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Essays on Emissions Trading Markets

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ESSAYS ON EMISSIONS TRADING MARKETS

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by

Kishore Kumar Dhavala

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To: Dean Kenneth Furton
College of Arts and Sciences

This dissertation, written by Kishore Kumar Dhavala, and entitled Essays on Emissions Trading Markets, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this dissertation and recommend that it be approved.

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The dissertation of Kishore Kumar Dhavala is approved.

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Florida International University, 2012

DEDICATION

I dedicate this dissertation to my grand parents, Dhavala Ellu Buktha, Dhavala Laxmi, Oruganti Krishna Murty and Oruganti Visalakshi; my parents, Suryaprabha and Subba Rao. Without their support the completion of this work would not have been possible. I would also like to dedicate this doctoral thesis to my brother, Kiran, sister, Laxmi; aunt Ratnam; uncles Satya Prasad Oruganti, Vijay Ramabhushan Nookala, Ganti Subramanyam; cousins, Sridhar Dhavala and Suryanarayana Sastry Peri.

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ABSTRACT OF THE DISSERTATION

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This dissertation is a collection of three economics essays on different aspects of carbon emission trading markets. The first essay analyzes the dynamic optimal emission control strategies of two nations. With a potential to become the largest buyer under the Kyoto Protocol, the US is assumed to be a monopsony, whereas with a large number of tradable permits on hand Russia is assumed to be a monopoly. Optimal costs of emission control programs are estimated for both the countries under four different market scenarios: non-cooperative no trade, US monopsony, Russia monopoly, and cooperative trading. The US monopsony scenario is found to be the most Pareto cost efficient. The Pareto efficient outcome, however, would require the US to make side payments to Russia, which will even out the differences in the cost savings from cooperative behavior.

The second essay analyzes the price dynamics of the Chicago Climate Exchange (CCX), a voluntary emissions trading market. By examining the volatility in market returns using AR-GARCH and Markov switching models, the study associates the market price fluctuations with two different political regimes of the US government. Further, the study also identifies a high volatility in the returns few months before the market

collapse. Three possible regulatory and market-based forces are identified as probable causes of market volatility and its ultimate collapse. Organizers of other voluntary markets in the US and worldwide may closely watch for these regime switching forces in order to overcome emission market crashes.

The third essay compares excess skewness and kurtosis in carbon prices between CCX and EU ETS (European Union Emission Trading Scheme) Phase I and II markets, by examining the tail behavior when market expectations exceed the threshold level. Dynamic extreme value theory is used to find out the mean price exceedence of the threshold levels and estimate the risk loss. The calculated risk measures suggest that CCX and EU ETS Phase I are extremely immature markets for a risk investor, whereas EU ETS Phase II is a more stable market that could develop as a mature carbon market in future years.

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LIST OF ABBREVIATIONS AND ACRYNOMS

ARCH	Autoregressive conditional heteroskedasticity
ARDL	Autoregressive distributed lag
$C(e_B)$	Cost function of the buyer
$C(e_S)$	Cost function of the seller
CCX	Chicago climate exchange
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CDM	Clean development mechanism
CFI	Carbon Financial Instruments
ECX	European Climate Exchange
EPA	Environmental Protection Agency
ES	Expected Shortfall
EU	European Union
EU ETS	European Union Emission Trading System
EVT	Extreme Value Theory
FINRA	Financial Industry Regulatory Authority
FSU	Former Soviet Union
GARCH	Generalized Autoregressive Conditional Heteroskedasticity
GATT	General Agreement on Tariffs and Trade
GEV	Generalized Extreme Value
GHGs	Greenhouse Gasses
GPD	Generalized Pareto Distribution
IPCC	Intergovernmental Panel on Climate Change
JI	Joint Implementation
KP	Kyoto Protocol

MAC	Marginal Abatement Cost
MGGRA	Midwestern Greenhouse Gas Reduction Accord
MIT-EPPA	Massachusetts Institute of Technology's Emissions Prediction and Policy Analysis.
MLE	Maximum Likelihood Estimation
MRS	Markov Regime Switching
Mmts	Million metric tons
NAP	National Allocation Plans
NASD	National Association of Security Dealers
POT	Peak Over Threshold
RGGI	Regional Greenhouse Gas Initiative
SBC or BIC	Schwarz Bayesian information criterion
S&P	Standard and Poor's Index
TC	Total Cost
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
VaR	Value at Risk
WCI	Western Climate Initiative

CHAPTER 1
ECONOMICS OF EMISSIONS TRADING IN THE CONTEXT OF KYOTO PROTOCOL FOR GREENHOUSE GAS REDUCTION

1.1 Introduction

The international community established the Kyoto Protocol in 1996 for reducing the greenhouse gases (GHGs). At the Kyoto global conference, a group of 41 industrial and economies-in-transition nations[1] and European Union (called Annex I countries) agreed to reduce their carbon emission level by 5.2 percent from the 1990 level during the Phase I period of 2005-2012 (UNFCCC, 2012)[2]. During Phase I of the Kyoto Protocol, the countries of the Former Soviet Union (FSU) acquired enormous number of permits which allowed them to monopolize the emission sellers' market. Despite being one of the largest emitters, the United States (US) did not ratify the protocol during Phase I because of political and domestic forces against it. However, recent developments in the US environmental policy have signaled that the country might participate in the international emissions trading program (Kropp 2009).

If the US participates in the emissions trading, it could become the largest buyer. If both the FSU and the US participate in the program it will lead to a situation where both parties will attempt to exert market power. The US might emerge as a monopsony power (single buyer) while Russian Federation as a monopoly power (single seller).

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[1] Annex I countries: Australia, Austria, Belgium, Bulgaria, Canada, Croatia, , Czech Republic , Denmark, European, Union, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Liechtenstein, Luxembourg, Malta, Monaco, Netherlands, New, Zealand, Norway, Poland, Portugal, Romania, Slovakia , Slovenia Spain, Sweden, Switzerland, Turkey, United Kingdom, United States of America and Former Soviet Union countries (Belarus, Estonia, Latvia, Lithuania, Russian Federation , Ukraine).

[2] http://unfccc.int/kyoto_protocol/items/2830.php

Under the above situation, it is plausible that the buyer as well as the seller may have a disagreement over the emission prices. While US as a monopsonist would try to demand a price lower than the competitive price, FSU as a monopoly would demand a price higher than the competitive price. The purpose of my research is to analyze the market outcomes of the interactions between the two diametrically opposite market powers (monopsonist versus monopolist), and compare the results with the outcomes of a cooperative market interactions.

Few studies in the literature have examined the Kyoto Protocol under the assumption that FSU led by Russia was considered the monopoly seller (Burniaux 1998; Bernstein, *et al.,* 1999; Grubb 2003, 2004; Bernard *et al.,* 2003; Chevallier 2007; Bernard *et al.,* 2008; Montero 2009). These studies mostly analyzed the supply side of the emission market. The market works only when there is enough demand for carbon credits. Burniaux (1998) showed that Former Soviet Union (FSU) countries led by Russian Federation exploit market power and reduce the supply of tradable permits to exploit the market price. Bernstein *et al.* (1999), investigating Russia's monopoly power within the Annex I countries, reveal that Russia's monopoly power vanishes if the Protocol allows India and China in the trading market. Grubb (2004) analyses Russia's political interest in Kyoto Protocol. Bernard *et al.* (2008) discuss the monopoly power of Russia with and without China in the trading program. Chevallier (2007) and Montero (2009), using a leader-follower game structure, investigate how FSU led by Russia could act as a leader and exploit the market power. No studies consider the presence of the US; more specifically these studies ignore the buying power of US and/or its desire to be a player in the emission market. Arguably, the status of the US as the largest emitter of

GHGs makes it potentially the largest buyer in the emissions trading market. If US were to sign the Kyoto Protocol today and comply with its 2010 target, it had to lower the emission by more than a billion tons of greenhouse gases. Therefore, the US could potentially become a monopsonist and exert its market power. The key economic question that needs addressed is to what degree the market powers on both sides of the permit exchange US and Russia will influence the market efficiency, particularly in terms of the abatement costs and their emission paths. The study also addresses the question if such a dual market power increases the level of difficulty in reaching a cooperative agreement. Further, this study assess a mechanism, which encourage two countries enter into a self-enforceable cooperative agreement that minimizes the overall costs of the emission control program. In particular, the study determines an optimal amount of side payment that one of the countries might have to pay to the other, in order to ensure a Pareto-efficient cooperative agreement.

The issue of market power in the context of emission trading was first formally discussed in the seminal work of Hahn (1984). Hahn analyzed the market power in a static framework, where he considered one large polluting firm and a group of small polluting firms. He assumed that all polluting firms took output prices as given. Initially, emission permits were allocated to firms for free, which needed to use them in the same period for which they were issued. That is, firms cannot store permits for future use or borrow from future allocations i.e., banking or borrowing option is not possible. Hahn's study shows that market power vanishes when the permit allocation of the large agent is exactly equal to its "efficient allocation", i.e., its emissions under perfectly competitive pricing.

Later several studies extended Hahn's work and analyzed the market power. In particular, Cronshaw and Kruse (1996), Rubin (1996) and Kling and Rubin (1997) analyzed the market power of a monopsonist. Unlike Hahn, these studies allowed banking and borrowing of the permits and analyzed the optimal behavior of the buyer. The main conclusion of these studies is that the monopsonist tries to bargain a lower price than the competitive market price so that she can minimize the cost of emission control. The buyer's market power depends on the nature of the permit market. If seller has a relatively flat marginal abatement cost function, i.e., higher the elasticity of abatement supply, she will have less market power for the monopsonist and vice versa.

Liski and Montero (2005a, 2005b) and Chevallier (2007) analyzed the market power of a single largest seller or monopolist. Liski and Montero (2005b) extended the static model of Hahn (1984) by introducing the provision for banking of permits and examine the effect of market power on permit prices in a dynamic framework. Their study reveals that the large agent might manipulate the market by banking allowances when it owns all the stock of permits. Liski and Montero (2005a, 2005b) and Chevallier (2007) argue that the large agent will take an advantage of banking permits and create demand by selling few credits. The monopoly power of the seller over the permits will artificially raise the market demand for the permits. By creating demand for emissions, the large firm demands a price higher than the market price and it will retain permits for future purpose. The firm can maximize its revenue and control the supply of the permit market by exploiting the market power.

However, studies analyzing the simultaneous presence of monopoly and monopsony are limited to my knowledge. Muller *et al.* (2002), Nordhaus and Boyer (1999), and Bernstein *et al.* (1999) only mention the possibility of a leader – leader game in a permit trading market but do not actually investigate the effects of market power on market outcome. My study extends the existing literature on emission trading with unilateral market power by comparing the dynamic models of monopsony and monopoly against each other. In particular, the study compares the cost efficiency and emission paths under the monopsony-monopoly interactions with those under more common market solutions of autarchy (no-trading) and cooperative trading. Using a cost–minimization dynamic optimal control model, I explore the temporal behavior of the two countries in terms of emission abatement, banking and permit trading under different market scenarios. The model also allows us to figure out how the relative costs of the two countries influence the market powers of the emission trading partners.

In this chapter, I extend the basic methodologies developed by Rubin (1996) for a monopsony buyer, and Liski and Montero (2005a) and Chevallier (2007) for monopoly seller. Following Liski and Montero (2005a), I allow banking of the permits. Further, comparing Rubin's (1996) monopsony model and Liski and Montero's (2005a) monopoly model against each other allows us to create a leader-leader scenario and to analyze the two market powers simultaneously. Further, I analyze the circumstances under which the two parties may fail to reach a permit trading agreement by characterizing and comparing their non-cooperative and cooperative price and emission paths. The paper also provides the market outcomes especially the net abatement cost savings for the buyer and net permit revenue for the seller if and when there is a mutually agreeable trade.

The leader-leader game assumes a regulator and he has complete information of abatement cost functions of both the countries. Initially the regulator allots permits to each nation according to the benchmark level[3]. If the country has more emissions than allotted permits, the same can either reduce emissions or buy from the market. If the country has surplus permits, i.e., more allotted permits than the current emission; it will have a chance to bank the permits for future purpose or sell the excess permits in the market. The seller country has surplus permits, i.e., its emission is less than its allotted permits. Seller country can either sell the excess credits in the market or bank them for the future purpose.

Using the above information, I construct different scenarios for the buyer and the seller. Scenario 1 is a non-cooperative regime, i.e., when both the countries commit to an emission target and reduce the emissions independently. Each country is simply a price taker and a non-cooperative, competitive agent in market power. Scenario 2 is when there exists a market power of a monopsony buyer. In the monopsony structure, I consider one large buyer (US) who has the market power to decide price or quantity. I assume that both the monopsonist and the seller (Russia) have complete information of each other's abatement cost functions. The buyer observes the marginal abatement cost of the seller and assumes that this marginal abatement cost is the least possible price he can offer if the trade happens. The buyer (US) takes seller's price as a reaction function and solves

[3] Under the Kyoto agreement, each Annex I country acquired permits based on their 1990 level. USA's benchmark is 93% of their 1990 level, Russia 100% of their 1990 level.

for a price which maximizes his benefit function. Scenario 3 is when the single seller (Russia) exerts its market power. The monopoly setup of the market is similar to the monopsony market structure. The seller assumes that the buyer will accept any price below her (seller) marginal abatement cost and solves for emission which maximizes her (buyer) revenue function[4]. Scenario 4 is the cooperative strategy where both players cooperate and try to optimize the emission market. They minimize the aggregate emission reduction costs and solve for the optimum price and emission path which is agreeable to both the seller and the buyer.

In order to analyze the above scenarios, I develop a strategic leader – leader game in a dynamic framework. I use dynamic optimization technique to analyze the optimal emission and price paths of the two players, assuming that each tries to optimize the respective payoff function. Further, based on existing studies, I develop estimates of the marginal abatement costs for the US and Russia, and numerically solve for the non-cooperative and cooperative emission paths over time. Later, I calculate the present value of total cost of all scenarios for US and Russia. Based on the cost estimates, I develop a payoff matrix to identify the Nash-Cournot equilibria for the leader-leader model. I observe three possible equilibria, one with no-trade scenario, one with cooperative scenario and one with side payments. I observe that equilibrium with side payments is Pareto efficient and gives best outcome for both countries.

[4] By the time Russia signed the agreement in 2005, its total emission was far less than its 1990 level due to economic downturn. Russia entered the protocol on the condition that it be allowed to increase its emission until it reaches certain target. In the empirical analysis later, therefore, I assume that Russia will follow a fixed emission growth path until it reaches a set emission target (for about ten years) and then stays in compliance with the Protocol-mandated emission path.

The chapter is organized as follows. In section 1.2 presents the motivation and relevance for this study and section 1.3 presents the basic set up of the model. In this section I discuss the above mentioned four possible scenarios of the emissions market. Section 1.4 presents an empirical application of the above scenarios. Section 1.5 provides the conclusion.

1.2 Motivation and background of Kyoto Protocol

For the past fifty years, many countries have experienced a rapid industrialization growth. In this process huge amount of carbon dioxide and the greenhouse gases (GHGs) were released into the atmosphere. Greenhouse gases mostly come from burning fossil fuels, industrial production and some agricultural practices. "Greenhouse gases act like a blanket around Earth, trapping energy in the atmosphere and causing it to warm. This phenomenon is called the greenhouse effect and is natural and necessary to support life on Earth. However, the buildup of greenhouse gases can change Earth's climate and result in dangerous effects to human health and welfare and to ecosystems" (Environmental Protection Agency, 2012)[5]. On a per capita basis, Australia, Canada and the US are the largest emitters of GHGs of more than 22 tons of CO_2eq per person[6]. These high emissions are partly explained by their widespread use of air conditioning, high meat consumption, coal based power industry, transport systems, oil and gas extraction, and mining.

[5] http://www.epa.gov/climatechange/basics/

[6] United Nations Statistics (2010), http://unstats.un.org/unsd/environment/air_greenhouse_emissions.htm

The total global emissions of GHGs were around 26 $GtCO_2e$ in 2005; with a population of approximately 6.5 billion people, this amounted to 4 tons of per capita carbon emission. The earth's ecosystem is able to absorb about 11 $GtCO_2e$ (3GtC) (IPCC 2007), i.e., only 1.7 tons of per capita carbon emission. Taking into account of a higher expected population growth, if we are to stabilize the global climate, the per capita GHG emissions would have to be much lower. The 2007 IPCC report indicates that the main sources of global carbon emission are from power generation (26 percent), industry (20 percent), and deforestation (17 percent). To control for GHG emissions, in 1988 the United Nations took an initial step by tasking IPCC, a group of scientists, with conducting a climate change study and making appropriate recommendations.

The IPCC submitted its first report to UN in 1990 and alarmed the world about the atmospheric concentrations of the greenhouse gases. Many countries had taken this report seriously and agreed to start emission reduction programs. In 1997 under the United Nations Framework Convention on Climate Change at Kyoto, 41 industrial and economies in transition nations (Annex I countries) agreed to reduce their carbon emission by 5.2 percent from their 1990 levels. This agreement, popularly known as the Kyoto Protocol, also allowed member countries to trade emission credits among themselves in order to meet their targets. This was the first major international agreement involving an emission trading scheme.

After years of negotiation the United States announced that it would not ratify the Kyoto Protocol. The effectiveness of the protocol became questionable when the US withdrew its support for the agreement. According UNFCCC (1998), the US accounted for 36.1 percent and Russian Federation accounted for 17.4 percent of the total emission by Annex I countries. To become legally binding, the Protocol had to ratify at least 55 percent of total emissions from Annex I countries. When the US withdrew from the Kyoto Protocol it made the Russian Federation's participation essential.

Kyoto Protocol came into force when Russia ratified the protocol in 2005. The Kyoto Protocol set the emission targets for the Phase I (2008-2012). Under the Kyoto Protocol, participated countries were allowed to trade the emissions. After the collapse of the Soviet Union, many of the polluted industries in Russia were shut down. This de-industrialization made Russia as one of the largest potential supplier of emission permits in the market (Bernard *et al.,* 2008). Under the Kyoto Protocol Russia and other FSU countries can sell their excess emission permits to other Annex I countries. In literature these excess permits sometimes referred as "*hot air*"[7] (Paltsev 2000). Different studies have provided different estimates for hot air. Victor *et al.* (1998) estimated a combined total of 344 million tons of carbon (MtC) for the period of 1990-97. This study also provided a wide range of market value of hot air; the total value of the permits will be $4 to 34 billion. Paltsev (2000) study projected little more than the Victor *et al.* study, this study estimated a total of 500 million hot air permits for the period 1990-97.

As a result of domestic pressure and other political reasons, European Union, Japan and Canada opposed the hot air permits allotted to Russia (Bohringer and Loschel, 2001). In 2002, the European Union (EU) approved the protocol and the member states of EU agreed to ratify. Taking the guidelines of Kyoto Protocol the EU started a

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[7] Paltsev(2000), "As a result of decline in economic activity, carbon emissions decreased by 34% between 1990 and 1997. Despite the economic recovery, economies in transition have projected 2010 carbon emissions lower than in 1990. These countries can sell their excess emission permits to other Annex B parties. The situation in which a party can sell emission permits virtually at no cost to itself is sometimes referred to as *hot air*"

mandatory trading program, called European Union's Emission Trading System (EU ETS). The EU ETS was the first international emissions trading system and covers more than 10,000 installations in the energy and industrial sectors (Soleille, 2006). EU ETS is a very successful, mandatory emission program for the European Union countries.

The recent developments in the US have rekindled interests in the international carbon emission trading. At a more recent UN convention on climate change held in 2009 in Copenhagen, the US Government rallied other countries to agree to an international treaty. President Obama even agreed to cut US emissions by three per cent below 1990 levels by 2020 (Obama, 2009). However, a broad-based political support for such a cut is still lacking in the US. Stone (2011) remarks, "Bargaining remains a substantial obstacle to international cooperation. Every GATT round faced delays and teetered on the edge of collapse before it was finally successfully concluded". So in this study, we assume that an international emission trading agreement along the lines of the Kyoto Protocol will come into effect in the near future.

1.3 Model

1.3.1 Basic setup of the model

Let us assume that there are n countries, each with different marginal abatement costs. The international regulator wants to bring back the emissions to a safe level. To do so, he sets a global emission cap N. This cap is fixed at any given time but could change over time. Initially the regulator allots permits to each eligible nation according to the benchmark level[8].

Each nation receives a share out of the global emission cap. Let α denote the share of emission cap, and $0 < \alpha < 1$. The share of country i can be written as $\alpha_i N$. We assume that the global endowment *N* is fixed and exogenous to the model. Following Montogomery (1972), Hahn (1984) and Rubin (1996), we assume that the abatement cost function for country i is $C_i(e_i(t))$, which is continuous, twice differential and convex in e_i That is, marginal abatement costs $C_i'(e_i(t))$ are negative and strictly increasing, i.e., $C_i'\big(e_i(t)\big) < 0$ *and* $C_i''\big(e_i(t)\big) > 0$. This means that the higher the emission the lower the abatement costs.

Countries will either buy the permits if their permit quota is less than the actual emission or sell/bank if they have excess permits. Let *y* be the number of permits either bought or sold. So, *y>0* if permits are bought and *y<0* if permits are sold. The market price of the permit is *P*.

Countries may bank permits without any restrictions[9]. Let $b_i(t)$ be the number of permits in the bank for country i. Whenever $b_i(t) > 0$, it means that the permits are banked for future purposes. We assume that permits in the bank are either positive or zero at any given time. Also, there is a small annual cost "ε" (\$/permit) for banking the permits.

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[8] In the Kyoto agreement, the benchmark level is 5% below of 1990 emissions level.

[9] At international level, under the Kyoto protocol, countries can bank or sell the emission. Borrowing the emissions is strictly prohibited. At domestic level, very successful programs like Environmental Protection Agency and California Air Resource Board allow banking but not borrowing.

Recognizing that certain emission trading programs require depreciation of the banked permits, I assume that a small percent of banked permits φ depreciate annually. Therefore, the net time rate of change in the permits bank is equal to the sum of the annual permit allotment and permits bought in the market *minus* the sum of the number permit depreciation and the annual permit consumption (i.e., emissions). The banking and withdrawing constraint can be formally written as:

$$\dot{b} = \alpha_i N + y - \phi b_i - e_i \qquad (1.1)$$

Assume that $b_i(0) = 0$, i.e., no permits are banked in the initial period. The country i is assumed to select the annual emission e_i and y_i that minimize the present value of the sum total costs during the planning horizon $[0,T]$.

1.3.2 Individual country problem without market-power

In this section, I develop a dynamic optimal control model for an individual non-cooperative buyer or seller. Both the countries are assumed to operate in a competitive market and to be price takers. They are non-cooperative and act independently. No market power is assumed. Each country's goal is to minimize its own combined total abatement costs. The model lays the necessary analytical foundation for the optimal emission control models of agents with market power (monopoly and monopsony), to be developed in the subsequent sections. The optimality conditions derived from this initial model of non-cooperative, competitive emission market will become an integral component (i.e., constraints) of the leader-leader game models of market power.

