to the return on the *Clean Dark Spread*, $Switch$ refers to the return on the *Switch*, $Ngas$ refers to the natural gas return, $Brent$ refers to the Brent crude oil return, $Power$ refers to the electricity return, and $Coal$ refers to the coal return.

4 Empirical analysis

Our econometric methodology may be broadly summarized in four different steps: *(i)* we estimate a GARCH model with a dummy variable to compare the level of (unconditional) volatility of the underlying allowance market *before* and *after* the introduction of the option market[28]; *(ii)* we include other factors in the variance equation of the GARCH model to control for exogenous effects from relevant variables; *(iii)* we discuss volatility dynamics issues during sub-periods; and *(iv)* we finally run rolling estimations to further identify the effects of the introduction of the option market on the volatility dynamics of the EU ETS.

4.1 GARCH model

The GARCH modeling approach adopted here is common for financial time-series, and has been applied to carbon prices in previous literature (Paolella and Taschini (2008), Benz and Truck (2009)). GARCH models allow to take into account volatility clustering, indicated by fat-tails in the distribution of financial time-series.

The impact of options trading is tested by amending the conditional variance equation of the GARCH model with a dummy variable which takes values 0 for the pre-option period, and 1 for the post-option period. This methodology has been applied by Antoniou and Holmes (1995), Gulen and Mayhew (2000) for financial markets, and Antoniou and Foster (1992) for the crude oil market.[29] Then, we adopt the structure of a GARCH(1,1) model:

$$R_t = \beta_0 + \beta_1 R_{t-1} + \epsilon_t \tag{4}$$

$$\epsilon_t \sim \sqrt{h_t} e_t \qquad \text{with} \qquad e_t \sim iid(0,1)$$

$$h_t = E(\epsilon_t^2 \mid \phi_{t-1}) = \alpha_0 + \alpha_1 \epsilon_{t-1}^2 + \alpha_2 h_{t-1} + \gamma DF_t \tag{5}$$

with R_t the daily return on carbon futures prices, ϕ_{t-1} is the set of past information, and ϵ_t the error term in Eq. (4). In the conditional variance Eq. (5), DF_t is a dummy variable taking the value of 0 before the 'true' effect of the introduction of options, and 1 thereafter. This dummy variable allows to test for the influence of the introduction of options on the volatility of the underlying carbon market. When creating the dummy variable DF_t, it is crucial to classify the beginning of the impact such that it is not too far from the beginning of the 'true' effect of the introduction of options. In light of the liquidity analysis derived from Figure 1, we have set the beginning of the 'true' effect of the introduction of options on May 18, 2007 (instead of October 13, 2006 which is the official creation of the options market)[30].

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[28] To avoid any confusion, we recall that the dummy variable in the volatility equation of a GARCH model has an effect on the unconditional level of volatility as it is invariant through time.

[29] Fleming and Ostdiek (1999) also consider the issue of the impact of derivatives trading on the spot crude oil market, but using GMM methods as in Bollen (1998).

[30] Recall that this date was chosen when the volume of calls traded doubled and hit the 1Mton daily volume for the first time. Also, May 18, 2007 for calls is chosen instead of June 27, 2007 for puts since calls are more actively traded than puts in the EU ETS. We wish to thank an anonymous reviewer for suggesting to adopt this methodology.

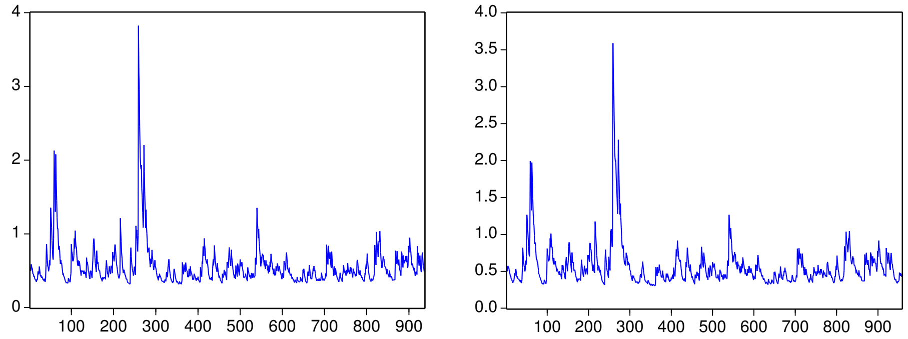

Figure 8
From left to right: conditional standard deviation for the December 08 and 09 returns from a GARCH (1,1)

4.1.1 Estimation

We first test Eq. (4) and (5) with a GARCH(1,1) model *without* the dummy accounting for the introduction of the options market in the variance equation. A preliminary analysis of the returns autocorrelation shows that modeling the conditional mean as an AR(1) eliminate the autocorrelation for each contract. Those results, presented in Table 5 (regressions (1) and (3)), reveal a strongly persistent process, as the sum of α_1 and α_2 is close to 1.[31] This characteristic is a classic feature of financial time-series, and applies for both carbon futures contract of maturity December 2008 and 2009. The time profile of the estimated conditional standard errors from this GARCH model are respectively displayed in Figure 8 for the December 2008 and 2009 contracts. These graphs are very similar for both contracts. During our study period, we observe that the carbon market has been more volatile during the first 300 days, and that the level of volatility is quite lower after April 2006.