Individual countries try to minimize the following cost function.

$$\min_{e_i} \int_0^T e^{-rt}[C_t(e_i) + \varepsilon b_i]dt \tag{1.2}$$

Subject to

$$\dot{b}_i(t) = \alpha_i N - \varphi b_i - e_i(t) \tag{1.3}$$

$$b_i(0) = 0;\ b_i(T) \geq 0 \tag{1.4}$$

Where r is the discount rate, $b(t)$ is the banked permits at time (dot denotes the time derivatives). $\alpha_i N$ is the country i's share in the global cap or in other words we can say the initial endowment allotted by the regulator. The objective function (1.2) reflects that each individual country tries to minimize its own abatement cost when there is no trading among the countries. Equation (1.4) means there are no permits available at the beginning of the program and at the terminal period T, available permits in the bank may be zero or some are left over. Now using the banking constraint each country will solve for their optimal emission path.

$$H^{PV} = e^{-rt}[C(e_i(t)) + \varepsilon b_i(t)] + \lambda(\alpha_i N - \varphi b_i(t) - e_i(t)) \tag{1.5}$$

The corresponding Kuhn-Tucker necessary conditions are:

$$b_i: \quad \dot{\lambda} = -\frac{\partial H}{\partial b_i} = -e^{-rt}\varepsilon + \lambda\varphi \tag{1.6}$$

$$\lambda: \quad \frac{\partial H}{\partial \lambda} = \dot{b} = \alpha_i N - \varphi b_i - e_i \tag{1.7}$$

$$e_i: \quad \frac{\partial H}{\partial e_i} = e^{-rt}\, C'(e_i) - \lambda \geq 0; \quad e_i > 0,\ e_i \frac{\partial H}{\partial e_i} = 0 \tag{1.8}$$

$$b_i(T) \geq 0, -\lambda(T) \geq 0 \quad and \quad b_i\,(T)\lambda(T) = 0 \tag{1.9}$$

Equation (1.8), if $\frac{\partial H}{\partial e_i} > 0$, then $e_i = 0$ and if $e_i > 0$, then $\frac{\partial H}{\partial e_i} = 0$. We assume an interior solution for this problem i.e., $e_i > 0$. Equation (1.8) requires that the present value of marginal abatement cost of country *i* be equal to the marginal cost of an additional unit of banked emissions, i.e., the shadow price of an extra unit of emission banked. Following Montogomery (1972) and Rubin (1996), the price of the permit will equal to a unit of emission discharged by abatement i.e., $-C_i'(e_i(t)) = -C_j'(e_j(t)) = P(t)$. If there exists a permit trading, countries who want to buy the permits will accept any price below their marginal abatement cost and countries who sell the permits will accept any price which is above their marginal abatement cost. The permit prices are determined by the equilibrium conditions of all the countries. Equation (1.9) is the transversality condition, which requires that at the terminal period no permits are left in the bank, or even if there are, the shadow price of the permits is zero.

By differentiating equation (1.8) with respect to time, we can solve for the following expression involving the time derivative of optimal emission $\dot{e}_i$ (dot refers for time derivative),

$$-re^{-rt}\, C'(e_i) + e^{-rt}\, C''(e_i)\dot{e}_i - \dot{\lambda} = 0 \qquad (1.10)$$

Replacing the $\dot{\lambda} = -e^{-rt}\varepsilon$ and $e^{-rt}C'(e_i) = \lambda$ in the above equation and solving for the emission path gives the following expression,

$$\dot{e}_i = (r + \varphi)\frac{C'(e_i)}{C''(e_i)} - \frac{\varepsilon}{C''(e_i)} \qquad (1.11)$$

Since $C'(e_i) < 0$, $C''(e_i) > 0$, and $\varepsilon, r, \varphi > 0$, one can show that the emission path is downward sloping and the optimal emissions decline over the time. Later in section (1.4) the above emission paths are numerically solved for Russia and US. The results so obtained confirm that the emission paths are indeed downward sloping.

1.3.3 Monopsonist's optimization problem

I begin the investigation into optimization problem of a single buyer country with market power by assuming there is a national agency that makes buying decision on behalf of all the emitters of this country. With the allotment of the permits by the international agency, each country tries to minimize its abatement costs. When the country's abatement cost is higher than the market price, it buys the credits from the market. As I assume a single largest buyer, the buyer country agent will have market power over the seller country. To make banking constraint binding and more visible in the model, I followed Liski and Montero's (2005a) idea of considering two different benchmark levels. I assume that the regulator requires participating country to comply with a higher emission target of $\alpha_i N^H$ for some length of time, say, T_0 periods. After the T_0 period, the regulator imposes a lower benchmark level of $\alpha_i N^L$, where $\alpha_i N^H \gg \alpha_i N^L$. I will show this distinction between higher and lower caps, and some exception in the case of Russia more clearly in the empirical section. The buyer's objective is to choose optimal levels of emissions in order to minimize the present value combined costs of emission abatement, permits and banking. Formally,

$$\min_{e_B, e_S} \int_0^T e^{-rt}[C_t(e_B) + P_s y_S + \varepsilon b_B]dt \qquad (1.12)$$

Subject to

$$\dot{b}_B = \alpha_B N + y - \varphi b_B - e_B \qquad (1.13)$$

$$P_s = -C_S' \qquad (1.14)$$

$$y = \alpha_s N - e_S \qquad (1.15)$$

$$b(0) = 0,\ b(t) \geq 0 \qquad (1.16)$$

where *B* is for buyers and *S for* sellers. The objective function (1.12) indicates that buyer country minimizes the present value costs. The total cost consists of three components: abatement cost, the costs of the permits purchased from the market, and the storage cost of the banked permits. Since the buyer's objective is to minimize his cost, purchasing permits from the market is most favorable option when his marginal abatement cost is higher than the market price. Equation (1.13) is the state equation, which implies that the annual change in the permit bank equals the sum of the current period shares allotted by the regulator and the number of permits purchased *minus* the sum of the number depreciated permits and the country's own emission. Equation (1.14) is the constraint that captures the buyer's market power. Equation (1.14) is the lowest possible price the seller can accept, which is equal to the seller country's marginal abatement cost. The buyer tries to minimize his costs by offering the lowest acceptable price. Equation (1.15) gives the total available permits in the market, i.e., the difference between the annual permit share and the current emission level of the seller country. Equation (1.16) is the usual non-negativity constraint on banked permits. The present value of Hamiltonian and the first order conditions for the above problem can be written as:

$$H^{PV} = e^{-rt}[C_B(e_B) + P_S(\alpha_s N - e_S) + \varepsilon b_B] + \lambda(\alpha_B N + y - \varphi b_B - e_B) \qquad (1.17)$$

$$= e^{-rt}[C_B(e_B) - C_S'(e_S)(\alpha_s N - e_S) + \varepsilon b_B] + \lambda(\alpha_B N + y - \varphi b_B - e_B)$$

First order conditions:

$$b_i: \quad -\dot{\lambda} = \frac{\partial H}{\partial b_i} = e^{-rt}\varepsilon - \lambda\varphi \qquad (1.18)$$

$$\lambda: \quad \frac{\partial H}{\partial \lambda} = \dot{b} = \alpha_B N + y_S - \varphi b_B - e_B \qquad (1.19)$$

$$e_B: \quad \frac{\partial H}{\partial e_B} = e^{-rt}\, C_B'(e_B) - \lambda = 0 \tag{1.20}$$

$$e_S: \quad \frac{\partial H}{\partial e_S} = -e^{-rt}\, C_S''(e_S) * (\alpha_s N - e_S) + e^{-rt}\, C_S'(e_S) - \lambda = 0 \tag{1.21}$$

From equations (3.3.7), (3.3.9) and $-C_S'(e_S) = P_s$ we can derive the following expression,

$$-e^{-rt}\, C_S''(e_S) * (\alpha_s N - e_S) - e^{-rt}\, P_s - e^{-rt}\, C_B'(e_B) = 0 \tag{1.22}$$

Rearranging the above equation (1.22) gives,

$$C_B'(e_B) = C_S'(e_S) - C_S''(e_S)y \tag{1.23}$$

In equation (1.23), when $y = 0$, i.e., no permits are available in the market, the above expression boils down to the condition that the marginal abatement cost of the seller is equal to the marginal abatement cost of the buyer and it is exactly the same as the optimality condition obtained for the perfectly competitive, non-cooperative market situation in the previous section, $P = -C'(e_i) = -C'(e_j)$. This result suggests that the buyer has the market power only when there are enough permits available in the market. Through further simplification of the above equations, we arrive at,

$$C_S''(e_S)y + P_s = MAC_B \tag{1.24}$$

$$P_s\left(1 + \frac{C_S''(e_S)y}{P_s}\right) = MAC_B \tag{1.25}$$

$$P_s\left(1 + \frac{\partial C_S'(e_S)}{\partial e_S}\frac{y}{P_s}\right) = P_s\left(1 + \frac{-dC_S'(e_S)}{dy}\frac{y}{P_s}\right) = MAC_B \tag{1.26}$$

Equation (1.26) can be written as,

$$P_s\left(1 + \frac{1}{\epsilon_S}\right) = MAC_B \tag{1.27}$$

Whereas, $\epsilon_S > 0$ is the supply elasticity of the seller. Equation (1.27) reflects the degree of buyer's market power over the seller. In the context of permit purchase, the term

MAC_B reflects the buyer's marginal benefit or marginal avoided abatement cost (realized through increased emission and permit buying). If the supply elasticity is large enough, i.e., seller has a flat marginal cost function, then the gap between the seller's price, P_S, and the buyer's marginal benefit of permit buying, MAC_B, becomes narrow. In other words, the monopsonist would have less market power over the seller. Note that the two sides of equation (1.27) are dependent on the abatement technology. Thus, the degree of the market power will ultimately depend on the abatement technology.

Further, one can derive the emission path of the buyer by differentiating equation (1.20) and with respect to time;

$$-re^{-rt}\, C_B'(e_B) + e^{-rt}\, C_B''(e_B)\dot{e}_B - \dot{\lambda} = 0 \tag{1.28}$$

Replace $\dot{\lambda}$ and λ with equations (1.18) and (1.21) in the above equation and rearrange the terms to obtain the following expression

$$\dot{e}_B = (r + \varphi)\left[\frac{C_S'(e_S) - C_S''(e_S)y}{C_B''(e_B)}\right] - \frac{\varepsilon}{C_B''(e_B)} \tag{1.29}$$

Since $C_B'(e_B) < 0,\ C_B''(e_B) > 0;\ C_S'(e_S) < 0;\ C_S''(e_S) > 0; and\ y,\ r, \varphi, \varepsilon > 0$, the above expression becomes negative. In other words we can say that emissions path is a downward sloping and emissions decline over the time. Equation (1.29) shows that the monopsonist will optimize his emissions by observing the marginal abatement cost, curvature of the cost function and total available permits of the seller. In addition, the rates of discount and permit depreciation and storage costs influence the optimal emission path. The monopsonist tries to buy as many as permits, when its marginal abatement cost is greater than the seller's marginal abatement cost.

1.3.4 Monopolist's optimization problem

In the subsection 1.3.4, I characterize the optimal price and emission path for a seller who has complete control over the emission permit market. It is assumed that the seller country S is a large seller of permits and is a monopolist. The seller's goal is to maximize his revenue by setting an optimal price or quantity of permits and emission. The model structure follows that of Liski and Montero (2005a), which they developed for the United States' sulfur dioxide market. The setup of my model is slightly different form theirs[10]. Unlike their model[11] we maximize the present value of revenue from permit sales net of total abatement costs, with respect to the current emission, not with respect to the abatement like in Liski and Montero. Additionally, I assume a positive storing cost of banked permits.

Given his current emission levels and cost of the abatement, the seller's objective is to choose the emission levels and permits which maximize his profit;

$$max \int_0^T e^{-rt}(Py - C_S(e_S) - \varepsilon b) \quad (1.30)$$

subject to

$$P = -C_B'(e_B) \quad (1.31)$$

$$y = e_B - \alpha_B N \quad (1.32)$$

$$\dot{b}_s = \alpha_s N - e_s - y - \varphi b_s \quad (1.33)$$

[10] Liski and Montero (2005a) analyzed the market power of a monopolist firm. The cost function used in their model is a function of quantity reduced by abatement; in this model I use cost as a function of actual emissions. The reason for this is the availability of the data. To test our model empirically, we obtained UNFCCC's emissions data, which provided actual emissions of all the participating countries. The other difference is "storage cost"; Liski and Montero had assumed a zero storing cost.

Equation (1.31) is the maximum acceptable price of the buyer, i.e., marginal abatement cost of the buyer, a condition derived from the model of non-cooperative competitive model in section 1.3.2. The seller takes this price as a reaction function of the buyer and assumes that the buyer accepts this price. Equation (1.32) computes the number of permits that seller has available for sale in the market. Equation (1.33) represents the usual banking constraint..

The present value Hamiltonian for the above problem is:

$$H^{PV} = e^{-rt}[P(e_B - \alpha_B N) - C_S(e_s) - \varepsilon b_s] + \lambda(\alpha_s N + \alpha_s N - e_S - \varphi b_s - e_s) \quad (1.34)$$

$$= e^{-rt}[-C_B'(e_B)(e_B - \alpha_B N) - C_S(e_s) - \varepsilon b_s] + \lambda(\alpha_s N + \alpha_s N - e_S - \varphi b_s - e_B)$$

The first order conditions are given as:

$$b_i: \quad -\dot{\lambda} = \frac{\partial H}{\partial b_i} = -e^{-rt}\varepsilon - \lambda\varphi \quad (1.35)$$

$$\lambda: \quad \frac{\partial H}{\partial \lambda} = \dot{b} = \alpha_B N + \alpha_s N - e_S - \varphi b_S - e_B \quad (1.36)$$

$$e_S: \quad \frac{\partial H}{\partial e_s} = -e^{-rt}\, C_S'(e_s) - \lambda = 0 \quad (1.37)$$

$$e_B: \quad \frac{\partial H}{\partial e_B} = -e^{-rt}\, C_B''(e_B)y - e^{-rt}\, C_B'(e_B) - \lambda = 0 \quad (1.38)$$

From equations (3.4.6) and (3.4.7) we can obtain the following expression

$$-e^{-rt}\, C_B'(e_B) + e^{-rt}\, C_S'(e_s) - e^{-rt}\, C_B''(e_B)y = 0 \quad (1.39)$$

$$-e^{-rt}\, C_S'(e_s) = -e^{-rt}\, C_B'(e_B) - e^{-rt}\, C_B''(e_B)y \quad (1.40)$$

$$MR_S = P_B\left(1 - \frac{C_B''(e_B)y}{-C_B'(e_B)}\right) = P_B(1 - \frac{1}{\epsilon_d}) \quad (1.41)$$

where, $\epsilon_d < 0$ is the demand elasticity of the buyer. When the buyer has no permits left and need to buy the permits from the market to comply with the regulator's requirement, monopolist take advantage of the situation and let the prices to rise. By doing this, he maximizes his revenue function.

We can derive the emission path of the monopolist by differentiating equation (1.37) with respect to time and replacing $\dot{\lambda}$ and λ with (1.35) and (1.38), which will give the following expression:

$$\dot{e}_S = r\frac{C_S'(e_S)}{C_S''(e_S)} + \varphi\left[\frac{C_B'(e_B)+C_B''(e_B)y}{C_S''(e_S)}\right] - \frac{\varepsilon}{C_S''(e_S)} \quad (1.42)$$

As mentioned in earlier section that $C_B'(e_B) < 0, C_S'(e_S) < 0; C_B''(e_B) > 0;\ C_S''(e_S) > 0;$ $C_B'(e_B) < 0, C_B''(e_B) > 0;\ and\ y, r, \varphi, \varepsilon > 0$ the above expression becomes negative. Equation (1.42) tells that monopolist optimal emission path depends on the permits demanded by the buyer. When buyer agent demanded more permits, the monopolist emits fewer emissions and sells the permits to the fringe agent. I ignored the above optimal path and assumed a linear growth for Russia in the empirical section. Theoretically, a monopolist would follow the above emission path but recent developments in the Russia's emission reduction programs suggest that Russia do not follow the emission path for next 10 years[12].

Monopsony response to monopoly:

In this sub-section, I characterize the monopsonist's (US) optimal response when the monopolist (Russia) exerts its market power by charging a price that is equal to US's own marginal abatement cost, as in equation (1.31). This solution is particularly necessary for the empirical analysis later, in order to estimate the total (combined) costs

[12] In recent Rio+20 summit, Russia's former president and current chairman of the Govt. of the Russian Federation , Dimitry Medvedev announced that Russia is committed to reduce their emissions to 25 percent below 1990 levels by 2020. However, Russian emissions have already reached to 34 percent below 1990 level. This means, to meet 75 percent of 1990 level in 2020, they can able to increase their current emission level by 9 percent between 2010 and 2020 (Executive, The Russian government documentation, 2012).

of the emission abatement program for the Russia-Monopoly scenario. Formally, in response to Russia's monopoly price, the monopsonist attempts to solve the following problem: Based on this information the monopsonist solve for his optimum emission path.

$$\min_{e_B} \int_0^T e^{-rt}[C_t(e_B) + P_B y_S + \varepsilon b_B]dt \tag{1.43}$$

subject to

$$\dot{b}_B = \alpha_B N + y - \varphi b_B - e_B \tag{1.44}$$

$$P_B = -C_B' \tag{1.45}$$

$$y = \alpha_s N - e_S \tag{1.46}$$

$$b(0) = 0,\ b(t) \geq 0 \tag{1.47}$$

$$\begin{aligned} H^{PV} &= e^{-rt}[C_B(e_B) + P_B y + \varepsilon b_B] + \lambda(\alpha_B N + y - \varphi b_B - e_B) \\ &= e^{-rt}[C_B(e_B) - C_B'(e_B)y + \varepsilon b_B] + \lambda(\alpha_B N + y - \varphi b_B - e_B) \end{aligned} \tag{1.48}$$

First order conditions:

$$b_i: \quad -\dot{\lambda} = \frac{\partial H}{\partial b_i} = e^{-rt}\varepsilon - \lambda\varphi \tag{1.49}$$

$$\lambda: \quad \frac{\partial H}{\partial \lambda} = \dot{b} = \alpha_B N + y_S - \varphi b_B - e_B \tag{1.50}$$

$$e_B: \quad \frac{\partial H}{\partial e_B} = e^{-rt}\, C_B'(e_B) - e^{-rt}\, C_B''(e_B)y - \lambda = 0 \tag{1.51}$$

To obtain the emission path, differentiate equation (1.51) with respect to time and re-arrange the terms so that

$$\dot{e}_B = (r + \varphi)\left(\frac{C_B'(e_B) - C_B''(e_B)y}{C_B''(e_B) - C_B'''(e_B)y}\right) - \frac{\varepsilon}{C_B''(e_B) - C_B'''(e_B)y} \tag{1.52}$$

Equation (1.52) indicates that the buyer's optimum emission path will be different from the emission paths we derived for its no-trade scenario (equation 1.11) and monopsony scenario (equation 1.29). The buyer accepts a price that equals his marginal abatement cost and buys the permits from the seller. By doing so, the buyer reduces emission at a slower than he would under the no-trade scenario.

1.3.5 Cooperative aggregate reduction model

The subsection 1.3.5 presents a cooperative trading program, built on the assumption that the agreement is binding on buyer and seller countries and is enforced by an international agency. Here, I am presenting two scenarios. Scenario (i) has that both buyer and seller follow optimal emission paths and solve for joint/aggregate optimal emission path. Scenario (ii) applies when only buyer follows the optimal emission path and seller follows a fixed emission path. The reason to formulate scenario (ii) is because of the current Russian climate policy. In a recent meeting at 2012 Rio Earth summit, Russia's Chairman of the Government, Dmitry Medvedev said, "...we need to develop sustainable production and consumption, which will ensure sustainable economic growth and to remove all threats - critical threat - to the environment…Russia is an environmental donor, which has considerable natural resources… We are successfully coping with the performance of its obligations, including the Kyoto Protocol. I would like to reiterate that by 2020, greenhouse gas emissions in Russia will be 25% below 1990 levels. We look forward to equally active measures on the part of other states. We are ready to be part of a global agreement on this issue, but it is global, which will be open to all, not the individual's major economies." One may infer from this statement that Russia is committed to maintaining emissions so that their 2020 level does not exceed 25% of its 1990 level. Russia's current emission level is much lower than its 2020 expected level. Therefore, in scenario (ii), we assume that Russia will follow a linear emission growth path to reach their 2020 target; thereafter they will stay at 2020 target. On the basis of Russia's emission pattern information, US will try to optimize their emission path.

Scenario (i): Following Rubin (1996) and Liski and Montero (2005), both countries solve for a joint optimization problem. Their goal is to minimize the total aggregate cost and jointly maintain the global emission level.

$$min \int_0^T e^{-rt} \left[\sum C(e_i)\right] \tag{1.53}$$

subject to

$$\dot{B} = N - \varphi B - E \tag{1.54}$$

$$B(0) = 0 \ and \ B(t) \geq 0 \tag{1.55}$$

Where, N, E represents global cap and aggregate emissions respectively. As in the previous cases, N is set at a higher level for the first T_0 years and then a lower level thereafter. Equation (1.54) represents the aggregate banking constraint. Equation (1.55) is non-negativity constrain on permits banked. The present value of the Hamiltonian is:

$$H^{PV} = e^{-rt}\left[\sum C(e_i)\right] + \lambda(N - \varphi B - E) \tag{1.56}$$

The first order necessary conditions for optimality are:

$$\dot{B} = \frac{\partial H}{\partial \lambda_i} = N - \varphi B - E \tag{1.57}$$

$$\dot{\lambda} = -\frac{\partial H}{\partial B} = -\varphi \tag{1.58}$$

$$e^{-rt}C'(e_i) - \lambda = 0 \tag{1.59}$$

Equation (1.59) requires that negative of the marginal abatement cost $-C_i'(e_i) = -C_j'(e_j) = P(t)$ for $i \neq j$, where $P(t)$ is calculated based on the equimarginal principle. Which we can take as equilibrium price of the market or aggregate marginal abatement cost. The emission path of this problem can be obtained by differentiating (1.59).

$$-re^{-rt}C'(e) + e^{-rt}C''(e)\dot{e} - \varphi\lambda = 0 \tag{1.60}$$

$$\dot{e} = \frac{(r+\varphi)C'(e)}{C''(e)} \tag{1.61}$$

Since $C'(e_i) < 0;\quad C''(e_i) > 0;\ \ \varepsilon, r, \varphi > 0$, based on this information, we can say that the emission path is downward sloping and emissions decline over the time.

Scenario (ii):

$$\min_{e_B} \int_0^T e^{-rt}[C_t(e_B) + Py_S + \varepsilon b]dt \tag{1.62}$$

subject to

$$\dot{b}_B = \alpha_B N + y - \varphi b - e_B \tag{1.63}$$

$$P = -C_a'(E) \tag{1.64}$$

$$y = \alpha_s N - e_S \tag{1.65}$$

$$E = e_B + e_S \tag{1.66}$$

$$b(0) = 0,\ b(t) \geq 0 \tag{1.67}$$

Equations (1.62) and (1.64) together require that the buyer minimizes his cost by paying a price that equals to the aggregate marginal abatement cost. The buyer (US) assumes that seller (Russia) follows a fixed emission path. To maintain a joint global emission level, the buyer optimizes his emission path by observing the joint aggregate emissions. Equation (1.65) gives the permits available in the market. Equation (1.66) represents an aggregate emission. The corresponding present value of Hamiltonian of the above scenario will be,

$$H^{PV} = e^{-rt}[C_B(e_B) + Py + \varepsilon b_B] + \lambda(\alpha_B N + y - \varphi b - e_B) \quad (1.68)$$

$$= e^{-rt}[C_B(e_B) - C_a'(E)y + \varepsilon b_B] + \lambda(\alpha_B N + y - \varphi b_B - e_B)$$

First order conditions:

$$b_i: \quad -\dot{\lambda} = \frac{\partial H}{\partial b_i} = e^{-rt}\varepsilon - \lambda\varphi \quad (1.69)$$

$$\lambda: \quad \frac{\partial H}{\partial \lambda} = \dot{b} = \alpha_B N + y_S - \varphi b_B - e_B \quad (1.70)$$

$$e_B: \quad \frac{\partial H}{\partial e_B} = e^{-rt}\,[C_B'(e_B) - C_a''(E)y] - \lambda = 0 \quad (1.71)$$

The emission path of the problem can be obtained by differentiating (1.71) and replace $\dot{\lambda}$ and λ with equations (1.69) and (1.71) will give the following expression;

$$\dot{e}_B = \frac{1}{C_B''(e_B) - C_a'''(E)y}[(r + \varphi)(C_B'(e_B) - C_a''(E)y) + C_a'''(E)y\dot{e}_S - \varepsilon] \quad (1.72)$$

Using the equimarginal principle and the optimality condition, the buyer equates his marginal abatement cost with the aggregate marginal cost function.

Now equation (1.72) becomes as,

$$\dot{e}_B = \frac{1}{C_B''(e_B) - C_a'''(E)y}[(r + \varphi)(C_a'(E) - C_a''(E)y) + C_a'''(E)y\dot{e}_S - \varepsilon] \quad (1.73)$$

Equation (1.73) shows that the buyer's optimal emission path depends on not only his own marginal abatement cost, but also aggregate marginal emission costs. Same as in other scenarios, the emission path of the buyer is downward sloping.

1.3.6 Comparative analysis of all three models

Figure 1.1 presents buyer's optimal emission paths under the three different scenarios. On the basis of theoretical models, I expect that the buyer's no-trade emission path will be the steepest than those under the monopsony and cooperative situations. The US will maintain its emission below the initial allowance level $\alpha_B N^H$, and thus, will bank the permits.

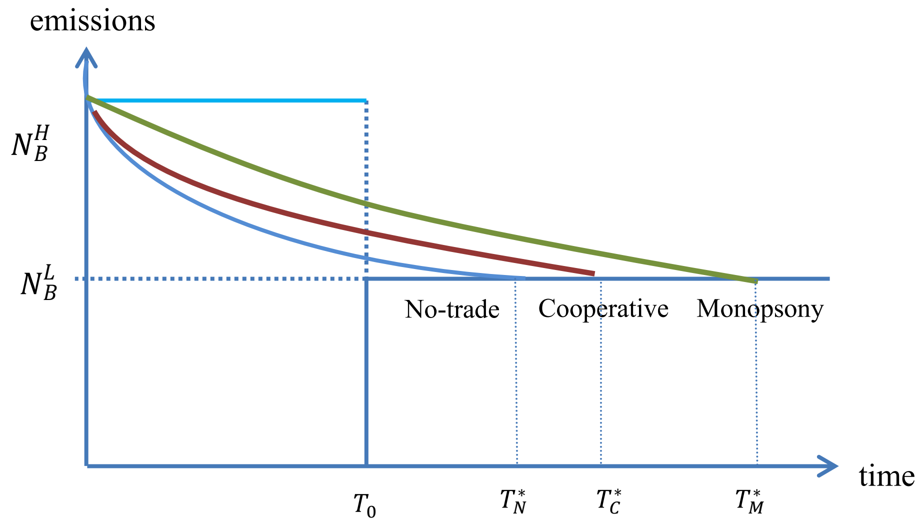

Figure 1.1. Buyer's emission reduction paths under different scenarios

At $t = T_0$ the allowance level is reduced to a lower level $\alpha_B N^L$ and the US will start drawing down its stored permits for a few more years. The lower level target allows the US to maintain its optimal emissions at levels higher than the annual allowance until $e_B = \alpha_B N^L$ at $t = T_N^*$ .Under the monopsony, the US will buy all the permits from the seller as long as the buyer's marginal abatement cost is higher than the seller's marginal abatement cost (MAC). In the initial periods, the US consumes more of its permits than it did under the cooperative scenario, although it banks much of the purchased permits for future use. Therefore, the monopsony optimal emission path is higher than the no-trading emission path. For the same reason it is able to hold the emission path above its allowance for a much longer period, i.e., $T_n^* < T_m^*$. In cooperative scenario, the buyer pays a price equivalent to the aggregate marginal costs and buys the permits from the seller. I expect the emission reduction path under the cooperative scenario to be steeper than that of the monopsony and gentler than the no-trade situation. For the reason, $T_n^* < T_c^* < T_m^*$.

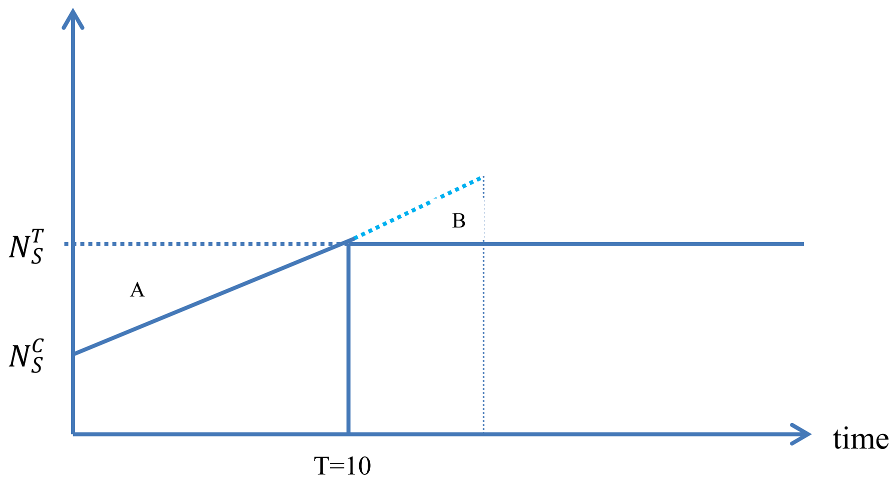

Figure 1.2. Seller's emission reduction paths under different scenarios

Figure (1.2) shows the emission reduction path of the seller under three different scenarios. I assume that seller's current emission level, i.e., N_S^C is much lower than the baseline level, N_S^T. The seller can sell the accumulated permits in the international market. Region "A" shows accumulated permits. Seller has no incentive to save the permits if there is no market for him. Seller will wait for T_0 periods then decide what to do with saved permits. In a no-trade scenario, seller consumes all his permits after T_0 periods. Once the permits get exhaust he will stay at baseline level. If seller acts as a monopoly, he expects a price equals the marginal abatement cost of the buyer, in order to maximize his revenue function, the seller sells all the accumulated permits and tries to abate further until his MAC equals to the price offered by the buyer. In the cooperative scenario, the seller sells the permits and stays at the baseline level once the permits exhaust.

1.4 Empirical application

1.4.1 Data and model parameters

According to the Kyoto Protocol, Annex I countries accounts for 55 percent of 1990 emissions, out of which US contributes 36.1 percent and the Russian Federation accounts for 17.4 percent (Bernard *et al.* 2008). With the absence of US, the Russian Federation has become the largest permit seller in the market and exploited the market by increasing the bargaining power and forced to a higher permit price (Manne and Richels, 2001). So in this section we have calibrated different scenarios for Russia, which I assumed as a largest seller (monopolist) and United States, which is the largest buyer (monopsonist).

I tried to estimate the MACs of the two countries, by assuming that both countries are aware of each other's total abatement cost functions, and solve for their optimal emission paths, particularly for the US. This assumption will allow us to estimate the dynamic interaction of the two countries.

There are four scenarios in the empirical model, which are as follows: (i) the autarkic or no-trading situation: Countries bind to the Kyoto agreement and agree to reduce their emission levels independently, i.e., non- cooperatively bind to the Kyoto agreement.

(ii) US as a monopsonist: US as the single largest buyer exerts its market power. Under this situation, the US attempts to minimize its cost function by offering Russia the lower possible price. That is, it observes the marginal abatement cost function of Russia. The buyer assumes that the MAC of the seller is the minimum acceptable price. The buyer takes the seller's MAC as a reaction function and solves for optimum emission reduction path.

(iii) Russia as a monopolist: Russia as the single largest seller exerts its market power. Its objective is to maximize the present value net revenue by fetching the highest market price for its permits. Russia observes US's MAC function, and assumes that the latter accepts any price below or equal to its MAC.

(iv) Cooperative trading: Both countries will achieve Nash-Cournot equilibrium when they cooperate and solve for a joint cost function. Russia is allowed to follow a fixed-growth emission path for the first ten years and then to stay at its annual allowance level. Russia and US both agree to the annual price that is equal to the aggregate marginal abatement costs. US optimizes its emission path so that $-C_i'(e_i) = -C_j'(e_j) = P(t)$.

Table 1.1 provides the parameters used in the empirical simulation. Liski and Montero (2011) and Jacoby *et al.* (1999) assumed a 5 percent discount rate. I think this is a little high number for an environmental policy which has a long time horizon. I apply two percent discount rate (i.e., the US current lending interest rate). For a lack of better information, the storage cost of the permits is assumed to be $1 per permit. Further, I consider a one percent annual depreciation rate for the banked permits. The latest year that emission information is available for is 2009. The starting year of the model simulation is 2010. For the US, the long-term Kyoto Protocol emission target is 93 percent ($\alpha_B N^L$ = 5,730 million metric tons) of its 1990 level (6,161 million metric tons). For Russia, the long-term emission target is set at 75 percent ($\alpha_S N^L$ = 2,527 million metric tons) of the 1990 level (3,369 million metric tons). The above emission levels are obtained from the UNFCCC and represent total CO_2 equivalent emissions from land use, land-use changes and forest degradation.

In addition, Russia has been claiming permits for its having maintained its emission much below the Kyoto target in the recent years. Russia had ratified the Kyoto Protocol in 2005 on the conditions that signatory countries give credit to its excess emission reductions in the form of tradable permits, which are popularly known as 'hot air' credits. Different studies have estimated the Russia's hot air credit to be in the range of one to one and one-half billion tons (Euractiv, 2009)[13]. For this study, therefore, I assume that Russia gets to trade an additional 1.2 billion permits during the first six years of the simulation. This assumption would be more reasonable than applying all the permits for just one or two years.

Table 1.1. Parameters used for calibration of the models

	$r = rate\ of\ interest$	Storage cost of permits	Depreciation	Initial emission (2010 level) (mmt)	Target level (mmt)
USA	0.02	\$1	0.01	6608	6608
Russia	0.02	\$1	0.01	2208	2527

[1]For US, the emission allowance is set at 93 percent of its 1990 emission level and for Russia, the allowance is set at 75 percent of its 1990 level. mmt- million metric tons

I choose the marginal abatement cost curve used by Ellerman and Decauz (1998), and the data points from Morris *et al.* (2008). As reported in Ellerman and Decauz

[13] http://www.euractiv.com/climate-change/russian-hot-air-threatens-un-cli-news-222798

(1998), the abatement cost function is a cubic function i.e., marginal abatement cost function (MAC) is twice continuously differentiable.

Morris *et al.* (1998) estimated the marginal abatement costs for US at different levels of abatement. I calculated the quantity of emissions (e_B) for each abatement quantity.

Although Morris *et al.* (1998) has MAC and e_S data, recent literature on abatement cost studies indicate that the costs have come down. I use recent estimates reported in the Russian socio-ecological union and climate secretary.[14] The Russia's metallurgical industry has the most expensive technology; it costs $72 per ton of carbon dioxide. Emission control in the energy sector (e.g., waste bark, wood coal and petroleum gas-fired units) costs $4 per ton of carbon dioxide. The study also reports that the current average unit cost of reducing greenhouse gas emissions and the cost to meet the 2020 target level would be around $12 per ton and $8 per ton. Table 1.2 presents the marginal abatement costs associated with different emission levels for the US and Russia. Using these data points, I estimate equation (4.1.1) using ordinary least squares regression method.

$$-MAC(e) = a + be + ce^2 \qquad (1.74)$$

[14] http://www.rusecounion.ru/kioto_7612

Table 1.2. MACs and emission data used for the cost function estimation

US		Russia	
MAC ($/ton)	e_B (million metric ton)	MAC ($/ton)	e_S (million metric ton)
-103.07	3679	-80	0
-80.15	4414	-72	100
-64.2	5150	-12	2120
-45.08	5886	-8	2524
-17.13	6622	-4	3600
-6.16	6989	--	--
-0.73	7284	--	--
0	7357	--	--

Source: Moriss *et al.* (2008); Russian socio-ecological union[15] (2012)

The aggregate MAC is calculated algebraically from the MACs of US and Russia, using the equimarginal cost principle. First, I calculate emissions associated with different MAC points for US, and then I used the same set of MAC points to calculate emissions for Russia. Since MAC is quadratic function, I take only positive roots and calculated combined emission. Then, I estimate the regression equation to obtain the coefficients of the aggregate marginal abatement cost. Table 1.3 provides the estimated coefficients for the US and Russia. Since these estimates are based on limited data, the results must be used with caution.

The model is simulated for 20 years under each scenario, using the Excel program. The simulation generates optimal paths of emission, permit traded, stock of stored permits, and prices. Finally, the present value sum of the costs of abatement and the costs of permit trading and banking are computed.

[15] http://rusecounion.ru/ang_kioto_7612

Table 1.3. Coefficients of marginal abatement cost curve approximations

	a	b	c
USA	-188.306	0.0209	0.000000683
Russia	-80	0.0473	-0.00000073
Aggregate	-177.96	0.0248	-0.00000007

Note: All coefficients are statistically significant at 5 percent level

1.4.2 Emiprical simulation results

Table 1.4 provides emission levels and prices at five year interval for all scenarios. The computed values of emissions and prices of all years and scenarios are reported in the Appendix 1.

Table 1.4. Emission reductions and prices of all three scenarios

year	No Trade US		Monopsony US		Cooperative US		No Trade Russia		Monopoly Russia		Cooperative Russia	
	e	P	e	P	e	P	e	P	E	P	e	P
2010	6608	21	6608	11	6608	15	2208	11	2208	21	2208	15
2015	6172	33	6359	9	6340	16	2367	9	2367	33	2367	16
2020	5730	46	5902	7	6004	18	2527	7	2527	46	2527	18
2025	5730	46	5730	6	5730	22	2686	6	2527	46	2527	22
2030	5730	46	5730	4	5730	22	2846	4	2527	46	2527	22

(e = emission in million metric tons; P = price in $/ton)

Table 1.5 presents the pay-off matrix of all scenarios. The total gains from the cooperative scenario are calculated as the difference of no-trade and cooperative outcomes.

Table 1.5. Present value costs of emission abatement, permit trading and permit banking of model scenarios ($ million)

Scenarios	US	Russia	Total Cost
No-trading	480,224	76,578	556,802
US Monopsony	431,257	40,747	472,004
Russia Monopoly	526,804	-4,864	521,940
Cooperative trading	448,557	25,988	474,545
Gain from cooperative trading	**31,667**	**50,590**	**82,257**

Scenario (i) Non-cooperative emission abatement without permit trading:

The two model countries meet the Kyoto commitment by following their respective optimal emissions paths and/or staying below the sum of their annual allotment and the permits withdrawn from the bank. In this process each country minimizes present value total costs. Figures 1.3, 1.4, 1.5 and 1.6 presents the optimal emission paths, and the stock of banked permits for the US and Russia under the non-cooperative scenario. The detailed calibration results are presented in the Appendix 1. The optimal emission path of the US is in full compliance with the two annual benchmark levels—a higher benchmark level of 6,608 million metric tons for the first 5 years and a lower benchmark level of 5,730 million metric tons thereafter. There will be a slow reduction in the emissions for the first five years. At the end of 2015, the US will have banked 552 million permits, and the corresponding emission level will be 6,172 million metric tons. The new benchmark level, 5730 million metric tons (mmts), will start in year 2016. To reach 5,730 mmts emission level, US starts consuming the banked permits until the year 2016 and thereafter it will stay at the 5,730 mmts. The computed present value total cost of the program for the US would be \$480.23 billion.

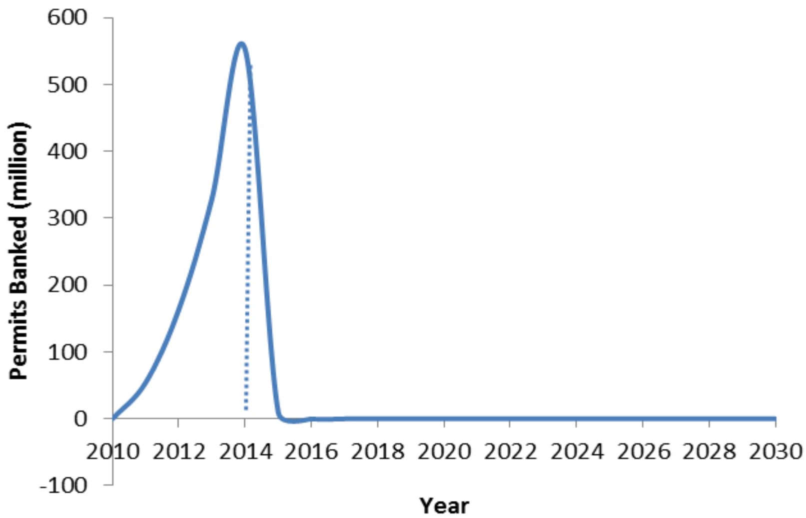

Figure 1.3. Permits banked and consumed by US in a no-trade scenario

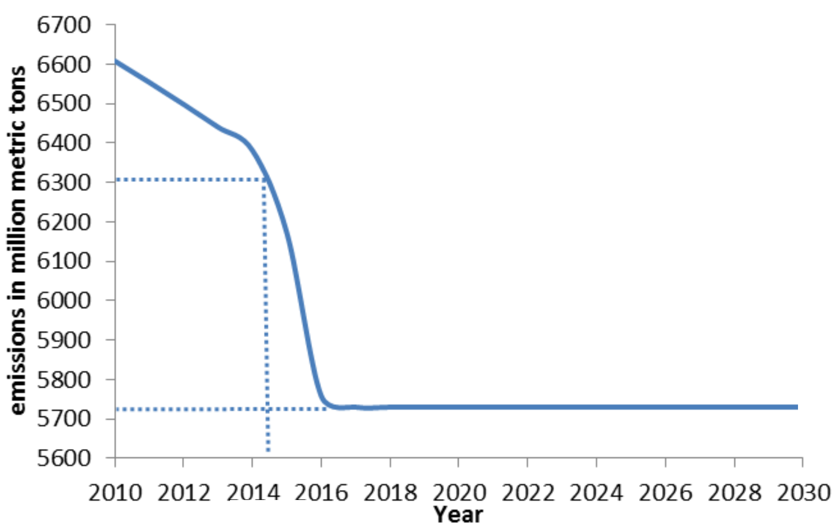

Figure 1.4 US's emissions' path when there is no-trade

Note: Initial benchmark starts in 2010, second benchmark level starts in 2015. US will use the banked permits and reach second benchmark in 2016, thereafter it will stay at that level

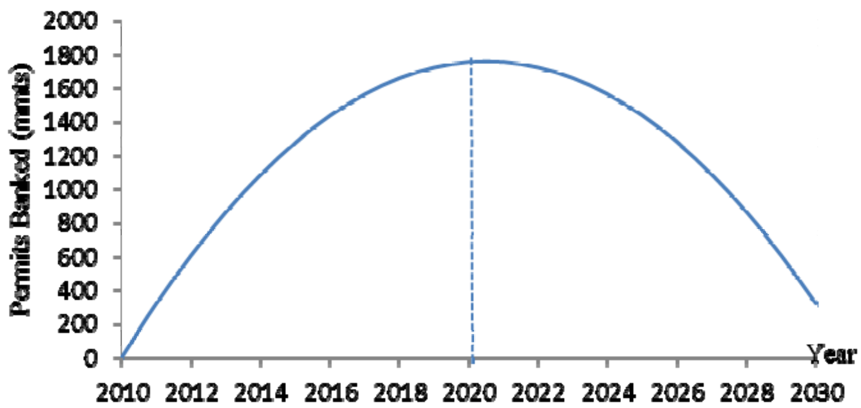

Figure 1.5. Permits banked and consumed by Russia in a no-trade scenario

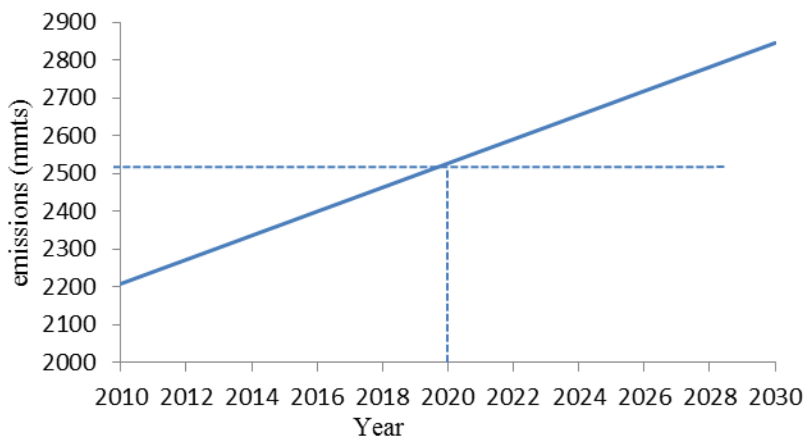

Figure 1.6. Emissions' path for Russia when there is no-trade
Note: Russia's benchmark level starts in 2020, their 2020 emission level is higher than 2010 level, so saved permits will used after 2020, and use them until permits exhaust.

Scenario (ii) US with monopsony power

See figures 1.7 and 1.8 for optimal emission, banking and prices paths of the US. As we have seen in the section 1.3.3, as a largest buyer US will try to exert the market power and tries to bargain for a lower price. As buyer, US's objective is to minimize the total cost, which includes the cost of permits it buys from Russia. The US observes the marginal abatement cost of Russia and offers a price equal to the marginal abatement cost of Russia. By doing this, US try to buy all the available permits and optimizes its own emission path. The emission reduction in this scenario will be slower than that of the no-trade situation. The US has more permits at its disposal than that in the case of no-trade situation, and therefore, uses some of it towards emission reduction obligation. Also, the US will bank more permits for future purpose. When the second benchmark level starts, US will start withdrawing permits from the bank and finally exhausts year 2020, which is five years later compared to the no-trade scenario.

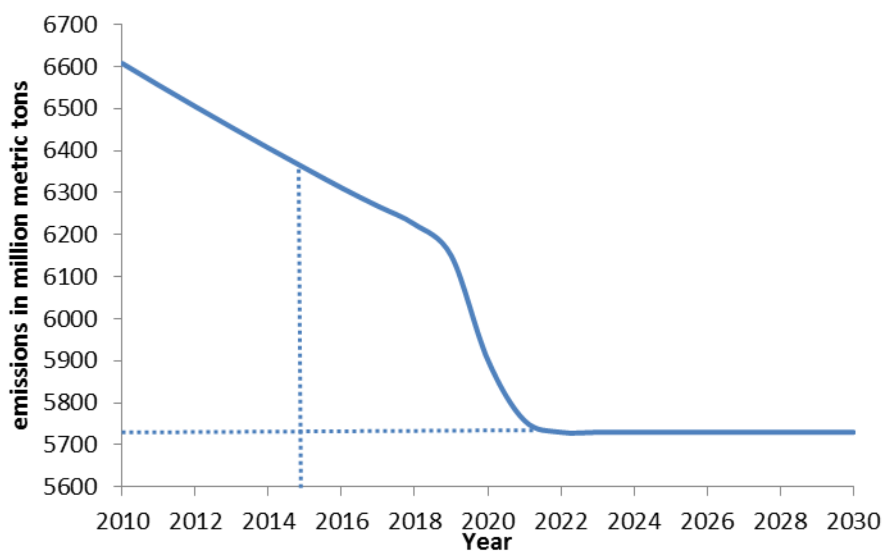

Figure 1.7. Emissions' reduction path when US act as a monopsony
Note: Initial benchmark starts in 2010, second benchmark level starts in 2015. US buys all the permits from Russia and save them for future. US will start use the banked permits after the year 2016 and consume until they exhaust.

Initially US offers a price of $11 per permit, which is the MAC of Russia. If Russia accepts the price offered by the US, the latter buys all 2,634 million permits from the former. The present value total cost in this setup would be $431.28 billion, which represents a cost saving of $49 billion to the US over the no-trade situation. This is the most beneficial option for US.