4.1.2 Modeling the option market introduction

We estimate Eq. (4) and (5) by introducing the dummy variable DF_t capturing the changes in volatility due to the 'true' effect of the introduction of options. Recall that DF_t takes the value of 0 before the 'true' impact (that was identified from Figure 1) on May 18, 2007, and 1 thereafter.

Estimation results are presented in Table 5 (regressions (2) and (4)).[32] In Table 5, regressions (2) and (4), we may observe that DF_t is statistically significant and negative at the 1% level. Despite the fact that we do not consider here any exogenous factor (see next section), this result appears as a first evidence of the impact of options introduction in the carbon market. Because options enable a more complete and liquid market, and a greater flexibility for market participants to hedge their position on the carbon market, they seem to have a significant impact on the level of volatility in the futures market. This effect may also be related, while it is difficult to consider it empirically, to the increasing maturity of the carbon futures market. This is a common argument in finance when

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[31] Namely 0.96 and 0.98 for regressions (1) and (3) respectively.

[32] Note that we tested for various GARCH specifications, such as the GARCH-M developed in Antoniou and Foster (1992), which is convenient for the modeling of a time-varying risk premium. None of them provided superior results. Similarly, various innovation distributions have been implemented (Student t, asymmetric Student t, GED) to better accommodate residual kurtosis, without further improving the results presented here.

Table 5
GARCH(1,1) model estimates *with* and *without* dummy variable for the carbon futures returns of maturity December 2008 and December 2009

	EUA_{DEC08}		EUA_{DEC09}	
	(1)	(2)	(3)	(4)
Mean equation				
β_0	0.0023**	0.0019**	0.0020	0.0017*
	(0.001)	(0.001)	(0.001)	(0.001)
β_1	0.1398***	0.1324***	0.1348***	0.1255***
	(0.048)	(0.049)	(0.048)	(0.048)
Variance equation				
α_0	7.74e-05***	9.39e-05***	5.41e-05***	7.17e-05***
	(1.45e-05)	(1.90e-05)	(1.24e-05)	(1.77e-05)
α_1	0.3039***	0.2870***	0.2638***	0.2518***
	(0.027)	(0.029)	(0.025)	(0.027)
α_2	0.6544***	0.6681***	0.7120***	0.7156***
	(0.037)	(0.041)	(0.034)	(0.039)
D_F		-4.62e-05***		-3.69e-05***
		(1.47e-05)		(1.34e-05)
LL	1680.86	1625.43	1694.26	1638.99

Notes: The dependent variables are the EUA carbon futures return for the contract of maturity December 2008 and December 2009, depending on the column under consideration. Other variables are explained in eq(4) and (5). Standard errors in parenthesis. *** indicates significance at 1%, ** at 5% and * at 10%. LL refers to the log-likelihood.

efficiency is under examination. In our framework, because we are more interested in volatility than in autocorrelation and efficiency, the same argument may not really apply. Indeed, as markets become more mature and the number of traders is larger, because information is more quickly reflected in prices the volatility may be expected to increase in view of the well-known volatility-volume relation. The latter result does not imply however necessarily that the dynamic component of volatility has not been impacted, as we discuss below. In addition, it is worth noting that the estimation results obtained in Table 5 concerning the introduction of the option market may be driven by exogenous factors affecting the volatility of carbon futures returns. As shown by Mansanet et al. (2007), Alberola *et al.* (2008), Chevallier (2009) and Hintermann (2010), the carbon market is impacted by various energy prices and macroeconomic risk factors. In other words, a change in the level of the volatility may be hidden by the presence of other risk factors. To deal with this issue, we now introduce exogenous factors in the variance equation of the GARCH model.

4.2 Exogenous variables in the conditional variance equation

A problem in Section 4.1 is that the date of the dummy variable is chosen *a priori*. Of course, this choice is intuitive since we are interested in modeling how the introduction of the option market affects volatility in the EU ETS. However, the impact of the introduction of the option market may have arisen at a date different from its official opening. Furthermore, other structural breaks may have affected the carbon market and the dynamics of conditional volatility. Detecting these breaks appears crucial to obtain a correct modeling of the conditional standard error. To do so, we implement below a test for structural breaks in the unconditional variance at unknown location.