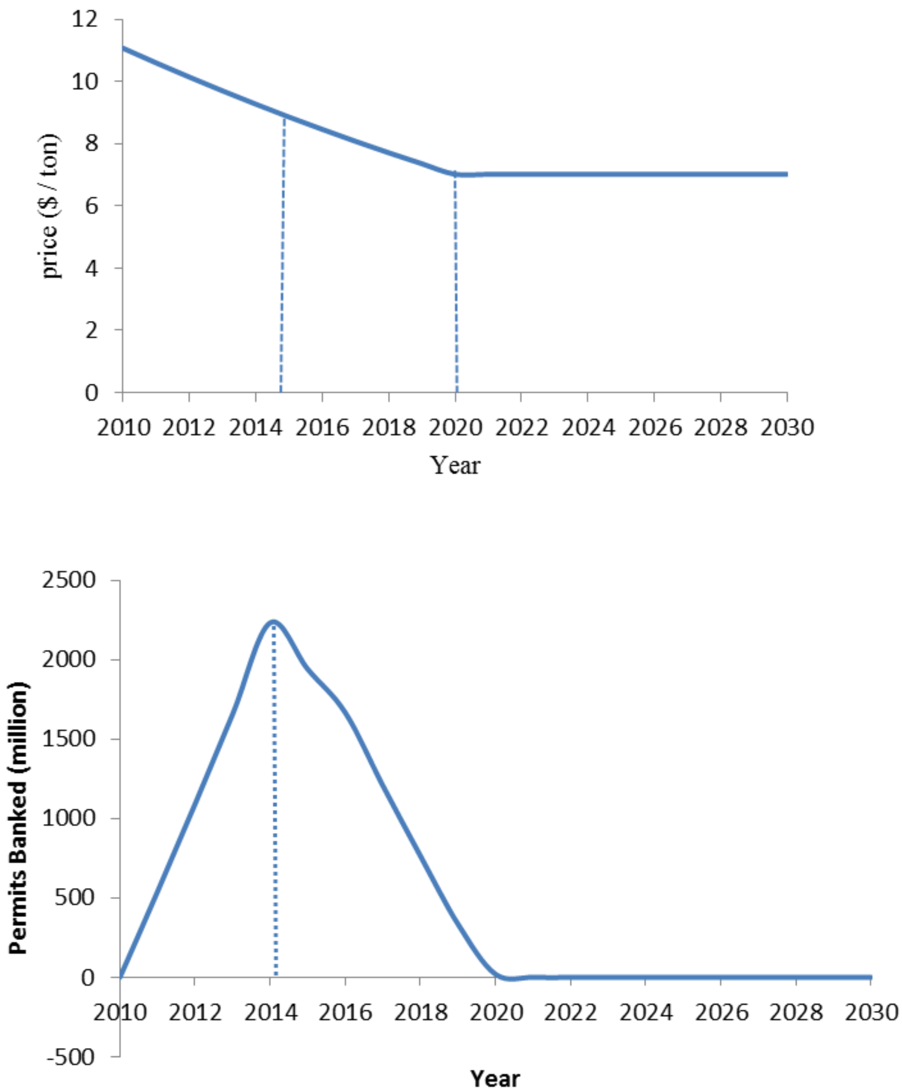

Figure 1.8. US Monopsony price and banked permits
Note: Upper panel shows the monopsony price and lower panel represents the banked permits. Second benchmark starts in year 2016

On the other hand, if Russia accepts the price equal to its own marginal cost, it will sell all the permits. In doing so, Russia incurs a cost of $40.8 billon. This cost is $35 billion less than the cost of the no-trading scenario. However, as we will see in the next section, this scenario is not the best option for Russia, who therefore may not accept the offer.

Scenario (iii) Russia with monopoly power:

In the literature several studies (Paltsev 2000; Bernard *et. al.,* 2003; Bohringer and Loschel, 2001) have estimated the monopoly power of Russia in the absence of the US. All these studies argue that as monopoly Russia has less market power due to excess supply of permits and less demand. But Russia's situation might change if US enters into the market. As a monopoly Russia expects a higher price to maximize the revenue function. As mentioned earlier, I assume that the seller (Russia) is aware of the abatement cost function of the buyer (US). The seller's objective is to maximize its revenue by bargaining a higher price. The seller assumes that the buyer will pay any price lower than its (buyer) marginal abatement cost. So, seller takes marginal abatement cost of buyer as constraint and optimizes the monopoly price. If the US has no bargaining power, it will accept the monopoly price. I assume that Russia still considers their 2020 target and will sell all the saved permits. Russia's permits will exhaust in year 2020 and thereafter it maintains the 2020 target level. In doing so, Russia will earn a revenue of $4.8 billion. This is the most beneficial option for the Russia. But, by accepting the monopoly price, US incurs a cost of $526.8 billion, which is $46.58 billion higher than its no-trading cost and $95.55 billion more than the monopsony scenario. So, instead of buying permits from monopoly, US prefers to abate emission on its own without engaging in permit trade.

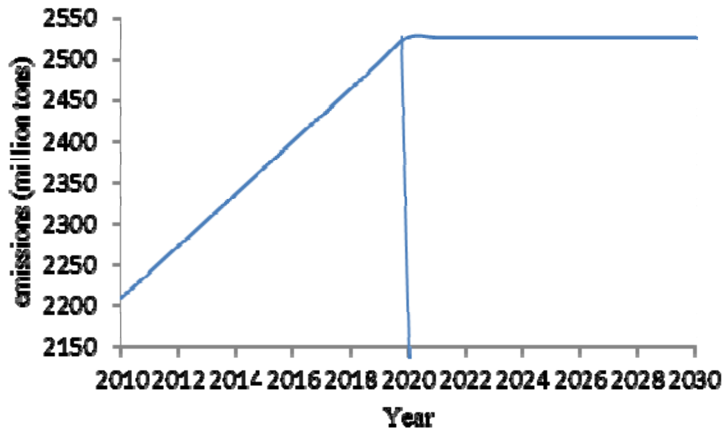

Figure 1.9. Russia emissions' path when there is cooperation
Note: Russia will follow linear growth path until it reaches 2020 target leve.

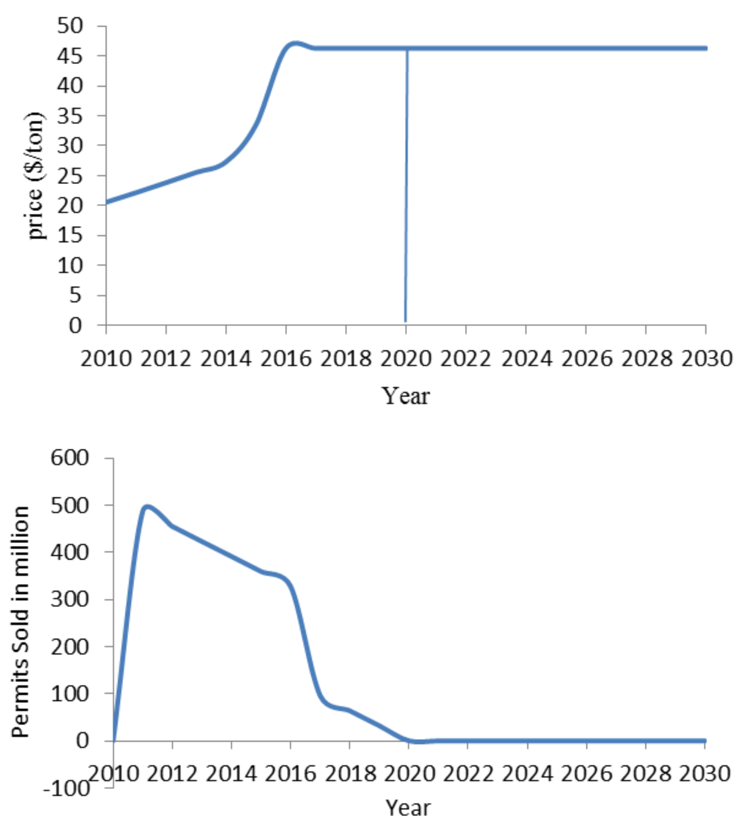

Figure 1.10. Russia as a monopoly, price and permits sold in the market
Note: Russia sell all the permits it has, no permits will be banked., Upper panel shows the monopoly price and lower panel shows the permits sold.

Scenario (iv) Cooperative trading and joint cost minimization:

In this scenario, both countries cooperate and commit to reducing the aggregate emission level. Here I assume that, only the US follows the optimum emission path whereas Russia follows its usual fixed growth emission path, i.e., reaching the level that is 25 percent below 1990 level in 2020. I assume that the US is aware of Russia's 2020 target and optimizes its emission path by buying the credits from Russia and offering a price equal to the aggregate marginal abatement cost.. The calculated marginal abatement cost or initial offer price will be $14.84; this price is higher than Russia's no-trade price or US monopsony's price. If Russia accepts this price, the US will buy all available permits from Russia. Now the US optimizes the emission path using the equation (1.73). In this scenario also I assume two benchmark levels explained in the above sections. US will start using the accumulated permits in the year 2016 and consumes until the permits exhaust in year 2021. The emission reduction path in this scenario is less steeper than that of no-trade situation (see figure 1.11). The US reaches its 1990 level benchmark in year 2021. As seen earlier, even with monopsony power US reaches its 1990 level in year 2020, but the problem is Russia will not accept the monopsony price and US ends up with no-trade situation. The total cost of abatement and trading for the US would be $448.56 billion, which is $ 31 billion less than the cost associated with the no-trade situation. For Russia, accepting the cooperative price will be beneficial compared to its no-trading situation. With the cooperative price, Russia incurs a total cost of $25.98 billion, which is $50 billion less than their no-trade scenario. The combined cost savings for the US and Russia from the cooperative trading would be $82.25 billion.

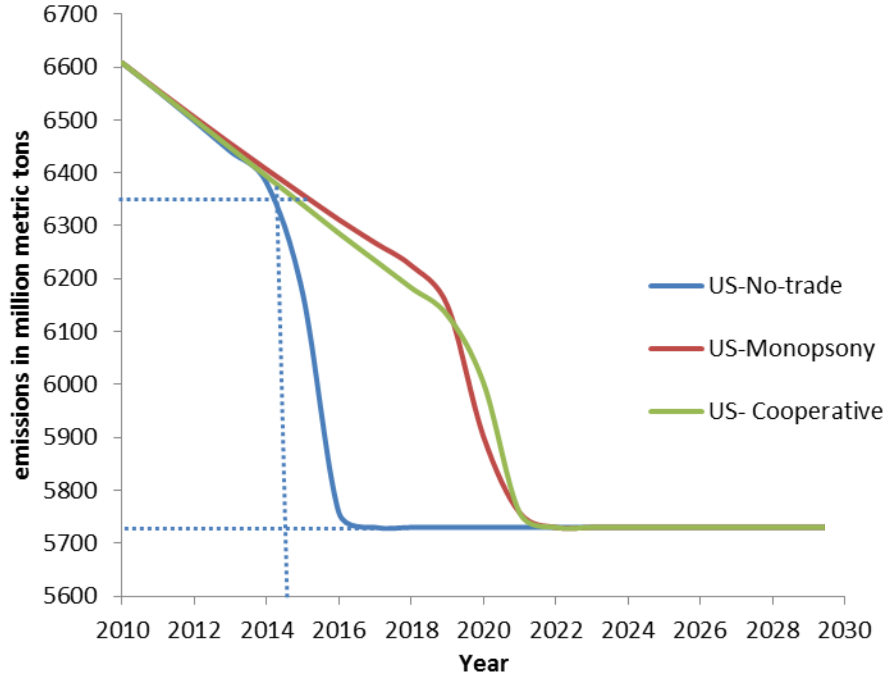

Figure 1.11. US emission reductions pattern of all three scenarios
Note: Higher benchmark level starts in 2010, lower benchmark level starts in 2015, US's target is to reach lower benchmark at a slower rate.

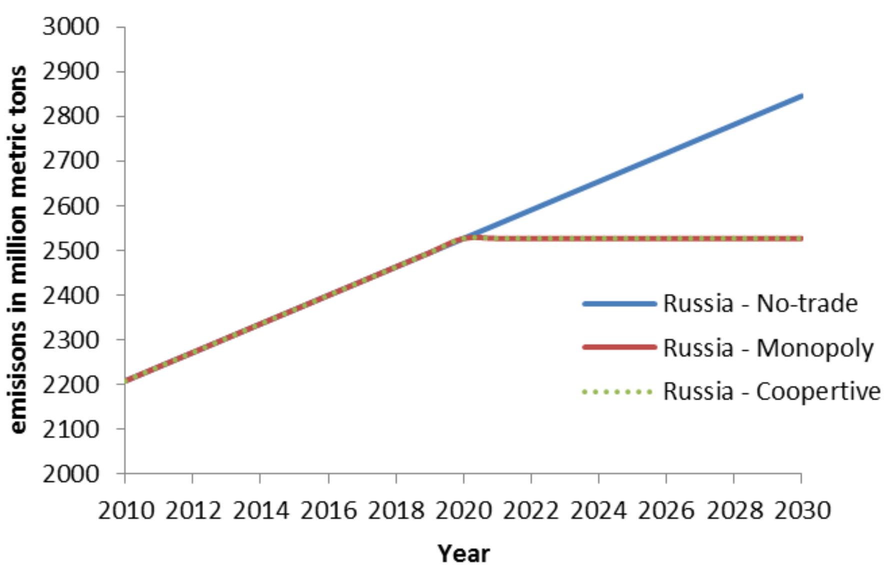

Figure 1.12. Russia emissions reductions patter of all three scenarios
Note: Russia benchmark level starts in 2020, i.e., 2527 mmts. Under no trade scenario, Russia consume all the saved permits after 2020.

1.4.3 Efficiency comparison of alternative permit trading scenarios

This sub-section analyzes all possible scenarios for the US and Russia. Table 1.6 pins down the pay-offs associated with various trading scenarios. If both countries agree to participate in the Kyoto Protocol in a cooperative way, the two parties will realize the best outcome. Reaching a cooperative agreement may not occur if either party attempts to exert its market power and demands a different price. The outcomes of the various scenarios analyzed suggest that there will be two Nash equilibria; one is the no-trade strategy, which is a default situation and the other is the cooperative strategy. Neither the Russia's monopoly nor US's monopsony power will be effective by itself on each other. The costs associated with the no-trade scenario are higher than the costs associated with the cooperative scenario. Table 1.6 provides the normalized pay-off in relation to the US's cost under the non-trade scenario.

Table 1.6. Costs associated with sequentially rational behavior by Russia and US

		Russia			
		No-Trade	Monopoly	Monopsony	Cooperative
US	No-Trade	1.00, 0.16	1.00, 0.16	1.00, 0.16	1.00, 0.16
	Monopoly	1.00, 0.16	1.16, -0.01	1.00, 0.16	1.00, 0.16
	Monopsony	1.00, 0.16	0.90, -0.01	0.90, 0.08	1.00, 0.16
	Cooperative	1.00, 0.16	1.00, 0.16	1.00, 0.16	0.93, 0.05

Initially the game is considered as a 4×4 matrix. No matter what the strategy of other player is, if either of them is not interested in permit trading, the result will be a no-trade outcome. Now the game is reduced to a 3×3 matrix. At this stage, if Russia can play as a monopoly, it will gain a revenue of 0.01 points compared to the US's no-trade cost level. In other words, from table 1.5 we can say that Russia will gain a revenue of \$4 billion (i.e., the lowest cost of all scenarios). If the US accepts the monopoly price, it will incur a higher cost (\$527 billion) than it would in the case of no-trade scenario (\$480 billion). So US will not accept the monopoly price and prefers not to participate in the trading program. Now the game is reduced to a 2× 2 matrix. Let us assume that the US can act as a monopsony and Russia accepts the US's price, which is the lowest price of all scenarios. Russia's cost will be 0.03 units more than that of cooperative trading, so Russia prefers cooperative price than monopsony price; on the contrary, the US will incur more cost in cooperative scenarion than its monospsony scenario. If US insists the monopsony price, Russia probably will not prefer monopsony price knowing that exerting its (Russia's) own market power would have fetched a much higher benefit. So at this stage Russia either prefer cooperative outcome or no-trade outcome. US observes the Russia's reaction and prefers cooperative outcome, which will be more cost-effective than its non-cooperative scenario. At this stage they agree to cooperate and jointly reduce their emissions. From cooperation, the US will gain \$32 billion while Russia will \$51 billion (table 1.5).

1.4.4 Mechanisms for reaching cooperation

Several studies have examined the transboundary pollution policies in the literature. In the absence of an external agency, the question is how to enforce a binding emission control agreement between two countries, In a seminal work on "Acid Rain Game", Maler and Zeeuw (1989) suggested a transfer payment method to achieve a full cooperation among the polluting countries. This study examined the strategies of Great Britain and other neighboring countries in dealing with the depositions of sulpher and nitrogen oxides loads. They examined the cooperative and non-cooperative outcomes related to the critical or benchmark levels. The compliance of critical emission level would result in a higher cost. To achieve lower pollution levels and cost reductions, their study showed that a full cooperation would be a favorable option vis-a-vis a non-cooperative outcome. In order to achieve a full cooperation, implementing a side payment scheme that would transfer the benefits from nations having higher net benefits to nations having lower net benefits. In this way each nation will be better off and there is a Pareto improvement.

As we observed in the earlier section, the game scenario developed in table 1.5 resembles the Maeler and Zeeuw's work. Table 1.5 illustrates two equilibria: a no-trade equilibrium and a cooperative equilibrium. In addition, I provide evidence of another equilibrium with side payments, which happens to be best outcome for both the countries. Since it is a two country problem, to achieve cooperative outcome, both countries have to agree for a joint reduction scenario as discussed in section 1.3.5. The US can lower the cost by $31 billion from cooperative trading, whereas for Russia will lower the cost by $51 billion. Thus, the combined cost savings would be $82 billion. However, if the two countries follow the US monopsony scenario, they together achieve a cost saving of $85 billion ($49 billion by the US and $36 billion by Russia), which is the highest cost savings of all scenarios. Thus from group efficiency point of you, monopsony scenario is the best scenario. That is, it meets the group rationality criterion. However, under this scenario, Russia does not meet its own individual rationality criterion in that its cost saving from cooperative monopsony is only $36 billion whereas the US's cost savings would be $49 billion from the monopsony behavior.

One way to ensure a self-enforcing cooperation (Russia having to agree to the US Monopsony situation) is to institute a side payment plan which would require the US to pay Russia so that the differences in the cost savings of the two countries are split at an agreed fraction. Under this scenario, following an egalitarion criterion, the US would have to pay a present value sum of $6,568 million to Russia such that both countries will end up enjoying a present value cost saving of $42,399 million over the life of the emission/trading program.

As indicated earlier, the literature suggests different ways to institute side payments. One option is an *ex ante* lump sum payment (Munro, 1979). Another option is to pay an annual fixed installment. The annual fixed installment program has an advantage in that if either party reneges in the middle of the game, the other country will adapt its trigger strategy by defaulting to its non-cooperative, no-trade scenario. The third option, is to pay the total cost saving differences in variable annual installments. Bhat and Huffaker (2006) show that the variable annual installment method meets both group and individual rationality criteria, in order to ensure a game that is *renegotiation proof.* The annual payment can be simply viewed as a fixed price premium over and above the Russia's annual MAC. For the above program, the estimated additional price premium is $2.675 per permit, which amounts to a present value lump sum payment of $6,568 million. Note that this is the side payment necessary to make Russia adhere to the US's monopsony behavior.

1.5 Conclusion

This chapter characterized the dynamic optimal emission control strategies of two nations when one of the nations had the ability to act as a monopoly and the other as a monopsony. In particular, under the Kyoto Protocol for greenhouse emissions, the US has the potential to become the largest buyer of permits. On the other hand, Russia has maintained its emission below it Kyoto Protocol target, and thus, has acquired a large number of tradable carbon permits. Therefore, Russia was assumed to be the largest seller of emission permits. In this study, the market interaction between the two nations has been modeled as a leader-leader game.

I have discussed four possible emission reduction scenarios: no-cooperative no-trading, US as a monopsonist, Russia as a monopolist, and cooperative agreement for trading. In each scenario, I have examined the optimal emissions in response to the available permits. The buyer will purchase the permits when the permit price is lower than his marginal abatement cost. Banking of the permits is allowed in the model, i.e., the saved permits can be banked for future use or sold in the market. I considered two levels of emission targets for the buyer. Initially, the buyer complies with the higher emission target for some time, T_0 periods. After T_0 periods, the second benchmark or lower emission cap will be introduced. When the lower emission cap is imposed, the buyer can either consume permits saved in the bank , purchase from the market, reduce his emission, or adapt some combination of all three options. Buyer's emission reductions will be faster in non-cooperative scenario than the monopsony or cooperative scenario. Since Russia is below its allowed target, in consistent with the Kyoto agreement, in the model I allowed this country to increase its emission until it reached its target.

As mentioned earlier, in the empirical section, I considered US as a monopsony and Russia as monopoly. For each scenario, I simulated the optimal emission path, stock of banked permits, permit trades, price paths, and the present value cost of emission control program. Looking at the present value costs of all scenarios, I observed two Nash equilibria. First, a non-cooperative equilibrium occurs if any one of them is either not interested in trading, or bargaining for high/low permit price. Second, the cooperative equilibrium occurs if both countries agree to reduce the emission costs jointly and agree to follow a price path that is equal to their aggregate marginal abatement costs.

The US incurs a cost of $480 billion when there is no trade, $431 billion in the monopsony scenario and $448 billion in cooperative trading scenario. Thus, US's best option would be acting as a monopsonist and bargaining for the lowest price on permit purchase. On the other hand, Russia incurs a cost of $76 billion and $26 billion under non-cooperative and cooperative scenarios, respectively. But it will have a benefit of $4 billion if it acts as a monopoly and bargains for a higher price. On the basis of these scenarios, I have observed that both countries will experience cost savings through cooperation.

Interestingly, I found that the scenario in which the US acted as a monopsonist resulted in the most Pareto efficient outcome, in terms of the combined present value costs of emission control. The practical question that arose then was how to enforce an agreement that resulted in Pareto efficient outcome. I introduced the side payment scheme into the game. In this scenario, without any side payment, the US offered a price equal to the marginal abatement cost of Russia each year, and purchased all the available permits. By buying the permits, US lowered the emission reduction costs by $49 billion from its no-trade scenario, and reached the lower emission cap in the year 2021. Whereas for Russia, the cost savings under the monopsony scenario was only $36 billion. Therefore, Russia would prefer either no-trade or cooperative trading to the US monopsony scenario. In order to institute a self-enforced, Pareto efficient binding agreement (i.e., the monopsony scenario), I proposed a transfer payment to Russia. The payment has to be sufficient enough to even out the differences in the cost saving advantage between the two countries (i.e., $49 billion for the US vs $36 billion for Russia). That is, the US would have to pay a present value sum of $6,568 million to Russia.

Following the past literature on transfer payments, there are three different options. One option is to pay an *ex ante* lump sum payment (i.e., in the beginning of the agreement). Obviously, with this option, the US would run the risk of losing the benefit of this payment if Russia changes its mind later in the game and resorts to no-trade scenario. The second and more self-enforcing agreement would be to pay a fixed annual sum throughout the life of the cooperative agreement. I also proposed a third and the most robust agreement. Such a payment program involves a variable annual payment that consists of paying a fixed price premium on every permit purchased throughout the life of the agreement. The variable annual payment program allows parties to monitor each other's emission control and payment compliance behavior in the past and continue to comply with the agreement year after year if they are satisfied with the ongoing agreement.

APPENDIX 1

Table 1.7. The calibrated model for US No-Trade scenario

Year	Emission	MAC	d(MAC)	d^2(MAC)	e-dot	b-dot	B
2010	6608	-20.54	0.03	1.37E-06			0.00
2011	6547	-22.36	0.03	1.37E-06	-60.92	60.92	60.92
2012	6484	-24.25	0.03	1.37E-06	-63.53	123.23	184.15
2013	6417	-26.22	0.03	1.37E-06	-66.26	187.02	371.17
2014	6348	-28.26	0.03	1.37E-06	-69.12	252.40	623.56
2015	6128	-34.73	0.03	1.37E-06	-72.10	-623.56	0.00
2016	5730	-46.27	0.03	1.37E-06	-81.70	0.00	0.00
2017	5730	-46.27	0.03	1.37E-06	0.00	0.00	0.00
2018	5730	-46.27	0.03	1.37E-06	0.00	0.00	0.00
2019	5730	-46.27	0.03	1.37E-06	0.00	0.00	0.00
2020	5730	-46.27	0.03	1.37E-06	0.00	0.00	0.00
2021	5730	-46.27	0.03	1.37E-06	0.00	0.00	0.00
2022	5730	-46.27	0.03	1.37E-06	0.00	0.00	0.00
2023	5730	-46.27	0.03	1.37E-06	0.00	0.00	0.00
2024	5730	-46.27	0.03	1.37E-06	0.00	0.00	0.00
2025	5730	-46.27	0.03	1.37E-06	0.00	0.00	0.00
2026	5730	-46.27	0.03	1.37E-06	0.00	0.00	0.00
2027	5730	-46.27	0.03	1.37E-06	0.00	0.00	0.00
2028	5730	-46.27	0.03	1.37E-06	0.00	0.00	0.00
2029	5730	-46.27	0.03	1.37E-06	0.00	0.00	0.00
2030	5730	-46.27	0.03	1.37E-06	0.00	0.00	0.00

Note: We assume that US adopt the Kyoto benchmark level after years of the agreement. In mean time US reduce the permit gradually and bank the saved permits for future use. MAC-marginal abatement cost, d(MAC)-first derivative of the MAC, $d^{2(}$MAC)-second derivative of the MAC; e-dot- time derivative of the emissions, b-dot-time derivative of the banked permits ; b – permits banked, emissions are in million tons.

Table 1.8. The calibrated model for Russia No-Trade scenario

Year	Emission	MAC	d(MAC)	d^2(MAC)	e-dot	b-dot	b
2010	2208	-11.07	0.02	-1.5E-05			0
2011	2240	-10.60	0.01	-1.5E-05	-81.16	318.75	318.75
2012	2272	-10.14	0.01	-1.5E-05	-83.11	286.88	605.63
2013	2304	-9.70	0.01	-1.5E-05	-85.20	255.00	860.63
2014	2336	-9.27	0.01	-1.5E-05	-87.47	223.13	1083.75
2015	2367	-8.86	0.01	-1.5E-05	-89.92	191.25	1275.00
2016	2399	-8.46	0.01	-1.5E-05	-92.57	159.38	1434.38
2017	2431	-8.08	0.01	-1.5E-05	-95.45	127.50	1561.88
2018	2463	-7.71	0.01	-1.5E-05	-98.58	95.63	1657.50
2019	2495	-7.36	0.01	-1.5E-05	-101.99	63.75	1721.25
2020	2527	-7.02	0.01	-1.5E-05	-105.73	31.88	1753.13
2021	2559	-6.69	0.01	-1.5E-05	-109.83	0.00	1753.13
2022	2591	-6.39	0.01	-1.5E-05	-114.35	-31.88	1721.25
2023	2622	-6.09	0.01	-1.5E-05	-119.34	-63.75	1657.50
2024	2654	-5.81	0.01	-1.5E-05	-124.89	-95.63	1561.88
2025	2686	-5.55	0.01	-1.5E-05	-131.08	-127.50	1434.38
2026	2718	-5.30	0.01	-1.5E-05	-138.03	-159.38	1275.00
2027	2750	-5.07	0.01	-1.5E-05	-145.87	-191.25	1083.75
2028	2782	-4.85	0.01	-1.5E-05	-154.78	-223.13	860.63
2029	2814	-4.64	0.01	-1.5E-05	-164.99	-255.00	605.63
2030	2846	-4.45	0.01	-1.5E-05	-176.78	-286.88	318.75

Note: We assume that Russia follow linear growth path in emission, in notrade scenario, after year 2020, Russia will use the saved permits in the later years. MAC-marginal abatement cost, d(MAC)-first derivative of the MAC, d^2(MAC)-second derivative of the MAC; e-dot- time derivative of the emissions, b-dot-time derivative of the banked permits ; b – permits banked, emissions are in million tons.

Table 1.9. Calibrated model for US as a monopsony

Year	Emission	MAC US	d(MAC) US	MAC Russia	d(MAC) Russia	d^2(MAC) Russia	e-dot monopsony	Permits Purchased	b-dot	b
2010	6608	-21	0.03	-11.07	0.02	-1.46439E-05				0
2011	6556	-22	0.03	-10.60	0.01	-1.46439E-05	-51.90	486.88	538.78	538.78
2012	6505	-24	0.03	-10.14	0.01	-1.46439E-05	-50.85	455.00	552.37	1091.15
2013	6455	-25	0.03	-9.70	0.01	-1.46439E-05	-49.84	423.13	564.81	1655.96
2014	6407	-27	0.03	-9.27	0.01	-1.46439E-05	-48.87	391.25	576.16	2232.12
2015	6359	-28	0.03	-8.86	0.01	-1.46439E-05	-47.94	359.38	-291.80	1940.32
2016	6312	-29	0.03	-8.46	0.01	-1.46439E-05	-47.04	327.50	-273.72	1666.60
2017	6268	-31	0.03	-8.08	0.01	-1.46439E-05	-43.70	95.63	-459.16	1207.44
2018	6225	-32	0.03	-7.71	0.01	-1.46439E-05	-42.97	63.75	-443.47	763.97
2019	6183	-33	0.03	-7.36	0.01	-1.46439E-05	-42.28	31.88	-428.63	335.34
2020	5902	-41	0.03	-7.02	0.01	-1.46439E-05	-41.63	0.00	-335.34	0.00
2021	5730	-46	0.03	-7.02	0.01	-1.46439E-05	-171.97	0.00	0.00	0.00
2022	5730	-46	0.03	-7.02	0.01	-1.46439E-05	0.00	0.00	0.00	0.00
2023	5730	-46	0.03	-7.02	0.01	-1.46439E-05	0.00	0.00	0.00	0.00
2024	5730	-46	0.03	-7.02	0.01	-1.46439E-05	0.00	0.00	0.00	0.00
2025	5730	-46	0.03	-7.02	0.01	-1.46439E-05	0.00	0.00	0.00	0.00
2026	5730	-46	0.03	-7.02	0.01	-1.46439E-05	0.00	0.00	0.00	0.00
2027	5730	-46	0.03	-7.02	0.01	-1.46439E-05	0.00	0.00	0.00	0.00
2028	5730	-46	0.03	-7.02	0.01	-1.46439E-05	0.00	0.00	0.00	0.00
2029	5730	-46	0.03	-7.02	0.01	-1.46439E-05	0.00	0.00	0.00	0.00
2030	5730	-46	0.03	-7.02	0.02	-1.46439E-05	0.00	0.00	0.00	0.00

Note: MAC-marginal abatement cost, d(MAC)-first derivative of the MAC, d^2(MAC)-second derivative of the MAC; e-dot- time derivative of the emissions, b-dot-time derivative of the banked permits ; b – permits banked, emissions are in million tons.

Table 1.10. Calibrated model for US when both agree to reduce emissions jointly

Year	Aggregate Emission	Emission	MAC	d(MAC) US	MAC Aggregate	d(MAC) Aggregate	d2(MAC) Aggregate	edot for US	Permits purchased	b-dot	b
2010	8816	6608	-20.54	0.03	-14.58	0.01	-1.42581E-06				0.00
2011	8794	6554	-22.14	0.03	-14.85	0.01	-1.42581E-06	-53.55	486.88	540.42	540.42
2012	8773	6501	-23.74	0.03	-15.11	0.01	-1.42581E-06	-53.60	455.00	556.75	1097.17
2013	8751	6447	-25.33	0.03	-15.38	0.01	-1.42581E-06	-53.65	423.13	572.96	1670.13
2014	8729	6393	-26.92	0.03	-15.65	0.01	-1.42581E-06	-53.70	391.25	589.06	2259.18
2015	8707	6340	-28.51	0.03	-15.92	0.01	-1.42581E-06	-53.76	359.38	-273.22	1985.96
2016	8685	6286	-30.10	0.03	-16.19	0.01	-1.42581E-06	-53.81	327.50	-248.56	1737.40
2017	8666	6234	-31.62	0.03	-16.44	0.01	-1.42581E-06	-51.55	95.63	-426.40	1311.01
2018	8646	6183	-33.13	0.03	-16.68	0.01	-1.42581E-06	-51.55	63.75	-402.45	908.55
2019	8626	6131	-34.64	0.03	-16.93	0.01	-1.42581E-06	-51.55	31.88	-378.75	529.80
2020	8530	6004	-38.36	0.03	-18.13	0.01	-1.42581E-06	-51.55	0.00	-529.80	0.00
2021	8257	5730	-46.27	0.03	-21.65	0.01	-1.42581E-06	0.00	0.00	0.00	0.00
2022	8257	5730	-46.27	0.03	-21.65	0.01	-1.42581E-06	0.00	0.00	0.00	0.00
2023	8257	5730	-46.27	0.03	-21.65	0.01	-1.42581E-06	0.00	0.00	0.00	0.00
2024	8257	5730	-46.27	0.03	-21.65	0.01	-1.42581E-06	0.00	0.00	0.00	0.00
2025	8257	5730	-46.27	0.03	-21.65	0.01	-1.42581E-06	0.00	0.00	0.00	0.00
2026	8257	5730	-46.27	0.03	-21.65	0.01	-1.42581E-06	0.00	0.00	0.00	0.00
2027	8257	5730	-46.27	0.03	-21.65	0.01	-1.42581E-06	0.00	0.00	0.00	0.00
2028	8257	5730	-46.27	0.03	-21.65	0.01	-1.42581E-06	0.00	0.00	0.00	0.00
2029	8257	5730	-46.27	0.03	-21.65	0.01	-1.42581E-06	0.00	0.00	0.00	0.00
2030	8257	5730	-46.27	0.03	-21.65	0.01	-1.42581E-06	0.00	0.00	0.00	0.00

Note: MAC-marginal abatement cost, d(MAC)-first derivative of the MAC, d^{2}(MAC)-second derivative of the MAC; e-dot- time derivative of the emissions, b-dot-time derivative of the banked permits ; b – permits banked, emissions are in million tons.

Table 1.11. US in response to Russia's monopoly price

Year	Emission	MAC-US	d(MAC) US	d2(MAC) US	e-dot monopoly	Permits purchased	b-dot	b
2010	6608	-20.54	0.03	1.37E-06				0
2011	6538	-22.64	0.03	1.37E-06	-70.22	486.88	557.09	557.09
2012	6466	-24.76	0.03	1.37E-06	-71.47	455.00	591.12	1148.21
2013	6394	-26.92	0.03	1.37E-06	-72.78	423.13	626.11	1774.32
2014	6319	-29.11	0.03	1.37E-06	-74.13	391.25	662.10	2436.42
2015	6244	-31.34	0.03	1.37E-06	-75.52	359.38	-179.14	2257.28
2016	6167	-33.60	0.03	1.37E-06	-76.98	327.50	-132.25	2125.02
2017	6095	-35.69	0.03	1.37E-06	-71.72	95.63	-291.09	1833.94
2018	6022	-37.82	0.03	1.37E-06	-73.04	63.75	-247.00	1586.93
2019	5948	-39.99	0.03	1.37E-06	-74.42	31.88	-201.99	1384.95
2020	5872	-42.18	0.03	1.37E-06	-75.85	0.00	-156.00	1228.95
2021	5793	-44.44	0.03	1.37E-06	-78.40	0.00	-76.04	1152.91
2022	5712	-46.77	0.03	1.37E-06	-81.05	0.00	5.77	1158.67
2023	5629	-49.17	0.03	1.37E-06	-83.79	0.00	89.50	1248.18
2024	5542	-51.64	0.03	1.37E-06	-86.65	0.00	175.26	1423.44
2025	5745	-45.84	0.03	1.37E-06	-89.62	0.00	-29.50	1393.93
2026	5745	-45.84	0.03	1.37E-06	-82.69	0.00	-29.21	1364.72
2027	5745	-45.84	0.03	1.37E-06	-82.69	0.00	-28.92	1335.80
2028	5745	-45.84	0.03	1.37E-06	-82.69	0.00	-28.63	1307.18
2029	5745	-45.84	0.03	1.37E-06	-82.69	0.00	-28.34	1278.83
2030	5745	-45.84	0.03	1.37E-06	-82.69	0.00	-28.34	1250.78

Note: MAC-marginal abatement cost, d(MAC)-first derivative of the MAC, d^{2}(MAC)-second derivative of the MAC; e-dot- time derivative of the emissions, b-dot-time derivative of the banked permits ; b – permits banked, emission are in million tons

Table 1.12. Calibrated model for Russia as a Monopoly

Year	Emission	MAC Russia	d(MAC) Russia	MAC US	d(MAC) US	d^2(MAC) US	e-dot monopoly	bdot	b
2010	2208	-11.07	0.02	-20.54	0.03	1.37E-06			0
2011	2240	-10.60	0.01	-22.15	0.03	1.37E-06	-81.16	318.75	518.75
2012	2272	-10.14	0.01	-23.82	0.03	1.37E-06	-83.11	286.88	1005.63
2013	2304	-9.70	0.01	-25.53	0.03	1.37E-06	-85.20	255.00	1460.63
2014	2336	-9.27	0.01	-27.29	0.03	1.37E-06	-87.47	223.13	1883.75
2015	2367	-8.86	0.01	**-33.46**	0.03	1.37E-06	-89.92	191.25	2275.00
2016	2399	-8.46	0.01	**-33.60**	0.03	1.37E-06	-92.57	159.38	2434.38
2017	2431	-8.08	0.01	**-35.69**	0.03	1.37E-06	-95.45	127.50	2561.88
2018	2463	-7.71	0.01	**-37.82**	0.03	1.37E-06	-98.58	95.63	2657.50
2019	2495	-7.36	0.01	**-39.99**	0.03	1.37E-06	-101.99	63.75	2721.25
2020	2527	-7.02	0.01	-42.18	0.03	1.37E-06	-105.73	31.88	2753.13
2021	2527	-6.69	0.01	-44.44	0.03	1.37E-06	-109.83	0.00	2753.13
2022	2527	-6.39	0.01	-46.27	0.03	1.37E-06	-114.35	0.00	2753.13
2023	2527	-6.09	0.01	-46.27	0.03	1.37E-06	-119.34	0.00	2753.13
2024	2527	-5.81	0.01	-46.27	0.03	1.37E-06	-124.89	0.00	2753.13
2025	2527	-5.55	0.01	-46.27	0.03	1.37E-06	-131.08	0.00	2753.13
2026	2527	-5.30	0.01	-46.27	0.03	1.37E-06	-138.03	0.00	2753.13
2027	2527	-5.07	0.01	-46.27	0.03	1.37E-06	-145.87	0.00	2753.13
2028	2527	-4.85	0.01	-46.27	0.03	1.37E-06	-154.78	0.00	2753.13
2029	2527	-4.64	0.01	-46.27	0.03	1.37E-06	-164.99	0.00	2753.13
2030	2527	-4.45	0.01	-46.27	0.03	1.37E-06	-176.78	0.00	2753.13

Note: MAC-marginal abatement cost, d(MAC)-first derivative of the MAC, $d^{2(}$MAC)-second derivative of the MAC; e-dot- time derivative of the emissions, b-dot-time derivative of the banked permits ; b – permits banked, emission are in million tons.

Table 1.13. US's abatement and total cost under No-Trade Scenario

Year	Emission	Banked permits	Abatement Cost	Total Cost	Present Value
2010	6608	0		0	480,224
2011	6554	54	8136	8029	
2012	6498	163	9419	9210	
2013	6441	329	10840	10525	
2014	6381	553	12412	11978	
2015	6172	0	18776	17006	
2016	5730	0	36387	32311	
2017	5730	0	36387	31677	
2018	5730	0	36387	31056	
2019	5730	0	36387	30447	
2020	5730	0	36387	29850	
2021	5730	0	36387	29265	
2022	5730	0	36387	28691	
2023	5730	0	36387	28129	
2024	5730	0	36387	27577	
2025	5730	0	36387	27036	
2026	5730	0	36387	26506	
2027	5730	0	36387	25987	
2028	5730	0	36387	25477	
2029	5730	0	36387	24977	
2030	5730	0	36387	24488	

Note: emissions are in million tons, permits in dollars, cost in million dollars

Table 1.14. US's abatement and total cost under monopsony scenario

Year	emissions	Abatement Cost	price of permit	permits purchased	banked permits	Total Cost	PV
2010	6608	0	11.07		0	0	431,257
2011	6556	8088	10.60	487	539	13517	
2012	6505	9250	10.14	455	1091	14375	
2013	6455	10464	9.70	423	1656	15288	
2014	6407	11725	9.27	391	2232	16246	
2015	6359	13031	8.86	359	1940	16444	
2016	6312	14379	8.46	328	1667	16709	
2017	6268	15690	8.08	96	1207	15383	
2018	6225	17033	7.71	64	764	15609	
2019	6183	18408	7.36	32	335	15880	
2020	5902	28857	7.02	0	0	23672	
2021	5730	36387	6.69	0	0	29265	
2022	5730	36387	6.39	0	0	28691	
2023	5730	36387	6.09	0	0	28129	
2024	5730	36387	5.81	0	0	27577	
2025	5730	36387	5.55	0	0	27036	
2026	5730	36387	5.30	0	0	26506	
2027	5730	36387	5.07	0	0	25987	
2028	5730	36387	4.85	0	0	25477	
2029	5730	36387	4.64	0	0	24977	
2030	5730	36387	4.45	0	0	24488	

Note: emissions are in million tons, permits in dollars, cost in million dollars

Table 1.15. US's abatement and total cost under the cooperative scenario

Year	Emissions	Abatement Cost	Price of permit	Permits purchased	Banked permits	Total Cost	PV
2010	6608		14.57	0	0	0	448,557
2011	6554	8125	14.85	487	540	15582	
2012	6501	9354	15.11	455	1097	16655	
2013	6447	10671	15.38	423	1670	17762	
2014	6393	12074	15.65	391	2259	18898	
2015	6340	13564	15.92	359	1986	19266	
2016	6286	15141	16.19	328	1737	19697	
2017	6234	16731	16.44	96	1311	17076	
2018	6183	18400	16.68	64	909	17388	
2019	6131	20147	16.93	32	530	17753	
2020	6004	24803	18.13	0	0	20347	
2021	5730	36387	21.65	0	0	29265	
2022	5730	36387	21.65	0	0	28691	
2023	5730	36387	21.65	0	0	28129	
2024	5730	36387	21.65	0	0	27577	
2025	5730	36387	21.65	0	0	27036	
2026	5730	36387	21.65	0	0	26506	
2027	5730	36387	21.65	0	0	25987	
2028	5730	36387	21.65	0	0	25477	
2029	5730	36387	21.65	0	0	24977	
2030	5730	36387	21.65	0	0	24488	

Note: emissions are in million tons, permits in dollars, cost in million dollars

Table 1.16. US's abatement and total cost in response to Russia's monopoly price

Year	Emission	Abatement Cost	Permit Price	Permits purchased	Banked permits	Total Cost	Present Value
2010	6608					0	526,805
2011	6538	8498	22.64	487	0	19136	
2012	6466	10192	24.76	455	557	21161	
2013	6394	12073	26.92	423	1148	23192	
2014	6319	14149	29.11	391	1774	25234	
2015	6244	16432	31.34	359	2436	27290	
2016	6167	18931	33.60	328	2257	28585	
2017	6095	21416	35.69	96	2125	23465	
2018	6022	24101	37.82	64	1834	24193	
2019	5948	26997	39.99	32	1587	24984	
2020	5872	30113	42.18	0	1385	25839	
2021	5793	33508	44.44	0	1229	27938	
2022	5712	37205	46.77	0	1153	30245	
2023	5629	41224	49.17	0	1159	32763	
2024	5542	45592	51.64	0	1248	35499	
2025	5745	35697	45.84	0	1423	27581	
2026	5745	35697	45.84	0	1394	27018	
2027	5745	35697	45.84	0	1365	26468	
2028	5745	35697	45.84	0	1336	25929	
2029	5745	35697	45.84	0	1307	25401	
2030	5745	35697	45.84	0	1279	24883	

Note: emissions are in million tons, permits in dollars, cost in million dollars

Table 1.17. Russia's abatement and total cost under no-trade scenario

Year	Emissions	Abatement Cost	Banked Permits	Total Cost	Present Value
2010	2208	0	0.00	0	76,578
2011	2240	5749	318.75	5948	
2012	2272	5418	605.63	5790	
2013	2304	5102	860.63	5619	
2014	2336	4800	1083.75	5435	
2015	2367	4511	1275.00	5240	
2016	2399	4235	1434.38	5034	
2017	2431	3971	1561.88	4817	
2018	2463	3720	1657.50	4589	
2019	2495	3480	1721.25	4352	
2020	2527	3250	1753.13	4105	
2021	2559	3032	1753.13	3848	
2022	2591	2823	1721.25	3583	
2023	2622	2625	1657.50	3310	
2024	2654	2435	1561.88	3029	
2025	2686	2254	1434.38	2740	
2026	2718	2081	1275.00	2445	
2027	2750	1916	1083.75	2142	
2028	2782	1758	860.63	1833	
2029	2814	1607	605.63	1519	
2030	2846	1462	318.75	1198	

Note: emissions are in million tons, permits in dollars, cost in million dollars, I excluded hot air from no trade scenario.

Table 1.18. Russia's abatement and total cost under monopoly scenario

Year	Emissions	Abatement Cost	Price of Permit	Permits Sold	Banked Permits	Total Cost	Present Value
2010	2208	0	20.54	0	0	0	-4,864
2011	2240	5749	22.64	487	0	-5169	
2012	2272	5418	24.76	455	0	-5622	
2013	2304	5102	26.92	423	0	-5926	
2014	2336	4800	29.11	391	0	-6089	
2015	2367	4511	31.34	359	0	-6115	
2016	2399	4235	33.60	328	0	-6010	
2017	2431	3971	35.69	96	0	486	
2018	2463	3720	37.82	64	0	1117	
2019	2495	3480	39.99	32	0	1845	
2020	2527	3250	42.18	0	0	2666	
2021	2527	3250	44.44	0	0	2614	
2022	2527	3250	46.77	0	0	2563	
2023	2527	3250	49.17	0	0	2513	
2024	2527	3250	51.64	0	0	2463	
2025	2527	3250	45.84	0	0	2415	
2026	2527	3250	45.84	0	0	2368	
2027	2527	3250	45.84	0	0	2321	
2028	2527	3250	45.84	0	0	2276	
2029	2527	3250	45.84	0	0	2231	
2030	2527	3250	45.84	0	0	2187	

Note: emissions are in million tons, permits in dollars, cost in million dollars, negative cost can be c consider as benefit, there won't be any permits when Russia able to sell all the permits.

Table 1.19. Russia's abetment and total cost under cooperative scenario

Year	Emissions	Abatement Cost	Price of Permit	permits sold	Banked Permits	Total Cost	PV
2010	2208	0	14.58	0	0	0	25,988.05
2011	2240	5749	14.85	487	0	-1450	
2012	2272	5418	15.11	455	0	-1401	
2013	2304	5102	15.38	423	0	-1325	
2014	2336	4800	15.65	391	0	-1223	
2015	2367	4511	15.92	359	0	-1097	
2016	2399	4235	16.19	328	0	-949	
2017	2431	3971	16.44	96	0	2089	
2018	2463	3720	16.68	64	0	2267	
2019	2495	3480	16.93	32	0	2460	
2020	2527	3250	18.13	0	0	2666	
2021	2527	3250	21.65	0	0	2614	
2022	2527	3250	21.65	0	0	2563	
2023	2527	3250	21.65	0	0	2513	
2024	2527	3250	21.65	0	0	2463	
2025	2527	3250	21.65	0	0	2415	
2026	2527	3250	21.65	0	0	2368	
2027	2527	3250	21.65	0	0	2321	
2028	2527	3250	21.65	0	0	2276	
2029	2527	3250	21.65	0	0	2231	
2030	2527	3250	21.65	0	0	2187	

Note: emissions are in million tons, permits in dollars, cost in million dollars, negative cost can be consider as benefit, there won't be any permits when Russia able to sell all the permits.

Table 1.20. Russia's abatement and total cost in response to the monopsony price

Year	Emission	Abatement Cost	Price of Permit	Permits Sold	Banked Permits	Total Cost	Present Value
2010	2208		11.07				40,747.22
2011	2240	5749	10.60	487	0	577	
2012	2272	5418	10.14	455	0	772	
2013	2304	5102	9.70	423	0	940	
2014	2336	4800	9.27	391	0	1083	
2015	2367	4511	8.86	359	0	1202	
2016	2399	4235	8.46	328	0	1300	
2017	2431	3971	8.08	96	0	2785	
2018	2463	3720	7.71	64	0	2755	
2019	2495	3480	7.36	32	0	2715	
2020	2527	3250	7.02	0	0	2666	
2021	2527	3250	6.69	0	0	2614	
2022	2527	3250	6.39	0	0	2563	
2023	2527	3250	6.09	0	0	2513	
2024	2527	3250	5.81	0	0	2463	
2025	2527	3250	5.55	0	0	2415	
2026	2527	3250	5.30	0	0	2368	
2027	2527	3250	5.07	0	0	2321	
2028	2527	3250	4.85	0	0	2276	
2029	2527	3250	4.64	0	0	2231	
2030	2527	3250	4.45	0	0	2187	

Note: emissions are in million tons, permits in dollars, cost in million dollars, negative cost can be consider as benefit, there won't be any permits when Russia able to sell all the permits.