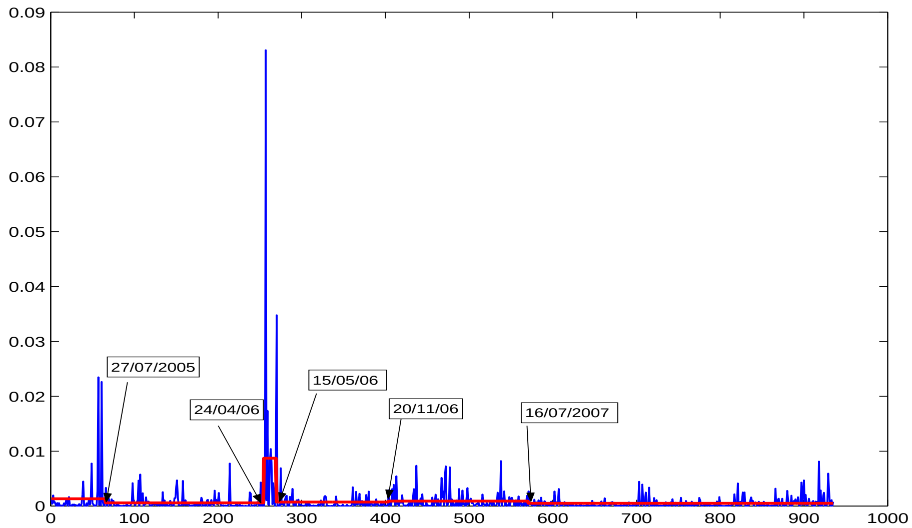

Figure 9
Unconditional variances with break
Note: the blue line represents the squared returns and the red line represents the time profile of the sample variance for the different periods detected from the breaks.

4.2.1 Structural breaks in the unconditional variance

Inclán and Tiao (1994) and Sansó, Aragó and Carrion (2004) have proposed a test for detecting a break in the unconditional variance at unknown date.[33]

Our sample of returns $\{R_t\}_{t=1}^{T}$ contains T observations. The test statistic is $AIT = sup_k|T^{-0.5}G_k|$ where $G_k = \hat{\lambda}^{-0.5}[C_k-(k/T)C_T]$, $C_k = \sum_{t=1}^{k} R_t^2$, $\hat{\lambda} = \hat{\gamma}_0+2\sum_{l=1}^{m}[1-l(m+1)^{-1}]\hat{\gamma}_l$, $\hat{\gamma}_l = T^{-1}\sum_{t=l+1}^{T}(R_t^2-\hat{\sigma}^2)((R_{t-l}^2-\hat{\sigma}^2)$, $\hat{\sigma}^2 = T^{-1}C_T$. $\hat{\gamma}$ represents a nonparametric adjustment factor used to correct for non dependent processes. It is based on a Bartlett kernel with the lag truncation parameter *m*.[34] The value of *k* that maximises $|T^{-0.5}G_k|$ is the estimate of the break date. Critical values are given in Sansó, Aragó and Carrion (2004).

Inclán and Tiao (1994) developed the Iterated Cumulative Sum of Squares (ICSS) algorithm for detecting multiple breaks in variance.[35] We apply this algorithm to our *AIT* statistics to find possible break dates in the unconditional variance of returns.

The *AIT* test statistic and the ICSS algorithm leads us to detect five breaks in the unconditional volatility. Figure 9 shows these breaks with their date. This graph also displays the time profile of the sample unconditional variance for the six periods defined by these breaks and the squared returns, considered as a proxy for the shocks hitting the market.

One obvious break in unconditional volatility occurs during the third (and shortest) period from *t=24/04/06* to *t=15/05/06*. During this time period, the market is highly volatile, as reflected by the high values of the squared returns. The sample variance reaches its highest value for this time period. This increase in unconditional variance can be connected with the first compliance break

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[33] Tests for breaks in the unconditional variance have been recently extended by Andreou and Ghysels (2002). See also Rapach and Strauss (2008).

[34] The lag truncation parameter is chosen as $m = E[A(T/100)^{1/4}]$ where T is the number of observations.

[35] A complete description of this algorithm can be found in their paper.

in the time-series of CO_2 returns due to the verification of 2005 emissions in April 2006 (Alberola *et al.* (2008)).

We identify two periods where the unconditional volatility increases: the first one going from the beginning of the sample to t_1 *=27/7/05*, and the second one from t_4 *=20/11/06* to t_5*=16/07/07*. We observe however that during these periods the sample variance does not increase significantly, and thus we do not further comment these breaks. In addition, only a minor increase in volatility is detected using the algorithm around the time options begin to be traded with significant volumes (*i.e.* March 2007).