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CHAPTER 2
PRICE DYNAMICS OF CARBON EMISSION ALLOWANCES AT THE CHICAGO CLIMATE EXCHANGE

2.1 Introduction

For the past twenty years climate change and global warming have become major environmental concerns. Scientists and policy makers have arrived at a consensus that greenhouse gases (GHG) including hydrocarbons, nitrogen oxides, and carbon dioxide negatively impact earth's atmosphere (Madden and Ramanathan, 1980; Meehl and Washington, 1996). Since these effects are global, climate experts have suggested a global response which should be mediated by international agreements. At the Kyoto global conference held in 1997, a group of 41 industrial and economies-in-transition nations (called Annex I countries) agreed to reduce their carbon emission level by 5.2 percent from the 1990 level for the period 2005-2012 (UNFCCC, 2010). The United States (US), then the largest emitter of GHGs, did not sign the agreement and make any formal commitment to lower GHG emission, much to the dissatisfaction of the international community. However, irrespective of the US federal government involvement, several voluntary and mandatory cap-and-trading emissions markets have emerged regionally and nationally.

In 2003, with the help of Joyce Foundation and Northwestern University, the Chicago Climate Exchange (CCX), a voluntary emissions trading market started. The CCX market initially began its trading operations with 13 companies and expanded its operation to more than 450 companies by the time it closed its operation in 2010. The participation in the market was voluntary but the participants had to commit to a legally binding requirement of meeting annual GHG emissions reduction targets. Those who reduce below the targets have surplus allowances to sell or bank; those who emit above the targets comply by purchasing CCX Carbon Financial Instruments. During the operation of this market a total of 700 million tons of carbon credits were transacted. As a result of political and administrative issues, the CCX market was shut-down in December 2010.

In 2005, ten northeastern states (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont) agreed to implement the first mandatory emissions trading market, the Regional Greenhouse Gas Initiative (RGGI) in the United States. The program RGGI has started its operation in September 2008. RGGI market set a cap on carbon dioxide (CO_2) emissions of certain electricity producers in the region. The RGGI is an auction based market and so far more than 250 million carbon allowances were traded in twelve auctions (RGGI, 2012)[16].

In 2007, two more state-controlled emission trading programs emerged. The Western Climate Initiative (WCI), seven western states (Arizona, California, New Mexico, Montana, Oregon, Utah, and Washington) formed a group and established a regional greenhouse gas emissions trading system, and states Alaska, Colorado, Idaho, Kansas, Nevada, and Wyoming have joined as observers. The first phase of WCI is scheduled to begin in 2012. The other program, the Midwestern Greenhouse Gas Reduction Accord (MGGRA) was formed by six states, Illinois, Iowa, Kansas, Michigan, Minnesota, and Wisconsin, and states, Indiana, Ohio, and South Dakota are observers. The operation of the MGGRA program will begin in 2012 as well. With these new trading

[16] http://www.rggi.org/market/co2_auctions/results

programs, the United States federal government, recently have been taken some crucial steps. The United States Environmental Protection Agency (EPA) is expected to act for the first time to regulate carbon dioxide and other GHGs. The 111th Congress has introduced several market-based climate change bills, the Liberman-Warner bill and The Waxman-Markey Climate Change bill are the popular ones.

The Lieberman-Warner bill or Climate Security Act of 2007 (S.2191, 2007) was introduced to create a national cap-and-trade policy for greenhouse gas emissions and allocate right-to-emit credits to the polluters, restricting their annual amount of greenhouse gas emissions. The bill proposed a reduction of emissions 70 percent below 2005 levels by 2050. The Waxman–Markey Climate Change bill, known as American Clean Energy and Security Act of 2009 (H.R. 2454) aims to implement a federal cap and trade system for GHG by reducing the emissions by three percent below 2005 levels in 2012, 20 percent below 2005 levels in 2020, 42 percent below 2005 levels in 2030, and 83 percent below 2005 levels in 2050 (Kim and Koo, 2010). However, both bills did not make any progress as a result of the recent political and economic uncertainties. But investors expect that the United States will come up with a cap-and-trade policy in the near future.

Given the importance of these newly emerging markets (CCX, RGGI, WCI and MGGRA), it is necessary to examine the price behavior and volatility of the returns. Such an examination is especially important to the risk investors and members who are involved in the market to buy or sell emission allowances and their derivatives (Benz and Trück, 2009). In particulary, in this essay I examine the price dynamics of CCX and discuss various reasons for the slowdown of the market, CCX is the first voluntary emission market and stands to serve as a real test run for other emerging and future voluntary and mandatory carbon markets.

Examining the price behavior and volatility of returns of tradable emission allowances is not new to the literature. In the United States, most studies have focused on electricity demand and emission allowances under the *Acid Rain Program* of US Environmental Protection Agency (Benz and Trück, 2009).

Studies analyzing the US emission market are limited. Sabbaghi and Sabbaghi (2011) explored a relationship between price of CCX emission credits and trade volume and suggested that generalized autoregressive conditional heteroskedasticity[17] (GARCH) effects were highly persistent and statistically significant during the study period. Kim and Koo (2010) analyzed the dynamics of US carbon allowance trading using the autoregressive distributed lag (ARDL) approach. They found that the price of coal was the major driving force to determine the spot prices and trading volume in the US emission market. They also found that prices of crude oil and natural gas had a significant effect in the short run on the spot prices but had little effect in the long run. Other than these two studies, I haven't come across any study which examines the price dynamics of the Chicago Climate Exchange. Whereas for EU ETS, quite a few studies have investigated the spot price behavior (Benz and Trück, 2009; Daskalakis and Markellos, 2009; Paolella and Taschini, 2008; Seifertet *et al.*, 2008; Uhrig-Homburg and Wagner, 2006; 2007).

[17] GARCH model is widely used in the areas of risk, portifilo managements, asset pricing, option pricing and exchnage rate volatility. This model helps to model the excess kutosis and volatility of the returns.

Like other financial asset markets, the EU ETS, a new class of asset markets has experienced price fluctuations in response to the market uncertainties. Daskalakis *et al.* (2009) found a significant implication for the derivative pricing from the prohibition of banking of emission allowances in EU ETS. They also discovered that market participants adopted standard no-arbitrage pricing using spot and futures prices. Paolella and Taschini (2008) provided an econometric analysis for unconditional tail behavior and the heteroskedastic dynamics of returns of EU ETS and US's SO_2 allowances. Their study proposed the use of stable-GARCH models. Uhrig-Homburg and Wagner (2006) investigated the relationship between spot and futures markets in the European Union Emissions Trading System (EU ETS). The EU ETS findings demonstrated that EU allowances futures maturing within a trading period were suitable instruments for hedging related risks.

Seifert *et al.* (2008) developed a stochastic equilibrium model and analyzed the resulting spot price dynamics of the EU ETS. They found that seasonal patterns have no effect on prices. The process should possess the martingale property and an adequate price process should exhibit a time- and price-dependent volatility structure. Benz and Trück (2009) evaluated price volatility and density forecasts allowing for heteroskedasticity using ARCH, GARCH and regime-switching models in markets; their findings revealed that EU ETS had different volatility behavior in different phases. They also observed asymmetry, excess kurtosis and heavy tails in the EU ETS emission allowances.

The primary goal of my paper is to model the extreme tail behavior of CCX returns, recognizing that the traditional mean-variance analysis is not adequate. I also recognize that there was a possible switch in the underlying stability condition of the fluctuations in the market return overtime. The paper then addresses several key questions of interest to risk managers, CCX investors, and policy makers. Was the switch in the underlying stability condition or the risk regime as a result of unstable economic conditions and/or shift in the political regime? As the CCX market ultimately came to a full halt in 2010, it is important to measure the degree of volatility in market returns during the final months of the market crash. Following Benz and Trück (2009), I observe negative skewness and excess kurtosis in the CCX returns, and then relate these market anomalies to changing international and national climate change debates and regulations. While identifying the above relationships I also ask to what extent the CCX market was influenced by other emerging carbon market in the US.

The paper is organized as follows. Section 2.2 explains the setup of new asset class market, Chicago Climate Exchange; in this section I provide the participating members information and their roles in the market. Section 2.3 explains the methodology used in this paper. I discuss two different methodologies, GARCH and Markov Regime Switching (MRS) models used to estimate the volatility in returns of the CCX spot price trading. Section 2.4 provides the data and empirical results estimated using the above methodologies. Section 2.5 suggest different mechanisms for the emerging markets to resolve the operational and policy related to issues. Finally, section 2.6 provides the conclusion of the paper.

2.2 The functioning of the Chicago Climate Exchange

The Chicago Climate Exchange (CCX) was the world's first voluntary and legally binding greenhouse gas reduction trading system. The trading market operated from December 2003 to December 2010. During this period the CCX was committed to reducing Greenhouse Gases (GHGs) in two phases. During Phase I (2003 – 2006), as per the regulation of the CCX market, the members were bound to reduce four percent below the average of their 1998-2001 emissions level. During Phase II (beginning in 2007), all the members who participated were supposed to reduce six percent below their 2000 emission level.

The baseline emissions were given to the members at the time of signing the contract with the CCX. The exchange was regulated by the National Association of Security Dealers (NASD). Based on the emission levels, the members can either buy or sell the permits in a legally binding trading platform, for transparency, all the transactions are carefully verified and monitored by an independent third party (Schnapf LLC, 2011)[18].

The exchange had more than 450 members when it was closed. As mentioned in the CCX webpage, this exchange was categorized into four membership categories. *Members*, who emit or generate GHGs through their activities, such as power plants, cement, and steel industries. When members sign the contract with CCX, they make a legally binding commitment to reduce the emissions and allow CCX authorized verifier to verify their annual emissions. *Registry Participant Members* are entities with direct GHG

[18]http://www.environmental-law.net/wp-content/uploads/2011/05/pub-4-VoluntaryGHGEmissionPrivate-SectorTradingMarkets.pdf

emissions that establish a CCX Registry account of their emissions and undergo data verification by a third party verifier. *Associate Members* are office-based businesses or institutions with negligible direct GHG emissions. *Offset Providers* are the owners of title to qualifying offset projects that sequester, destroy or reduce GHG emissions. Offset Providers register and sell offsets directly on the CCX.

The participant members belonged to different groups. About 25 percent of members were from the United States power utilities, 17 percent part of the Dow Jones Industrials, and 11 percent Fortune 100 companies. Multi-national corporations like Ford, DuPont, and Motorola, cities such as Oakland and Chicago, educational institutions such as University of California, San Diego, Tufts University, Michigan State University and University of Minnesota were members as well. Figure 1 presents the distribution of members across the United States. It is evident from the figure that more than 60 percent of the total members were located in the north-east region[19]. This had an important implication for the CCX market, which I will return to later in the paper.

[19] CCX members list obtained from www.chicagoclimatex.com

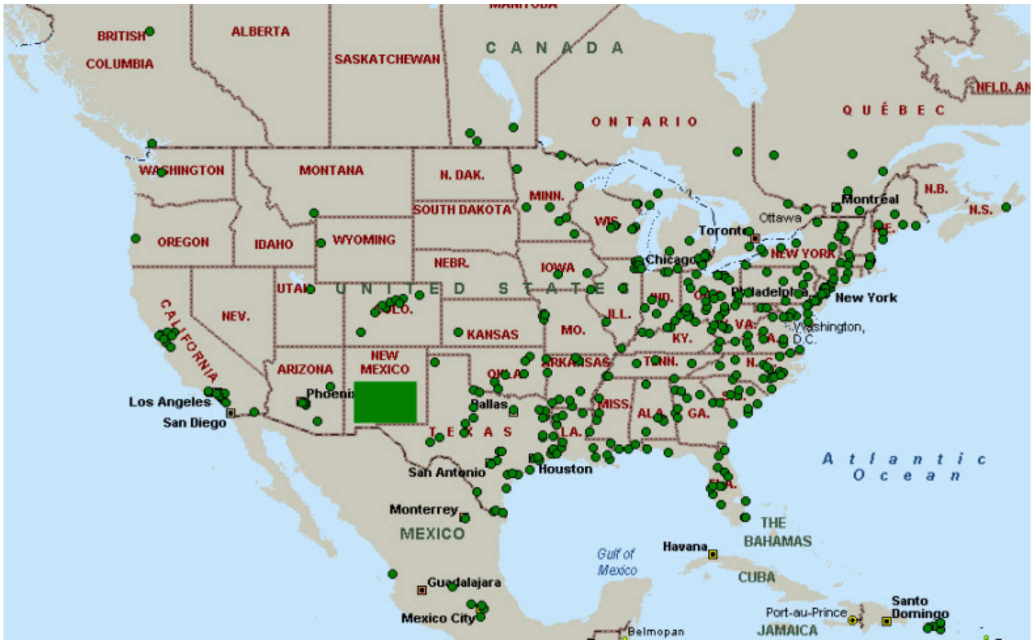

Figure 2.1. Participated Members - Chicago Climate Exchange

(Source: Chicago Climate Exchange, www.chicagoclimatex.com)

The members whose emissions do not meet annual emission reduction targets must use banked allowances from previous years or purchase carbon allowance which is called as Carbon Financial Instruments (CFI). Each CFI credit represents 100 metric tons of equivalents. Each participant member gets reduction target in the beginning of their contract and monitored continuously. The member has to report the yearly emissions to the Financial Industry Regulatory Authority (FINRA), which provides independent regulatory oversight to the CCX.

The CFI contract consists of an exchange allowance and an exchange offset. Exchange allowances are issued to members on the basis of their emission levels. The members who are beyond their reduction level can buy credits from other members who have surplus allowances or buy from offset providers (CCX, 2005). In 2007, with the starting of the Phase II program, CCX allowed several offset providers from agricultural methane emission reduction projects, landfill methane emission reduction projects, coal mine methane emission reduction projects, agricultural and rangeland soil carbon reduction projects, forestry carbon reduction projects, and offsets from renewable energy. These providers had to be approved, verified and reviewed by the FINRA before they were available for trading (Kim and Koo, 2010).

An offset provider is one, who has an offset project involving more than 10,000 metric tons of carbon dioxide (CO_2) per year can sell offsets on its own behalf, if offset provider has project involving less than 10,000 metric tons of carbon dioxide can sell through an offset aggregator. An offset aggregator is one, who represents for multiple offset generating projects. Smaller offset projects may be registered through an offset aggregator (CCX, 2005).

Unlike other trading markets, CCX trading is not conducted through brokers. Instead, the transactions are made through electronic trading platform, which is an online trading floor linked with the CCX registry. The online market gives live information of quotes posted by members.

There are three transaction methods: a traditional exchange-cleared offer and bid system, an electronic exchange for agreements between the members of CCX and per-negotiated cash transactions (Schnapf LLC, 2011). Exchange-cleared transactions are completed on the trade day while the bilateral agreements are settled according to the requirements of the participating parties. All trade settlements are made in U.S. dollar amounts[20].

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[20] http://science.howstuffworks.com/, www.chicagoclimatex.com/

2.3 Modeling the volatility of CCX returns

The market prices of carbon are dependent on a number of economic, environmental and regulatory factors. Burtraw and Jo (2009) grouped price determinants of emission credits into two categories: (i) regulatory determinants and (ii) market determinants. Regulatory determinants refer to the factors such as market caps, compliance mechanism, third party verification, voluntary versus mandatory participation, etc. These factors are known to shape the carbon market mostly in the short term and are the better predictors of extreme events in the short-term markets.

On the other hand, market determinants relate to the alternative supply of allowances, and emission abatement technology and costs, which have impact on the carbon prices in the long term. As noted earlier, the focus of this paper is not to model the cause and effect of carbon price dynamics, but rather model the price volatility of the CCX market during its short existence. The approach I take in this study is first to model the temporal aspects of extreme variations and then to relate that variation to known historical changes in regulatory and market conditions. Such an approach has been found simple and extremely useful for investors as well as policy makers. I choose the models of GARCH and regime-switching for CCX returns. First I estimate the volatility using GARCH (1,1), and then observe that CCX spot prices have two phases and that both have different volatility structure in returns. So, later I attempt the regime-switching model to estimate separate phases with different underlying stochastic processes.

2.3.1 GARCH Modeling

Autoregressive Conditional Heteroskedasticity (ARCH) and Generalized Autoregressive Conditional Heteroskedasticity (GARCH) models are widely used in estimating volatility of the financial return. Engle (1982) introduced the original form of ARCH and Bollerslev (1986) extended a generalized version of ARCH process. The relevance and underlying assumptions of these models for this paper are that the market returns of carbon go through different periods of normal price fluctuations interspersed by volatile drops or spikes that are heteroskedastic in nature. Following Benz and Truck (2009), and Daskalakis *et al.* (2009), I begin by estimating log-returns with first order autoregressive conditional mean, i.e., a GARCH (*p,q*) conditional variance specification, and normally distributed innovations[21]. Formally,

$$y_t = c_0 + c_1 y_{t-1} + \varepsilon_t \tag{2.1}$$

Where equation (2.1) represents a first order auto regressive process and y_t denotes a random variable drawn from a conditional density function and ε_t is white noise with a mean zero and variance σ_t^2. Now the GARCH (*p,q*) model for the time series ε_t can be expressed as

$$\varepsilon_t = \sigma_t z_t \tag{2.2}$$

$$\sigma_t^2 = a_0 + \sum_{i=0}^{p} a_i \varepsilon_{t-i}^2 + \sum_{j=1}^{q} b_j \sigma_{t-j}^2 \tag{2.3}$$

$$z_t \;\; iid \;\; N\,(0,1) \tag{2.4}$$

Variable σ_t^2 represents the conditional variance of error term (ε_t) given $V_t = \varepsilon_{t-1}, \varepsilon_{t-2}, \ldots,$

[21] The difference between the observed value at time *t* and the forecast value based on information available prior to time *t* is known as innovation . If the difference is zero then we can say the series cosists of white noise or stationary, i.e., ε_t is normally distributed with zero mean and costant variance.

and equation (2.4) tells that z_t are independent and identically distributed with the mean equal to zero and the variance equal to one. The parameters of the model $(a_0, a_1, \dots, a_p, b_1, \dots, b_q)$ are restricted in way to get $\sigma_t > 0$. In order to examine the fat tail behavior, I assume that z_t allows a fourth moment, this assumption allows us to estimate the kurtosis of the errors (ε_t) (Bai *et al.*, 2001).

The probability density function for the residuals is assumed to be the standard normal distribution with density function $f(z_t) = \frac{1}{\sqrt{2\pi}} e^{-z_t^2}$. The AR(1) conditional mean is assumed to take into consideration the non-synchronous trading effect (Hamilton 1994). To check the best model for volatility of CCX, I estimate the AR(1)−GARCH(*p,q*) for the equation (2.1) where *p*=0,1,2 and *q*=1,2,3. For a sample of "*T*" observations, the estimated parameter can be written as,

$$\omega^{(T)} = (c_0^{(T)}, c_1^{(T)}, a_0^{(T)}, a_1^{(T)}, \cdots, a_q^{(T)}, b_1^{(T)}, \cdots, b_p^{(T)}) \quad (2.5)$$

and conditional standard deviation estimations are computed as:

$$\hat{\sigma}_{t+1} = \sqrt{a_0^{(T)} + \sum_{i=1}^{q} a_i^{(T)} \varepsilon_{t-i+1}^2 + \sum_{j=1}^{p} b_j^{(T)} \sigma_{t-j+1}^2} \quad (2.6)$$

$$\hat{\varepsilon}_t = y_t - c_0^{(T)} - c_1^{(T)} y_{t-1} \quad (2.7)$$

The value $\hat{\sigma}_{t+1}$ denotes the sample estimator of the conditional standard deviation at time *t*+1. $\hat{\varepsilon}_t$ represents the shock in period *t.* The vector of the unknown parameters, $\omega^{(T)}$, has been estimated on the basis of all the *T* available observations. I estimate Schwarz Bayesian criterion (SBC) to select the model that fits the data best (Schwarz, 1978). There are a number of criterion for model comparison. Bayesian information criterion (BIC) is very popular in time series. It measures the quality of model and suggests an adequate model. The models with lowest BIC is preferred to be a best model (Sparks and Yurova, 2006). The likelihood function of SBC can be written as

$$SBC = -\frac{2}{T} L_T\left(y_t;\ \widehat{\omega}^{(T)}\right) + \frac{\widehat{\omega}}{T}\ \log(T) \tag{2.8}$$

where $L_T(.)$ is the maximized value of the log-likelihood function, $\widehat{\omega}$ is the MLE of ω derived from a sample of size T, and $\widehat{\omega}^{(T)}$ denotes the dimension of ω .

2.3.2 Regime-Switching Model

Hamilton (1989,1990) introduced the regime switching models in the finance literature. In later studies, others have used Markov Switching to estimate the volatility (Hamilton, 2005; Kim *et al.*, 2004; Kim and Nelson, 1999). Benz and Truck (2009) estimated Markov regime switching model for the European Union emissions trading system. Their findings reveal that Markovian models are more appropriate than GARCH modeling for the analysis of the short-term spot price behavior of carbon dioxide. In this paper I have adopted this methodology to identify structural change in the carbon market. The main feature of regime-switching model is the possibility for some or all the parameters to switch across different regimes. In the context of carbon market, the spot prices or returns of carbon dioxide emission allowances outcome depends on a number of variables, including weather and unquantifiable regulatory, policy and sociological factors. These factors can cause an unexpected and irrational buyout or lead to price jumps and periods of extreme volatility. Hence I assume that the switching mechanism between the states could be a result of these unobserved random variables.

Assuming that the CCX market had more than one heterogeneous state during its tenure, the Markov Regime Switching model is formulated as below:

$$y_t = c_{St} + \varphi y_{t-1} + \varepsilon_t \quad (2.9)$$

Where $S_t = 1 \cdots k$ is refered to as a state, and each state can stay for certain time periods then jump to another state. More clearly, let us assume that there are two states, $S_t = 1$ for $t = 1,2,\dots,t_0$ and $S_t = 2$ for $t = t_0 + 1, t_0 + 1, \dots$ A random shock ε_t, follows a normal distribution with zero mean and a variance. The intercept changes with the states, and therefore, we can say that intercept refers to switching states. The state is a random variable; it can be institutional, political, policy or any other changes which influence the system. If there are *k* states, there will be *k* values for intercept *c* and variance σ^2. Let us assume that equation (2.9) has two states $k = 2$.

$$y_t = c_1 + \varphi y_{t-1} + \varepsilon_t \quad \textit{for state } 1 \quad (2.10)$$

$$\varepsilon_t \approx (0, \sigma_1^2) \quad (2.11)$$

$$y_t = c_2 + \varphi y_{t-1} + \varepsilon_t \quad \textit{for state } 2 \quad (2.12)$$

$$\varepsilon_t \approx (0, \sigma_2^2) \quad (2.13)$$

The log-returns of the CCX spot prices have revealed that pre-democratic (December 2003- December 2007) and democratic (January 2008 – December 2010) regimes of the United States government in 2000's have had very different conditional variances and conditional means, leading us to believe there were two different regimes. Initially we do not observe nature of the state, i.e., high or low volatility. The property of Markov chains states that the current state only depends on the past through the most recent value. Probability theory plays a central role in determining the state and causes to change one state from other state. The general of expression of a two-state Markov chain is represented as:

$$\Pr\left(S_t = j \middle| S_{t-1} = i, S_{t-2} = k, \cdots y_{t-1,} y_{t-2}, \cdots\right) = \Pr\left((S_t = j | S_{t-1} = i\right) = p_{ij} \quad (2.14)$$

Between the periods of time t and t+1, the probability of a switch from state 1 to state 2 is given by p_{12}, and the probability of staying in state 2 is given by p_{22}. Equation (2.14) assumes that the probability of a change in regime depends on the past only through the value of the most recent regime. A probability of $p_{22} = 1$ refers a permanent shift or change, but in general we can see a possibility of $p_{22} < 1$ (Hamilton 2005). In a two state regime model, the transition probability matrix can be written as,

$$\begin{bmatrix} p_{11} & p_{21} \\ p_{12} & p_{22} \end{bmatrix} = \begin{bmatrix} p & (1-q) \\ (1-p) & q \end{bmatrix}$$

and the unconditional probability of being in the state 1 is given by $\pi_1 = \frac{(1-q)}{(2-p-q)}$ (Hamilton 1994).