More importantly, to control for the sharp increase in volatility due to the 2006 compliance event, we include the dummy variable D_{APR06} which takes the value of 1 during the period going from April 25 to June 23, 2006, and 0 otherwise. This variable reflects the institutional development of the EU ETS that occurred in April 2006 during Phase I (Alberola *et al.*, 2008).

4.2.2 Introducing exogenous variables

As highlighted in previous literature (Christiansen *et al.* (2005), Mansanet-Bataller *et al.* (2007), Alberola *et al.* (2008), Chevallier (2009), Hintermann (2010)), the main risk-driving factors on the carbon market are linked to institutional decisions and energy prices. Another source of risk may be linked to the variation of global commodity markets, which may be captured by various indices.

To take into account the impact of these factors on the volatility of carbon futures (besides considering the impact of the option market), we include the volatility of several energy- and commodity-related factors. We compute the sample standard deviations by using a moving window of 25 days (about one trading month) for all factors described in the data section. This methodology is in line with Hadsell and Shawky (2006) and Oberndorfer (2008), and has more formal support than "demeaning" the mean equation (as in Bologna and Cavallo (2002) for instance) when the quantity of interest is the volatility.

For energy variables, we use the volatility of returns on Brent, coal and natural gas prices, as well as the volatility of clean dark and clean spark spreads and the switch price, to proxy for the influence of power producers' fuel-switching behavior on carbon price changes. The relationship between carbon price changes and power producers' fuel-switching behavior appears especially important to bear in mind. Fuel-switching constitutes an important determinant of the CO_2 price, given the proportion of allowances distributed to the power sector, and the arbitrages being made by producers concerning their energy-mix including the CO_2 costs (Delarue *et al.* (2008), Ellerman and Feilhauer (2008)). For global commodity markets, we include the Reuters/Commodity Research Bureau (CRB) index.

We test below for the potential impact of *vol brent, vol gas, vol coal, vol power, vol clean spark, vol clean dark, vol switch*, and *vol CRB* on ECX futures returns volatility modelled using a GARCH framework, by including the estimated volatility of returns of these potential explanatory variables into the variance equation.

4.2.3 Results

Equation (5) is modified as follows:

$$h_t = \alpha_0 + \alpha_1 \epsilon_{t-1}^2 + \alpha_2 h_{t-1} + \gamma DF_t + \varphi X_t \tag{6}$$

with X_t a vector of exogenous variables including the dummy variable D_{APR06} for the April 2006 structural break, estimated standard deviations for energy and the CRB variables.

As shown in Table 6, estimates from our extended model feature the statistical significance of several factors for 2008 contract (regressions (1) to (4)) and for the December 2009 (regressions (5) to (8)) as well. Some of these significant variables are not exactly the same for both contracts and their significance is more robust for the December 2009 contract.

Concerning energy variables, *vol clean spark* and *vol clean dark* are significant for both the December 2008 and 2009 contracts alone or in conjunction with other regressors.

The dummy is almost always significant at the 1 or 5% level thereby providing evidence that our result in the previous section are not driven by exogenous factors.

Concerning energy variables, *vol clean spark*, *vol clean dark*, *vol oil*, *vol coal* and *vol power* are significant for the December 2008 contract while *vol oil*, *vol clean spark* and *vol clean dark* significantly impact the volatility of the December 2009 futures contract. The rationale behind the negative role of coal on CO_2 price volatility is that, when confronted to a rise of the price of coal relative to other energy markets, firms have an incentive to adapt their energy mix towards less CO_2 intensive sources, which yields to less needs of EUAs. This result is conform to previous literature (Mansanet-Bataller *et al.* (2007), Alberola *et al.* (2008)). The negative sign of *vol spark* for both contracts may be explained by the rather decreasing price pattern of natural gas by contrast to coal during our sample period[36]. *vol oil* positively impacts the volatility returns of CO_2 prices for the December 2009 contract. This positive impact can result from the fact that oil is an input of installations covered by the ETS and that changes in its price also affect economic activity. Therefore, an increase in oil price volatility induces uncertainty about economic perspectives which can increase volatility on the CO_2 market. Finally, note that the D_{APR06} dummy for institutional developments is statistically significant (regressions (2) and (6)), but not the CRB proxy for global commodity markets. The *vol switch* variable is never significant in our regressions, so we do not report results related to this variable (regressions (1) and (5)).

To conclude, we have shown that even after controlling for other relevant energy, institutional and risk factors, the DF_t dummy variable accounting for the introduction of the option market remains significant. This result is very robust to the introduction of factors known as carbon price drivers, such as institutional decisions, energy and global commodity markets (Christiansen *et al.* (2005), Mansanet-Bataller *et al.* (2007), Alberola *et al.* (2008), Hintermann (2010)). The finding appears robust enough to be an evidence of the impact of the introduction of options. We therefore conclude that options introduction had a noticeable impact on the unconditional volatility of CO_2 returns.

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[36] While the *clean spark spread* is the profit contribution of using gas for electricity production, the *clean dark spread* is the profit contribution for using coal for electricity production. Depending on the relative price of gas and coal, power producers *switch* between their fuel inputs when one source of energy becomes relatively cheaper to the other. Hence our comments of the *vol clean spark* variable based on that economic logic.

Table 6
GARCH(1,1) model estimates with the dummy variable for the carbon futures returns of maturity December 2008 and December 2009 and exogenous factors in the variance equation

	EUA_{DEC08} (1)	EUA_{DEC08} (2)	EUA_{DEC08} (3)	EUA_{DEC08} (4)	EUA_{DEC09} (5)	EUA_{DEC09} (6)	EUA_{DEC09} (7)	EUA_{DEC09} (8)
Mean equation								
β_0	0.0019*	0.0015	0.0017*	0.0025***	0.0017*	0.0015	0.0020**	0.0018*
	(0.0010)	(0.0010)	(0.0010)	(0.0009)	(0.0010)	(0.0010)	(0.0009)	(0.0009)
β_1	0.1323***	0.1342***	0.1331***	0.1239**	0.1256***	0.1200**	0.1302***	0.1232***
	(0.0487)	(0.0467)	(0.0481)	(0.0534)	(0.0486)	(0.0470)	(0.04772)	(0.0479)
Variance equation								
α_0	9.99e-05**	0.0001***	0.0001***	0.0002***	8.69e-05***	0.0001***	-0.0001***	7.04e-05*
	(3.96e-05)	(2.25e-05)	(4.08e-05)	(5.23e-05)	(3.05e-05)	(2.19e-05)	(2.52e-05)	(4.06e-05)
α_1	0.2854***	0.2224***	0.2434***	0.4189***	0.2485***	0.2058***	0.2281***	0.2101***
	(0.0295)	(0.0349)	(0.0304)	(0.0419)	(0.0.0276)	(0.0332)	(0.0309)	(0.0324)
α_2	0.6702***	0.6148***	0.6934***	0.5523***	0.7207***	0.6658***	0.7090***	0.7230***
	(0.0415)	(0.0473)	(0.0434)	(0.0391)	(0.0386)	(0.0465)	(0.0438)	(0.0442)
DF_t	-4.52e-05***	-4.47e-05***	-6.46e-05***	-5.72e-05**	-3.42e-05***	-4.15e-05***	-4.80e-05	-3.82e-05**
	(1.47e-05)	(1.72e-05)	(1.85e-05)	(2.74e-05)	(1.32e-05)	(1.56e-05)	(1.51e-05)	(1.69e-05)
$DAPR06_t$		0.0012***				0.0010***		
		(0.0001)				(0.0001)		
vol CRB	-0.0021				-0.0054			
	(0.0113)				(0.0079)			
vol oil				0.0080***				0.0098*
				(0.0007)				(0.0052)
vol clean spark			-6.88e-06***	-1.45e-05***			-8.08e-05***	-8.15e-06***
			(1.85e-06)	(2.34e-06)			(1.76e-06)	(1.73e-06)
vol clean dark				9.75e-06***			6.94e-05***	6.22e-06***
				(3.16e-06)			(2.15e-06)	(2.25e-06)
vol coal			-0.0007	-0.0123***				-0.0052
			(0.0030)	(0.0042)				(0.0034)
vol power				0.0005***				8.00e-05
				(0.0002)				(0.0001)
LL	1625.45	1637.89	1629.08	1629.64	1639.23	1648.42	1650.70	1652.73

Notes: The dependent variables are the EUA carbon futures return for the contract of maturity December 2008 and December 2009, depending on the column under consideration. Other variables are explained in Eq. (4) and (6). The algorithm for optimization is BHHH. Standard errors in parenthesis. *** indicates significance at 1%, ** at 5% and * at 10%. LL refers to the log-likelihood.