2.4 Data and Empirical Results

2.4.1 Data

In this section I present the empirical results of the price dynamics of the Chicago Climate Exchange (CCX). The empirical price dynamics model used the daily closing spot price of CCX for the period from December 2003-December 2010. A total of 1783 observations i.e. daily closing spot prices were obtained from the CCX web page. The data are divided in two parts: the first 1020 observations (from December 12, 2003 to December 31, 2007) were considered as pre-democratic regime, while the remaining 763 observations (from January 1, 2008 to December 31, 2010) were taken as the democratic regime.

The CCX carbon trading started in Dec 2003 with a price of \$0.96 per ton of carbon dioxide. During the period Jan 2004 – Dec 2007 the market has experienced a steady growth in the prices; for this period the prices ranged from \$1 per ton to \$4 per ton. However, the situation changed after January 2008; the prices went up very rapidly. Between January 2008 and June 2008 prices of carbon units traded on the CCX market were as high as \$7.50 per ton carbon dioxide at one time, but later collapsed to around \$2 per ton in the next 6 months. The sudden downfall of the spot price indicates that the carbon market was highly volatile as a result of political reasons, management decisions and other competitive trading markets. It appears that the investors of CCX responded favorably in early 2008 to the presidential election, in anticipation of a win by the democratic party. They expected that the Obama government would come up with a new cap-and-trade program in the United States. When the Congress delayed the cap-and-trade bill later in the year; investors stopped buying the credits. Figure 2.2 shows a plot of spot prices and the price fluctuations of the CCX market.

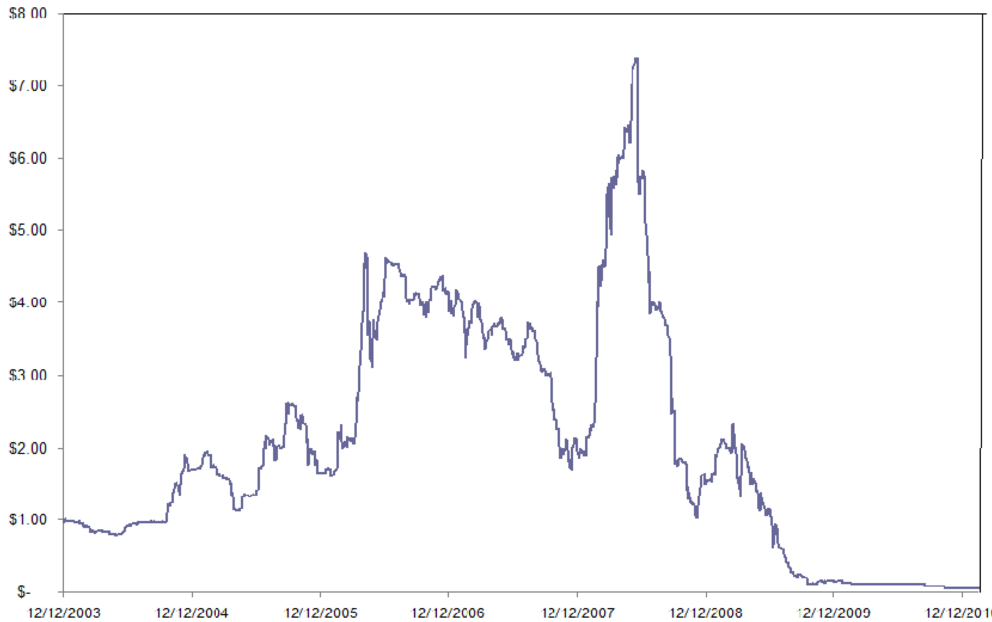

Figure 2.2. Daily closing prices of CCX from Dec 2003 - 2010

Before estimating the empirical model, daily closing spot prices (x_t) were converted to "log-returns" which can be expressed as $y_t = \log(x_t) - \log(x_{t-1})$ for the period Dec 2003-Dec 2010. Table 2.1 descriptive statistics of log-returns for different periods of CCX. Looking at the descriptive statistics, we can say that kurtosis is significantly higher than the kurtosis of a normal distribution of 3 indicating that fat-tailed distributions are necessary to correctly describe the log-returns' conditional distribution. Volatility clustering, or alternation between periods of high and low volatility, is clearly visible in the figure thus suggesting the presence of heteroskedasticity. Figure 2.3 provides the log returns of the full sample.

Table 2.1. Summary statistics of log-returns, for different periods of CCX

	Pre-Democratic (Dec 2003 – Dec 2007	Democratic (Jan 2008 – Dec 2010)	Full Sample Dec2003-Dec 2010
N	1020	763	1783
Mean	0.0701	-0.4782	-0.1658
Median	0	0	0
Max	12.93	27.19	27.19
Min	-20.86	-63.25	-63.25
Std.dev	2.659	5.331	4.036
Skewness	-0.241	-3.23	-3.357
Kurtosis	14.512	39.996	54.686

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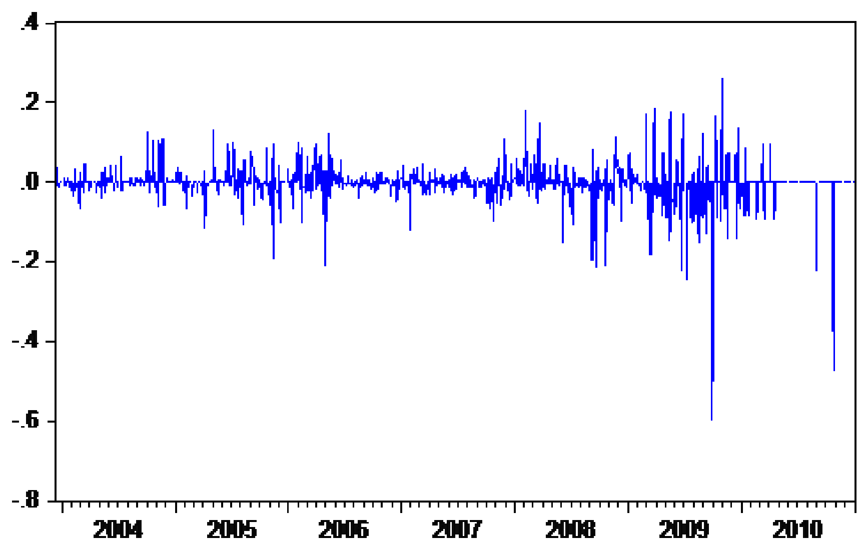

Figure 2.3. Daily CCX log-returns for the period Dec 2003 - Dec 2010
Note: Y-axis log-returns, X-axis represents days of trading

2.4.2 Estimated results of GARCH (1,1)

I have estimated different models and selected the best model based on Schwarz Bayesian criterion. Table 2.2 gives the best fit models for pre-democratic and democratic period samples. I have used Eviews package to estimate GARCH modeling. On the basis of the computed SBC values, GARCH(1,1) has the lowest computed value in both the samples and therefore, it is the best model fit among all the computed models.

Table 2.2. SBC for the pre-democratic (Dec 2003- Dec 2007) and democratic (Jan 2008 - Dec 2010) sample

Model	Pre-democratic	Democratic
ARCH(1)	4.678567	6.179098
ARCH(2)	4.670092	6.172519
ARCH(3)	4.654806	6.176125
GARCH(1,1)	**4.594127**	**6.146481**
GARCH(1,2)	4.594260	6.195569
GARCH (1,3)	4.600632	6.253090
GARCH(2,1)	4.598480	6.155542
GARCH(2,2)	4.600500	6.218946

Note: Lowest value of the SBC corresponds to a best model

Table 2.3 presents the parameters of the GARCH (1,1) model. I observe that the estimated conditional variance increased substantially when the market experienced extreme positive or negative returns. Benz and Truck (2009) had observed similar phenomena in the case of EU ETS. The autoregressive parameter is not statistically significant in both samples, providing no evidence of non-synchronous trading effect[22] and shows that spot prices I used in the analysis have equally spaced time intervals. The conditional variance parameters, however, are statistically significant.

[22] If the market experiences a first order serial correlation, one can say that this is due to nonsynchronus trading effect (Perry 1985). According to Levy (2006), "The nonsynchronus trading effect arises when data is assumed to be recorded at certain times when in fact it is collected at other times. As an example the daily closing security prices, which give the last transaction price for each security on the previous day, do not occur at the same time each day. By referring to these values as daily closing prices we incorrectly assume that the occur at equally spaced time intervals".

Table 2.3. Parameter estimates of GARCH(1,1) model for pre-democratic period Dec 2003 - Dec 2007 and democratic period Jan 2008-Dec 2010.

Coefficient	Pre-democratic	Democratic
c_0	0.000764	-0.3004
	(0.0621)	(0.1899)
c_1	0.035	0.1958***
	(0.042)	(0.055)
a_0	0.304***	0.6309
	(0.021)	(0.939)
a_1	0.0948***	0.0177**
	(0.034)	(0.011)
b_1	0.868***	0.9614***
	(0.049)	(0.043)

Note: Standard errors in parenthesis, *** indicate statistical significance level of 1%, ** indicate 5% and * indicate 10% .

The sum of the coefficients on the lagged squared innovation and lagged conditional variance, i.e., the estimated volatility persistence, of $a_1 + b_1 > 0.95,$ reveals that shocks to the variance are highly persistence in the both models. In both samples the estimated coefficients b_1 are around 0.9, and statistically different from zero. These results suggest that large values of σ_{t-1}^2 were followed by large values of σ_t^2 , and small values of σ_{t-1}^2 were followed by small values of σ_t^2. Such results are commonly found in other financial asset markets as well. Both models have different means and conditional variances, indicating that in-sample forecasting will not give proper prediction of the the out-sample. Figure 2.4 shows the conditional variances of these two models.

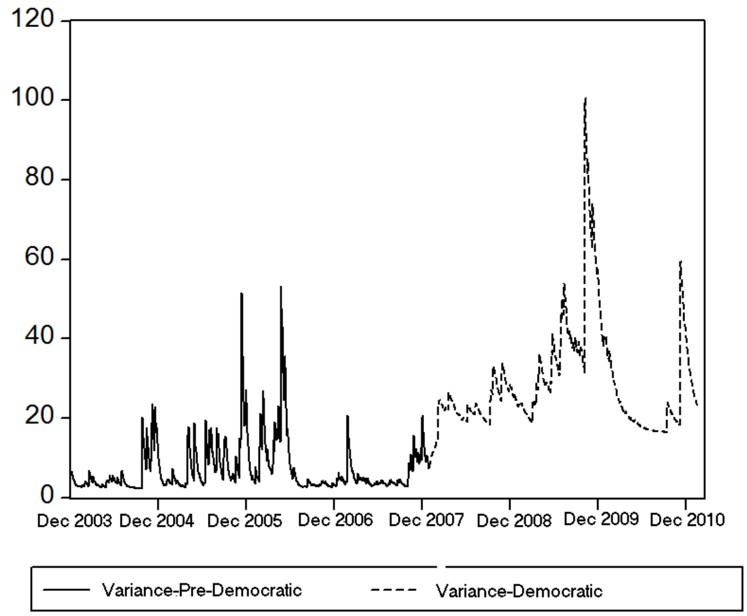

Figure 2.4. Conditional variances of the pre-democratic and democratic periods

When we look at the figure 2.4, we can observe that pre-democratic period has more stable spikes than the democratic period. There is a clear shift from pre-democratic period to democratic period. Lamoreux and Lastrapes (1990) , Susmel (1999) suggested that this type of behavior of conditional variance is mainly because of regime shift. Susmel (1999) argue the regime shifts might be due to market crashes, economic recession or changes in government policies. Further Samuel (1999) suggested that the regular ARCH models are not adequate enough to model the volatility behavior of the market when conditional variance changes with the regime shifts. To model the volatility by capturing the regime shifts, Hamilton and Susmel (1994) proposed another class of ARCH models, the regime-switching models. The regime switching model allow all the parameters of the ARCH process of different regimes, where the transitions between any two regimes processed by an unobserved Markov chain. In the following section I estimate volatility through Markov Regime Switching model.

2.4.3 Estimated results of Markov regime switching model

I have used Oxmetric's PCgive package and MS-regress package (Perlin 2010) to estimate the regime switching model. The parameters of estimated two regime-switching model are presented in table 2.4. We can see that parameters of state 2 are larger than the state 1 parameters, this is because of large number of zero returns followed by high positive or negative returns. More than 60 percent of the data were zero returns, which meant that the spot prices did not change much unless there was either positive or negative shock to the market. I also observed high positive and negative returns when there was a discussion on climate change in the Congress. From these observations we can conclude that the market is highly volatile with any political discussion on climate change issue. σ_1 is very small compared to σ_2, clearly indicating that both states have different phases of returns.

Table 2.4. Estimation results for log-returns with two-state regime-switching model with Gaussian distribution

Regime	Parameter estimates			
	C_i	ϕ	σ_i	p_{ii}
State 1 (i=1)	-7.53E-07 (1.17E-06)	1.62E-06 (2.49E-06)	3.59E-06*** (2.39E-06)	0.7476*** (0.013)
State 2 (i=2)	2.418*** (0.469)		10.576*** (0.428)	0.7649*** (0.012)

Note: Standard errors in parenthesis, *** indicate statistical significance level of 1%, ** indicate 5% and * indicate 10% .

State 2 has higher volatile periods yielding a higher mean and variance in the returns. Using the transitions probabilities we can estimate the unconditional probabilities of each regime, which reflect how much time the market experienced each regime. Unconditional probability of state 1 is $\pi_1 = \frac{1-p_{22}}{2-p_{11}-p_{22}}$ and state 2's unconditional probability is $1 - \pi_1$. The computed probabilities are 0.48 for state 1 and 0.52 for state 2. The unconditional probability of state 2 explains that more than half of the total trading days have experienced a high volatility in returns.

For the most part of phase I (2003-2006) the market had low volatility of returns except for few days. In 2004, the estimated trading volume was 2.4 million tons of carbon dioxide, and the trading prices were around \$1.0 - \$1.7 per permit. During the first half of 2005 the price was quite stable but started rising in the second half of 2005. In June 2005, Senate Energy and Natural Resources Committee voted 66-29 in favor of the Senate resolution on climate change (CCX 2006), which probably made investors to buy more credits in the second half of year 2005. The market experienced 77 per cent growth in prices and 600 percent growth in trade volume compared to year 2004. A total of 14.5 million tons of carbon dioxide were traded in 2005, of which about 80 percent were traded just in the second half of the year. Figure 2.5 shows the total volume and price of carbon credits for each trading period. This situation continued throughout the year 2006. Sabbaghi and Sabbaghi (2011) found smoother volatility in returns between the years 2003 - 2006.

Phase II period started in 2007 and ended in 2010. In figure 2.5, I plot smoothed probabilities of regime switching model. State 1, represented by the dotted path, reflects a low volatility state. On the other hand, state 2, represented by a solid path, represents a high volatility. The sudden spikes are evident of the fact that a higher degree of volatility persisted during that state. During the primary presidential election debate in 2007, the Republican party candidates, John McCain and Mike Huckabee, and the Democratic party

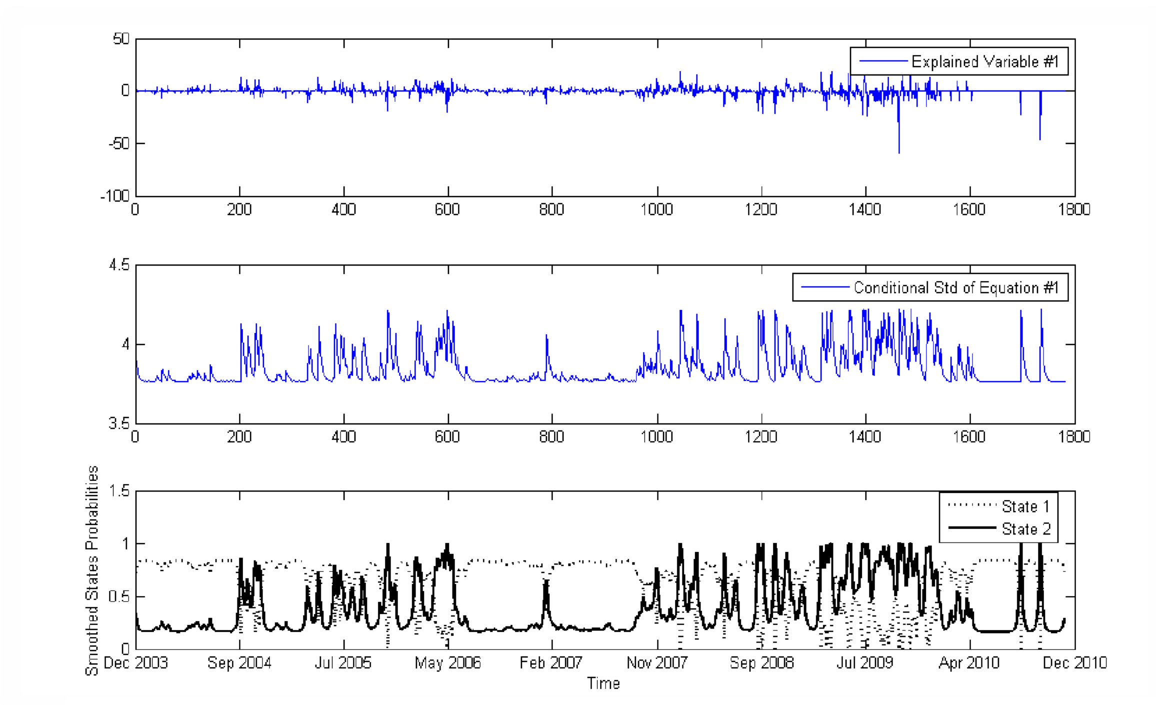

Figure 2.5. Log-returns, conditional standard deviations and smoothed probabilities of regimes of CCX from Dec 2003 to Dec 2010.
Note: Panel 1 gives the log-retrurns, panel 2 give conditional variances and panel 3 gives the smoothed probabilities of state 1 (low volatility) and state 2 (higy volatility)

candidates, John Edwards, Hillary Clinton, and Barack Obama, all favored a cap and trade system (CCX, 2007). Candidate Obama had insisted for a system that would auction 100 percent of the allowances at its inception. Investors predicted that the upcoming federal government would come up with a strong climate change bill and started buying the credits. Within a month the market experienced more than 75 percent jump in prices; prices rose from $2.45 per metric ton at the end of January to $4.50 per metric ton on February 29, 2008. A total of 11.34 metric tons of carbon credits traded in the month of February, which accounted 50 percent of total volume traded in the year 2007.

The market had crossed its previous year's total traded volume in the month of April; spot prices reached to $6.45 per metric ton. The rally continued until the month of May. In the month of May, spot price reached to $7.40 per metric ton, which is the maximum in the history of CCX. But the market price was drastically declined to 10 cents in the later periods and consequently the market was shut down in Dec 2010. I identified three major factors which influenced this market debacle.

First, Lieberman-Warner bill, or popularly known as Climate Security Act of 2007, was introduced to create a national cap-and-trade policy for greenhouse gas emissions and allocate right-to-emit credits to the polluters, restricting their annual amount of greenhouse gas emissions (S.2191, 2007). The Climate Security Act of 2007 was proposed in October 2007. The bill was approved by US Senate Committee on Environmetal and Public in Dec 2007 and forwarded to the Senate for discussion. The bill primarily targeted power, transportation and industrial sectors and proposed a reduction of emissions 70 percent below 2005 levels by 2050 (Murray and Ross, 2007; S.2191, 2007). The Senate debated this bill in June 2008 and disapproved. Investors expected that there would be a huge demand for credits if the bill had been passed in the Senate. Between Dec 2007 and June 2008, a total of 48 million tons of carbon credits traded and the price rose from $2 to $7.40. When the Senate disapproved the bill, investors probably became defensive and stopped trading, and consequently, prices touched $1 by the end of the year 2008. We can visually confirm this situation in figure 2.6.

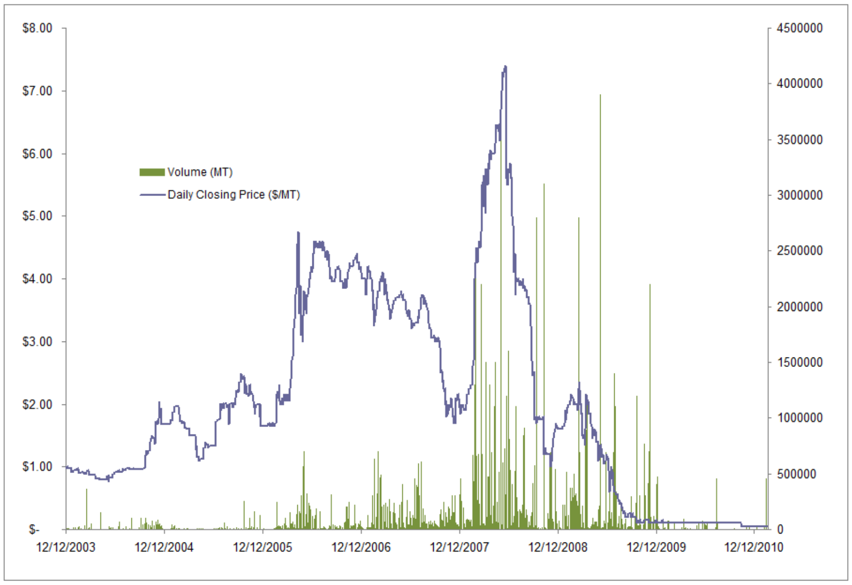

Figure 2.6. CCX daily settlement price and volume
Note: Prices are reported in dollars and traded volume in metric tons

Second, CCX had adapted an offset provision. Its members agreed to legally-binding reductions and traded Carbon Financial Instruments (CFIs). These CFIs were either offset credits or allowance-based credits, issued to emitting members according to their baseline emissions. According to CCX, offset users had constituted 12 percent of the program's total reductions; the majority of the members' green reductions (88%) were made at members' facilities (Bloomberg, 2010). During Phase I, CCX allowed 6 million tons of offsets. This number increased to 22.3 million tons in 2007 and 30.99 million tons in year 2008. This excess supply might have caused the price drop.

Third, the Regional Greenhouse Gas Initiate (RGGI) might have been the most recent contributor to the CCX downfall. RGGI, the first mandatory emissions trading scheme in the U.S., requires coal-fired power plants in ten U.S. Northeast and Mid-Atlantic states

(Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont) to cut greenhouse gas emissions by 10 percent from the 2009-2014 annual cap level of 188 million short tons by 2018. The first RGGI auction was held on September 25, 2008, offering 12.5 million allowances (representing 12.5 million short tons of CO_2) from six of the ten states involved in the program. Fifty-nine participants from the energy, financial, and environmental sectors participated. The auction clearing price for the RGGI allowances was $3.07 per ton. During this period the market price of CCX dropped to $1.6 per ton of carbon credits. I found that 15 large industries of the RGGI participants were also members of the CCX (see figure 2.1). The CCX trade volume was low whenever the RGGI auction took place.

2.5 Policy and financial lessons from CCX and suggested mechanisms to other climate exchange markets

In the aftermath of the collapse of CCX market, may have raised the policy question: could the government have done anything about it? Some believe that it is very important to provide suitable mechanisms for the emerging markets to resolve the operational and policy related to issues. CCX was shut down its operations in December 2010, as mentioned in the above section; the main reasons for the collapse of the market were excess supply of offset permits and political ambiguity on the cap and trade. Even though the market was closed, many of the member participants had expressed their interest to participate in future voluntary or regulatory cap and trade markets, and also suggested that the market should work transparently and legally controlled by federal agency (NY Times article author and year here)[23].

After the 1987 market crash, Brady (1988) submitted a report, "Report of the Presidential Task Force on the Market Mechanisms" to the US President. To control high volatility, the Brady report made several recommendations: (1) Margins[24] should be made consistent to control speculation and financial leverage; (2) Circuit breaker mechanisms (such as price limits and coordinated trading halts) should be formulated and implemented to protect the market system; and, (3) Information systems should be established to monitor transactions and conditions in related markets. Based on the Brady report, several studies have proposed different mechanisms to control the high volatility of spot prices of financial stocks returns. The popular ones are increase the margin levels, set a price celling, and taxing of each transaction of the contract (France et al., 1994).