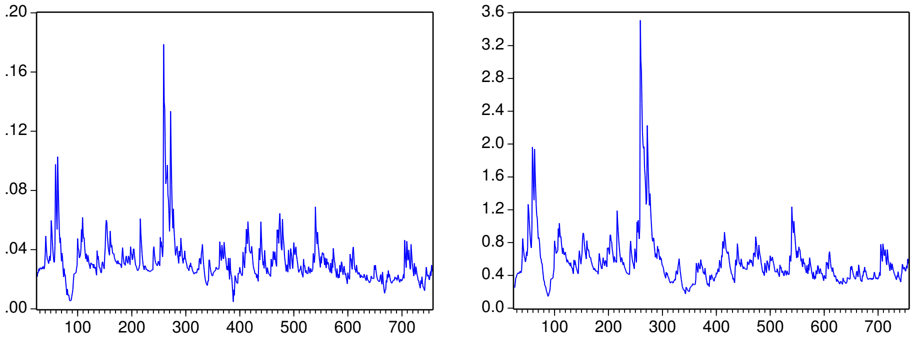

Figure 10
From left to right: conditional standard deviation for the December 08 and 09 returns from a GARCH (1,1) with a dummy for the option market

The conditional variances for both contracts displayed in Figure 10 show indeed a slight decrease in variance in the post "options introduction" period.

4.3 Sub-period decomposition

Besides, we estimate GARCH models during two sub-periods to study the changes in volatility dynamics of carbon futures returns *before* and *after* the introduction of options. According to Antoniou and Foster (1992), this procedure allows to investigate empirically the effects of the introduction of the option market by using both pre- and post-options volatility measures. Here, we do not precisely deal with the impact of the introduction of the option market on the unconditional variance, but rather on its *dynamics* (the *nature* of volatility) in the spirit of Antoniou and Foster (1992), who studied the volatility of futures and spot prices for brent crude oil products.

The methodology consists in comparing the GARCH coefficients *before* (Sample #1) and *after* (Sample #2) the introduction of the option market, by running separate estimates during sub-periods. Estimation results are presented in Table 7 (regressions (1) to (4)).

Our results are as follows. First, regarding the behavior of the autoregressive coefficient, we observe a significant decrease. The coefficients which were significant and of a value around 0.18 are not significant anymore, thus leading to confirm a convergence towards the random walk in the second sub-period.[37] Second, ARCH and GARCH coefficients are quite different in the two subperiods. For Sample #1 (Table 7, regressions (1) and (3)), the process is very persistent.[38] For Sample # 2 (Table 7, regressions (2) and (4)), we observe that the value $\alpha_1 + \alpha_2$ is close to 0.90, which suggests that the variance process as a whole is less persistent. However, the level of the ARCH coefficient, which represents the reaction to new information, is quite low in the second sub-period in comparison with its level in the first sub-period, suggesting that the informational efficiency of the carbon market has decreased. Indeed, the ARCH coefficient being an indicator of how news are impacting the

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[37] We provide some additional informations on this decrease using rolling estimation in the next section. A formal analysis of the efficiency of the carbon market remains nevertheless beyond the scope of the present paper and is left for future research.

[38] There is only a limited interest in estimating the so-called IGARCH model (Engle and Bollerslev, 1986) by constraining the sum of the ARCH and GARCH coefficients to one as the estimates in the present regressions do not bind the constraints.

Table 7
GARCH(1,1) model estimates *before* and *after* the May 18, 2007 (volumes in option trading reached 1Mton daily) for the December 2008 and 2009 carbon futures returns

	EUA_{DEC08}		EUA_{DEC09}	
	(1)	(2)	(3)	(4)
Mean equation				
β_0	0.0025**	0.0009	0.0023*	0.0009
	(0.0012)	(0.0012)	(0.0012)	(0.0012)
β_1	0.1904**	0.0012	0.1864***	0.0041
	(0.0640)	(0.0740)	(0.0652)	(0.0733)
Variance equation				
α_0	0.0001***	2.61e-05	8.05e-05***	2.42e-05
	(2.24e-05)	(1.72e-05)	(2.00e-05)	(1.55e-05)
α_1	0.3857***	0.1073*	0.3124***	0.1116**
	(0.0359)	(0.0555)	(0.0350)	(0.0538)
α_2	0.5745***	0.8358***	0.6638***	0.8332***
	(0.0437)	(0.0832)	(0.0438)	(0.0790)
LL	1134.57	555.51	1140.14	561.64

Note: The dependent variables are the EUA carbon futures returns for the contracts of maturity December 2008 and December 2009, depending on the column under consideration. Other variables are explained in Eq. (4) and (6). Standard errors in parenthesis. *** indicates significance at 1%, ** at 5% and * at 10%. LL refers to the log-likelihood.

volatility, a lower value for the ARCH coefficient is an indication of a **less** informationally efficient market (the variance adjustment following the arrival of new information is slower)[39][40]. In other words, a market where the GARCH coefficient is dominating exhibits higher autocorrelation[41] in variance which is the case in sample # 2.[42]

We did not find evidence of the influence of energy variables on the volatility of CO_2 returns during sub-periods. Overall, these results suggest that the dynamics and nature of the variance are quite different *before* and *after* the introduction of the options market, which may be inferred from GARCH standard deviations plots in Figure 8. However, note that the presented difference in the estimated parameters (in particular the lower coefficient in second period) is not necessarily a result of the introduction of options. Therefore, we may carefully conclude from these results that the estimated coefficients are not constant over the period of interest[43].

4.4 Checking the time dependency of the model

In this section, we use a rolling estimation procedure to detect some change in the dynamics of the conditional volatility. We estimate the same GARCH (1,1) model as in section 4.1.1. for a rolling window of *L*=200 observations. We obtain a sequence of time indexed estimates of the autoregressive coefficient $\{\beta_{1|t-L+1,t}\}$ and the coefficients of the GARCH model: $\{\alpha_{0|t-L+1,t}\}$, $\{\alpha_{1,t-L+1,t}\}$

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[39] See Conrad et al. (2010) for other techniques to investigate the reactions of returns or volatility of returns to new information.

[40] Recall that informational efficiency examined through the values for the GARCH coefficients of the efficiency generally examined using estimates of the autocorrelation of returns are two different, but non-contradictory, concepts of efficiency.

[41] Persistence in the volatility process (sum of ARCH and GARCH coefficients) and autocorrelation in the volatility process (GARCH coefficient) are distinguishable features of the volatility process.

[42] The same pattern with the December 2009 contract.

[43] We wish to thank one anonymous reviewer for highlighting this point.

and $\{\alpha_{2,t-L+1,t}\}$ where the *t-L,t* denotes the sample used for each estimation. Our first estimation is obtained for the sample ending in *t=200=03/02/2006*.

Figure 11 shows the rolling estimate of the autoregressive coefficient in the conditional mean regression. Figures 12 and 13 show the estimates for the ARCH and GARCH coefficients, respectively.[44] The estimates of the GARCH model clearly show some instability in the estimated coefficients. Changing patterns in the GARCH coefficients therefore indicate changes in the dynamics of conditional volatility.

A first sudden break appears at date *t = 258 = 05/05/2006* when the ARCH coefficient rises from 0.4 to 1, and the GARCH coefficient decreases from around 0.6 to 0.4. Both of these changes suggest that the impacts of shocks on conditional volatility were especially important during this time period. It coincides with the strong adjustment of market operators' expectations following the publication of the first report of verified emissions by the European Commission (Alberola *et al.*, 2008).

The second change in the estimated coefficient occurs at time *t=451=05/02/2007*. The ARCH coefficient suddenly drops after this date, while the GARCH coefficient increases. This result may also be interpreted in light of the 2007 compliance event, which relates to the verification of 2006 emissions. Market operators have anticipated the release of the report of the European Commission, and therefore the adjustment in market expectations occurs earlier than in 2006. Due to the "youth" of this commodity market and rules in the making concerning the second trading period (2008-2012), the first years of operation of the EU ETS were characterized by strong reversals in expectations around yearly compliance events (Chevallier *et al.*, 2009).[45] Overall, these rolling windows estimates do not support the view of a strong effect of option introduction on volatility dynamics. Nevertheless, the continuing change in volatility may be partly due to option introduction, despite this hypothesis could hardly be investigated further.

Once agents have integrated this information, we do not observe visually other changes in the estimates of the ARCH coefficient, except for the GARCH coefficient which increases after *t=636=11/10/2007*.

5 Conclusion

This article investigates the effects of the introduction of the option market on the volatility of the EU ETS. Following a brief review of key design issues on the EU ETS, we have presented the main characteristics of both the futures and option markets on ECX. Then, we have detailed our econometric methodology, which consists in capturing both unconditional and dynamic components of the volatility of carbon futures returns with GARCH models, rolling estimates and endogenous structural break detection following the introduction of ECX options. Based on the liquidity of traded options on a daily basis, we have been able to pinpoint the more 'correct' date of the introduction of options as being May 18, 2007. This date has been identified as the number of calls traded hitting for the first time the daily volume of 1Mton, and is thus different from the official creation date of the options market (October 13, 2006). This methodology has been robust to document changes in volatility on equity markets, but has not been applied yet on the carbon market.

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[44] Note that during the occurrence of large shocks (such as compliance breaks), volatility explodes which yields to larger confidence intervals as displayed by the blue dashed lines.

[45] In particular, National Allocation Plans for Phase II were more strictly validated than during the first trading period.

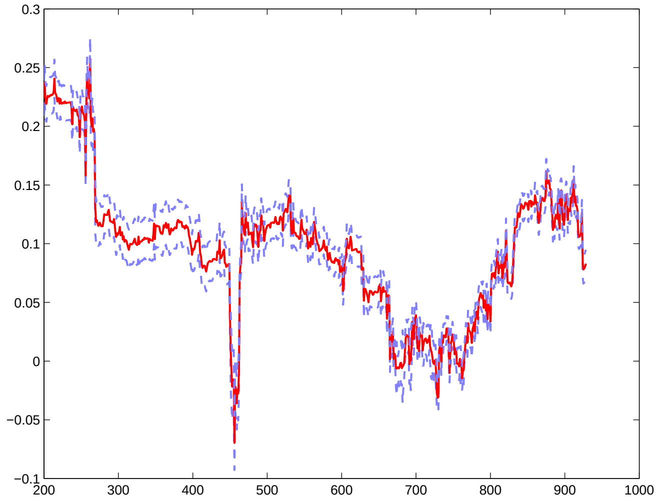

Figure 11
Rolling estimation of the autoregressive coefficient

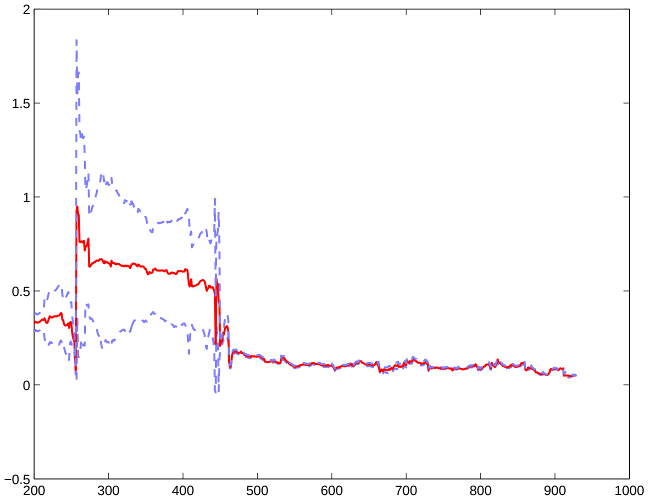

Figure 12
Rolling estimation of the ARCH coefficient

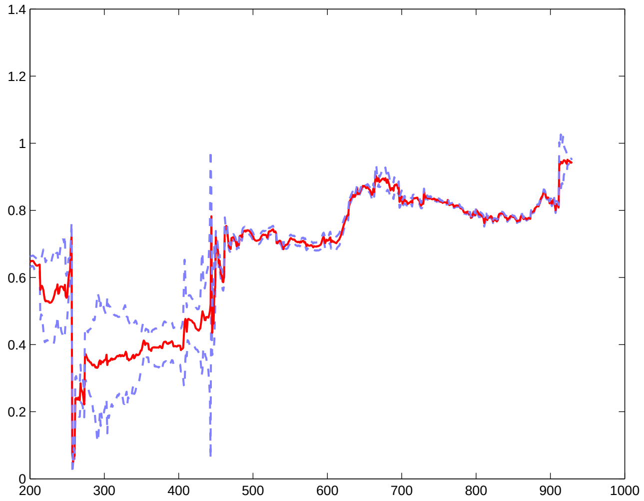

Figure 13
Rolling estimation of the GARCH coefficient

Based on daily data from April 2005 to April 2008, our results from our GARCH analysis suggest that the level of volatility has been significantly modified around this period. This static analysis is taken one step further with the investigation of the dynamic behavior of CO_2 return volatilities using rolling estimates with a window of 200 days. These estimations reveal the presence of shocks related to yearly compliance events in the EU ETS during April 2006 and February 2007. Additional analysis through an endogenous break test (Inclán and Tiao, 1994) provides evidence of breaks in the unconditional volatility during the period under consideration while it appears difficult, due to the nature of these tests (CUSUM), to relate these breaks to options introduction. As in Antoniou and Foster (1992), we also find that GARCH estimates are statistically different *before* and *after* the introduction of the derivatives market, thus leading to conclude that the nature (dynamics) as well as the level of volatility have changed. We have run sensitivity tests with institutional variables, energy and global commodity markets to capture the likely influence of other factors on the volatility of futures returns. Collectively, these results are conform to the view that options do not systematically impact the stability of the underlying market and may even have a stabilizing effect. Our results using the two sub-periods indicate a convergence to the random walk (in view of the decreasing autoregressive coefficient), while informational efficiency seems to have decreased (as indicated by a larger GARCH coefficient during the second sub-period).

A potential extension of this work using intraday data may be pursued relying on Liu and Maheu (2009), who test for breaks in realized volatility with Bayesian estimation and an autoregressive modeling of realized volatility (Corsi (2004), Andersen *et al.* (2007, 2009)). These methods have not been used to detect structural breaks following the introduction of derivative products yet.

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