Increased margin level: Margins are the minimum amount of cash that a buyer has to pay to the permit broker while the balance may be considered as loan borrowed from the broker against certain securities as collateral. Brady report suggests a higher margin level to control the high volatility. The low margin levels lead to greater speculations, which further lead to higher volatility in returns (Moser, 1992). Other studies (Hardouvelis 1990, Moser 1992, France et al. 1994) observed a negative relationship between the margin level and volatility, and therefore, suggested a high margin level in order to reduce the volatility.

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[23] The New York Times (January 3, 2011) http://www.nytimes.com/cwire/2011/01/03/03climatewire-chicago-climate-exchange-closes-but-keeps-ey-78598.html

[24] In the financial literature, margin is considered as a collateral i.e., a party which holds the financial instrument will cover the risk of the opponent party.

Price celling or price limit: Brady report suggested that price limit would be one powerful mechanism to control the volatility of the returns. In this setup, the regulatory authority has power to control or limit the price basing on the previous day's closing price. The regulatory authority can stop the trading if the opening price is below or over the previous day's closing price and can wait until the price touches the limit. Price limit mechanism provides the authority to set the boundaries.

Transaction taxes: According to France et al. (1994), transaction tax or taxing of the each contract can be considered as entry barrier condition. Their argument is that transaction cost excludes certain contracts which increase the volatility. Song and Zhang (2002) study observed that transaction tax discouraged the entry of short term traders and reduced the volatility. Further they argued that transaction tax would provide the revenue to regulatory authority.

When it comes to the emission trading markets, price limit and transaction tax mechanism seem more suitable options. As we already have seen in the earlier section, CCX has experienced high fluctuations in the spot prices. The phase I prices were in range between \$1 to 4 and phase II prices were in between 5 cents to \$7. Phase II program would have worked more efficiently if CCX had limited the lower bound prices and the quantity of the permits. The transaction cost mechanism would have stopped the short term or small offset providers in phase II as well. The policies on minimum margin and collateral requirements are worth considering if the market size grows substantially large and more cash-strapped buyers show up in the market.

2.6 Conclusion

In this chapter I have analyzed the short-term spot price behavior of carbon dioxide emissions allowances of the United States' first voluntary emissions trading market, Chicago Climate Exchange (CCX). I used the time series models, AR-GARCH and Markov switching models, to model the temporal aspects of extreme variations and then to relate that variation to known historical changes in regulatory and market conditions.

First, I have estimated the volatility using GARCH (1,1) and observed a huge variation in conditional variances of the two phases, Phase I (2003-2007) and Phase II (2008-2010) of the US government. The literarture (Hamilton and Susmel, 1994; Susmel, 1999) suggests that ARCH/GARCH models are not adequate to explain the behavior of the conditional variances and underlying structural changes. So, I have applied the Markov regime-switching model to identify the regimes. Markov model is considered an effective tool to estimate separate phases with different underlying stochastic processes. Based on Markov model, I have identified two regimes, pre-democratic (2004-2007) and democratic (2008-2010). Further, I have examined the tail behavior of these regimes to understand the reasons for high volatiliy.

The observed high volatiliy in the returns during the phase II of the CCX market explains the condition of the market. The spot prices fluctuated considerably throughout the first half of 2008, with a 67.5 percent volatility. During this time the price rose from \$3.25 to \$7.40 per ton of carbon, but collapsed to around \$2 per ton in the next six months. The prices were dropped further in the later years and reached to 5 cents. I have identifed three possible regulatory and market reasons, which might have caused the high volatility and dramatic price drop in the phase II of the CCX market.

The first cause was when Lieberman-Warner bill on climate change was approved by the Senate Committee on Environment and Public Works in December 2007. Investors expected that United States would implement its first cap and trade program for Greenhouse Gas emissions. Consequently, they showed more interest in buying the carbon credits. But the situation changed when the bill was not approved by the Senate in June 2008; investors showed less interest in buying the credits. The second cause was when CCX issued more offsets during the period 2007-2008 to meet the demand. The spot prices might have dropped due to this excess supply of offsets. The third cause could have been Regional Greenhouse Gas Initiative (RGGI), a mandatory emission reduction program of Northeastern states. The RGGI auctioned their first emission allowances in September 2008. We observed that a large number of CCX members were also part of RGGI and their participation in the auction might have reduced the demand for CCX credits.

While the subject market has ceased to exist, new voluntary markets of carbon credits and offsets are emerging in the US and worldwide. Finance literature is replete with measures for controlling price volatility. For instance, margin rules, price control, moratorium on market transactions and financial taxes are some popular financial tools commonly applied in other asset markets. The CCX owners or the government did not resort to such financial measures, leading to a complete collapse of the market. A timely action taken at the first sign of market volatility in 2008 could have avoided the collapse. Therefore, the results of this study should provide an important insight for risk managers, investors and policy makers for improving the design of the voluntary emission markets.

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CHAPTER 3
AN APPLICATION OF EXTREME VALUE THEORY TO IDENTFY AND EXAMINE THE THRESHOLD LEVELS OF CCX AND EU ETS EMISSION TRADING MARKETS

3.1 Introduction

In the recent years, carbon permits have become an important asset for financial institutions and risk investors. The Commissioner of European Commission on Climate Change stated in a news article, "...by treating emission allowances as other financial assets, the proposal (classifying of spot carbon-dioxide contracts as financial instruments) extends financial market protectiswon to the carbon market. It will provide further certainty for carbon market participants as the market grows and matures" (Bloomberg, 2011). However, before formally accepting carbon permits as an asset, some of the financial institutions and risk investors[25] have already played an important role in building and developing two major trading markets such as the Chicago Climate Exchange (CCX) and the European Union Emission Trading Scheme (EU ETS). The CCX market, as elaborated in Chapter 2, was the first North-American voluntary and legally binding agreement. CCX market started in December 2003 and closed in December 2010; during this period a total of 700 million metric tons of carbon dioxide (CO_2)equivalent were traded. EU ETS is a mandatory cap-and-trade program of the European Union, started in January 2005 and is in operation till now. EU ETS considers one of the largest emission trading markets, it covers 84 percent of the global trade volume with a total value of $119.8 billion in 2010 (Liancre *et al.*, 2011).

[25] For examples, banks such as Bank of America, financial service companies such as Access Industries and MB Investment, risk management institutions such as Managers' International Association and The Professional Risk have participated in the Chicago Climate Exchange.

Under the EU ETS, the European Union (EU) countries agreed to impose CO_2 emission caps on 12,000 emitting facilities and distribute free allowances in amounts equal to their caps. The eligible facilities must report their annual current CO_2 emission levels and give up one allowance for every ton of CO_2 they emit (Ellerman and Joskov, 2008). The EU sets a target for each member country as part of the National Allocation Plans (NAP). EU ETS operated in two phases. In Phase I (2005-2007), a total of 2.2 billion allowances per year were released. In Phase II (2008-2012), these allowances were down to 2.08 billion per year. The allowances released in Phase I should be consumed in the same period and cannot carry forward to the next phase. The surplus and deficit of these European Union Allowances (EUA) can be traded at an authorized trading platforms such as Nord Pool, European Energy Exchange (EEX), European Climate Exchange (ECX), SendeCO_2 and Powernext (now Bluenext).

EU ETS is slowly gaining attention from market intermediaries, such as risk managers, brokers and traders. These agents trade on behalf of their clients and help to own stocks of EUAs (Sanin and Volante, 2009). When financial investors, risk management consultants, brokers, or traders participate in a trading market and hold any financial assets, they are keen on understanding the price dynamics, especially the frequency and magnitude of sudden drops or rises in prices. Such fluctuations have implications for estimating traditional risk measures like Value at Risk (VaR) and Expected Shortfall (ES) in the investment portfolio analysis. VaR is a probability tool to measure any financial or market based risks. It estimates the worst loss over a target level and provides a single value for a given confidence interval (Jorion, 1996). Expected loss is also used as a risk measure and often referred to as conditional VaR or expected tail loss. The major difference between VaR and ES is the way they address the question, VaR asks the question, "how bad can things get?" whereas ES asks, "if things do get bad, what will be the expected loss?" (Hull,2012). Such measures not only help investors but also policy makers. Based on these risk measures, environmental regulator might want to implement a temporary moratorium on the permit market in order to prevent it from further financial collapse.

Several studies considered CO_2 allowances as a financial asset and have examined their price dynamics (Bunn and Fezzi, 2007; Rickels *et al.*, 2007; Mansanet-Bataller *et al.*, 2007; Alberola *et al.*, 2008, Milunovich and Joyeux, 2007; Paolella and Taschini, 2008; Benz and Trück, 2008; Chesney and Taschini, 2008; Seifert *et al.*, 2008). These studies reveal that EU ETS responds to political, administrative, climate and other economic factors. Bunn and Fezzi (2007) examine the relationship between the carbon emission prices and energy prices by using structural vector autoregressive model. They find that spot carbon prices are highly sensitive to the gas and electricity prices. Seifert *et al.* (2008) note that the returns of EU ETS possess the martingale property[26] and time dependent dynamic volatility; their study observed that as market approached a termination period there was a high volatility in prices. Their argument was that, due to the structure of EU ETS, which prohibits the transfer of permits from Phase I to Phase II, the market forces the investors to sell the leftover permits at a lower price. But CCX and EU ETS phase I have experienced high volatility in prices in different time frames. This chapter attempts to explain the reasons for extreme volatility behavior of the markets.

[26] Martingale property is said to occur when the expected futures values of an asset do not depend on its historical prices (LeRoy, 1973).

Milunovich and Joyeux (2007) estimate a dynamic volatility model and suggest that none of the futures contracts follow a cost-of-carry relationship with the spot prices and finds that evidence for existence of arbitrage opportunities in the market for carbon permits. Benz and Trück (2008) observed different volatility behavior in Phase I due to policy and regulated changes such as the National Allocation Plan's revisions and reductions in national emission caps. They also observed fat tails. Paolella and Taschini (2008) make similar observations and stress the need for applying more rigorous statistical models which concentrate on tail behavior. Both these studies are based on EU ETS Phase I. The third essay considers all three markets: CCX, EU ETS Phase I, and EU ETS Phase II. Our preliminary observations indicated that all three markets have had excess kurtosis, meaning the presence of fat tail distributions.

The early studies of financial markets have taken two approaches to studying excess skewness and kurtosis in the permit prices. The first approach was to use non-normal stable distributions instead of a normal distribution (Mandelbrot, 1963; Fama, 1963). As an alternative approach to studying tail behavior, Engle (1982) developed the ARCH model. Both these approaches focus on the entire distribution of returns, i.e., both tail and central parts of the distribution. DuMouchal (1983) argued that in order to capture the extreme volatility of financial returns, it was important to concentrate exclusively on the tail behavior. More recent studies in finance therefore suggest the use of extreme value theory (EVT) as a way to distinguish tails from the central part of the returns distribution.

The primary objective of this study is to provide an accurate risk measure for EU ETS and CCX markets by applying the EVT tool. The key logical question that arises is how frequently the fluctuations in the two carbon market prices exceeded their respective thresholds. While EU ETS is in its second phase and most probably will evolve into the third phase, CCX has totally collapsed. Therefore, an important question to ask is if the risk measures of extreme variations had changed over time in these two markets and if so, with what type of risk distributions. Further, in the cross-continental setting of these two markets, did the extreme variations behave in a similar manner?

The study makes two significant contributions to the literature on emission permit markets. First, to my knowledge, this is the first ever application of the extreme value theoretic tool to studying the price dynamics of emission permit markets. Second, a cross-continental investigation of emission market returns is very limited. This study sheds light on the extreme behavior of two different types of carbon markets: one that is mandatory and continues to grow robust (European Union Emission Trading System), and the other that was voluntary (Chicago Climate Exchange) and has ceased to exist.

This essay analyzes the tail behavior of CCX and EU ETS markets to determine the relation between the market structure and the attitude of the investors. Furthermore, the chapter discusses the policy and operational issues of these two markets, and suggests few policies, to make the market more attractive and gain attention of investors. The results of the study would be useful for regulated community, other investors, and the regulators.

This essay is organized as follows. Section 3.2 explains the relevance and importance of the extreme value theory in modeling the risk and expected short fall of an asset. Section 3.2 also discusses the different distributions of EVT. Section 3.3 discusses data and empirical results of the estimated models. Section 3.4 provides the comparative analysis of voluntary and mandatory markets. Section 3.5 gives the conclusion of the essay.

3.2 Extreme value theory and extreme risk modeling

Extreme value theory (EVT) is used for estimating the probability of events that have extreme fluctuations in their outcomes. Some common applications of EVT can be seen in forecasting extremes events of weather such as rains, floods, and hurricanes[27]. It is also very popular in modeling the risk losses of financial markets[28]. Financial literature demonstrates that EVT is a better approach to estimating VaR of heavy tail markets than the traditional methods.

The tail behavior of financial markets have been widely discussed in the financial literature. Singh *et al.* (2012), Gilli and Kellezi (2006), Mancini and Trojani (2010), Onour (2010), McNeil *et al.* (2005), McNeil and Fray (2000) applied EVT to analyze tail behavior of different financial series. Singh *et al.* estimated the risk levels of the S&P-500 index. Their studies suggest that application of EVT is quite useful in financial risk modeling. Mancini and Trojani estimated the VaR of S&P index using semi-parametric bootstrap method, which provided the extreme value estimator. Later they used the extreme value estimator to fit innovation tail distributions above some threshold levels. McNeil and Fray provided the dynamic extreme value theory, which was two stage extreme value process with GARCH (1,1) and allowed the investors to predict market

[27] Applications of extreme value modeling have been used in weather and environmental forecasts (Pielke and Downton, 2000; Pielke and Landsea ,1998; Smith, 1989; Tarleton and Katz, 1995; Dawson 2000 etc.), thermodynamics of earthquakes (Lavenda and Cipollone, 2000), and wind engineering (Harris, 2001).

[28] Engineering, insurance and financial markets (McNeil and Frey, 2000; Gill and Kellzi, 2003; Embrechts, 1999; Reiss and Thomas, 1997 etc.).

crash accurately. In this study, I followed the two stage model proposed by McNeil and Fray.

Broadly, there are two main methods to explain the extreme tail behavior and to forecast the risk (Singh *et al.* 2012): (i) generalized extreme value distribution or Distribution of maxima, which is further classified into three different distributions, namely, Frechet, Gumbel and Weibull distributions. (ii) generalized Pareto distribution or the peak over threshold approach. Both methods are based on the maximum likelihood estimation (MLE). What follows is a brief description of the two methods.

3.2.1 The distribution of Maxima or Generalized Extreme Value Distribution (GEV)

The GEV approach has been developed from the Fisher and Tippett's (1928) and Gnedenko's (1943) theorems (avilable in McNeil et al., 2005). Let us consider a series of random data points with cumulative distribution function . The cumulative distribution of stochastic maximum can be expressed as $F_{M_n}(x) = [F(x)]^n$. As n increases to infinity, this cumulative distribution function (cdf) degenerates to 0 for all x where $F(x) < 1$ and to 1 for all x where $F(x) = 1$. The cdf of can be written as,

(3.1)

And the distribution functions of GEV given by:

$$\begin{aligned} &\exp\left(-\left(1+\xi\cdot\left(\frac{x-\beta_n}{\alpha_n}\right)\right)^{-\frac{1}{\xi}}\right) \\ &\exp\left(-\exp\left(\frac{x-\beta_n}{\alpha_n}\right)\right) \end{aligned} \qquad (3.2)$$

where $1+\xi>0$, ξ is the shape parameter or tail index, β_n *or* μ is the location parameter, and α_n or $\sigma>0$ is the scale parameter. Based on the shape parameter, the extreme value distribution can take the form of Frechet distribution[29] when $\xi>0$, Gumbel distribution when $\xi=0$, or a Weibull distribution when $\xi<0$.

The GEV distribution has a major defect of losing data. To perform the analysis it takes only maximum losses in large blocks (MacNeil *et al.* 2005). In the appendix 2, I presented the figures of yearly maxima and minima of CCX, EU ETS phase I and phase II. There are seven large blocks for CCX, four for EU ETS phase I, and five blocks for EU ETS phase II. It is very difficult to estimate EVT with small sample. To overcome this problem, Pickands (1975), and Balkema and de Hann (1974) proposed a new theorem, called Generalized Pareto Distribution, which uses all data points that are exceed a threshold level.

3.2.2 The distribution of Generalized Pareto Distribution or Peak Over Threshold model

The Generalized Pareto Distribution is applied to variables that have skewed, long tails. The distribution function of GPD is defined in the following theorem (Picaands, 1975; Balekema and de Haan, 1974)(available in McNeil et al., 2005):

For a large class of underlying distributions F, the excess distribution function F_u can be approximated by GPD for an increasing threshold $'u'$.

$$F_u(y) \approx G_{\xi,\sigma}(y), \qquad u \rightarrow \infty$$

and

[29] Pareto, Cauchy, Student-t and mixture distributions are Frechet class of distributions; normal, exponential, gamma and lognormal distributions are Gumbel class of distributions (MacNeil *et al.* 2005).

$$G_{\xi,\sigma}(y) = \begin{cases} 1 - \left(1 + \frac{\xi y}{\sigma}\right)^{-\frac{1}{\xi}}, & \xi \neq 0 \\ 1 - \exp\left(-\frac{y}{\sigma}\right), & \xi = 0 \end{cases} \quad (3.3)$$

Where $y = x - u$, x is the original random variable, σ is scale parameter and ξ shape parameter, and also as $\sigma > 0$, and $y \in [0,\ x_F - u]$ when $\xi \geq 0$ and $y \in \left(0, {}^{-\sigma}/_{\xi}\right)$ when $\xi < 0$.

Now, the crucial step is to identify a proper threshold level, *u*. As stated in Singh *et al.* (2012) and Liu (2011), the *u* should be high enough to ensure the POT distribution will converge. However, it should not be too high to ensure that enough observations are available to test the distribution. Mean excess plot is very popular to determine the threshold level (McNeil, 2005). Figures 3.8, 3.11 and 3.14 show threshold levels based on the mean excess plot. Now, we need to define the distribution of exceedance based on the observed threshold levels.

Distribution of Exceedance:

For a random variable x with distribution function *F*, the conditional excess distribution function over a threshold u is given by

$$F_u(y) = P(x - u \leq y | x > u) = \frac{F(y+u) - F(u)}{1 - F(u)} = \frac{F(x) - F(u)}{1 - F(u)} \quad (3.4)$$

Equation (3.4) gives the probability that the value of return exceeds the threshold by at least *y*. Now, with given distributions, and threshold levels, our task is to compute the VaR and ES. The expression in equation (3.4) can be explained from figure 3.1. The right panel gives the probability distribution of *F*(x), the dotted line represents the observartions below the threshold level. The thick line represents the observations above the threshold level. In the left panel, the *F*(*x*) is truncated to below the threshold level.

The truncated or conditional distribution function takes the values below the threshold level.

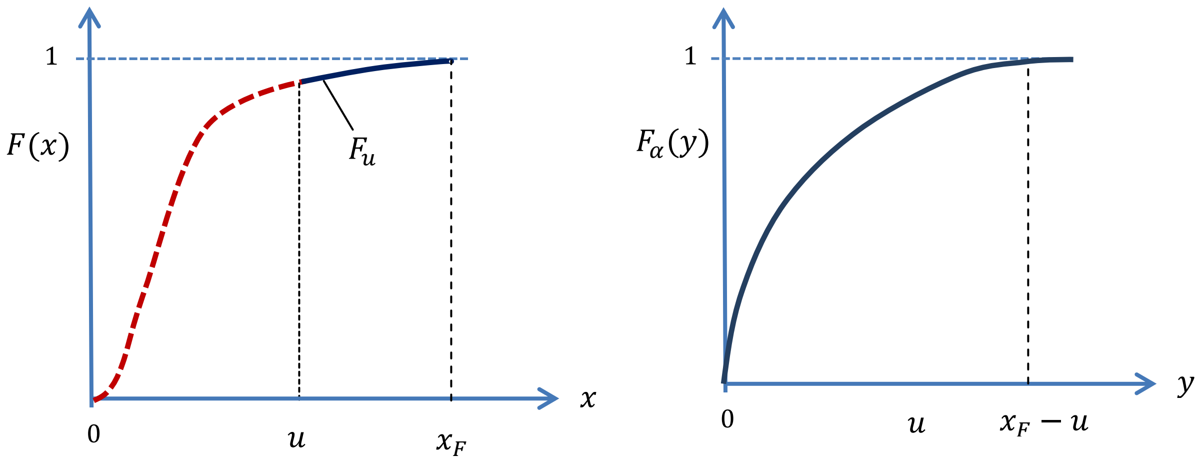

Figure 3.1. Distribution function F and conditional distribution function F_u
(Source: Gilli and Kellezi (2006))

3.2.3 Modeling the tails and measure of VaR and ES

Definition of Excess Losses. Let F be the loss distribution with right endpoint x_F and assume that for some high threshold u, we have $F_u(x) = G_{\xi,\sigma}(x)\ for\ \ 0 \leq x \leq x_F - u$ and some $\xi \in \mathbb{R}\ and\ \beta > 0$. By using this definition we can write the following expression, for $x \geq u$ (cite the original reference here),

$\bar{F}(x) = P(X > u)P(X > x|x > u)$

$= \bar{F}(u)P(X - u > x - u|X > u)$

$= \bar{F}(u)\bar{F}_u(x - u)$

$$= \bar{F}(u)\left(1 + \xi\frac{x-u}{\sigma}\right)^{-1/\xi} \qquad (3.5)$$

We will get the tail probabilities when we know $F(u)$. VaR then can be defined as the pth quantile of the distribution F.

$$VaR_\alpha = F^{-1}(1-\alpha)$$

$$VaR_\alpha = q_\alpha(F) = u + \frac{\sigma}{\xi}\left(\left(\frac{1-\alpha}{\bar{F}(u)}\right)^{-\xi} - 1\right) \tag{3.6}$$

For $\xi < 1$ the Expected Shortfall is given by,

$$ES_\alpha = \frac{1}{1-\alpha}\int_\alpha^1 q_x(F)\,dx = \frac{VaR_\alpha}{1-\xi} + \frac{\sigma-\xi u}{1-\xi} \tag{3.7}$$

We can rewrite equation (3.4) by assuming that there are n observations and that a total of N_u observations are above u. Replace F_u by the GPD and $(N_u)/n$, which is the sample estimator of $\bar{F}(u)$. Therefore, expression,

$$\hat{F}(y) = \frac{N_u}{n}\left(1 + \frac{\hat{\xi}}{\hat{\sigma}}(x-u)\right)^{-1/\hat{\xi}} \tag{3.8}$$

and the corresponding VaR and ES with p^{th} quantile can be written as

$$\widehat{VaR}_p = u + \frac{\hat{\sigma}}{\hat{\xi}}\left(\left(\frac{n}{N_u}p\right)^{-\hat{\xi}} - 1\right) \tag{3.9}$$

$$ES_p = \frac{VaR_p}{1-\hat{\xi}} + \frac{\hat{\sigma}-\hat{\xi}\hat{u}}{1-\hat{\xi}} \tag{3.10}$$

3.2.4 Dynamic extreme value approach

The basic extreme value theory (EVT) assumes that errors are normally distributed with mean zero and a constant variance. But, most of the financial returns exhibit excess kurtosis or leptokurtosis and serial correlation. If we assume that the variable is stationary and unconditional, then the model would be viewed as a static EVT. Otherwise, would have to estimate dynamic EVT model by taking the conditional distribution of *F* and the volatility of returns (McNeil and Fray, 2005; Singh *et al.*, 2011). As explained in the chapter 2, GARCH model is used to estimate the conditional variance of fat tail distributions. In the first stage the volatility of the returns are estimated using the GARCH (1,1) model. In the second stage, the residuals from the GARCH model are used to estimate the peak over threshold or Generalized Pareto Distribution to calculate the risk and expected shortfall.

3.3 Data and empirical results

To estimate the EVT model I used the daily closing spot price of CCX for the period from December 2003 - December 2010. A total of 1783 observations were obtained from the CCX web page. EU ETS spot prices were obtained from Bluenext[30]. For EU ETS, I considered two phases, Phase I (June, 2005 to February, 2008) and Phase II (March, 2008 – April, 2012). Phase I consisted of 669 observations and phase II consisted of 1049 observations. Figures 3.2, 3.3 and 3.4 present the daily trading spot prices of CCX, EU ETS Phase I, and EU ETS Phase II emission markets, respectively.

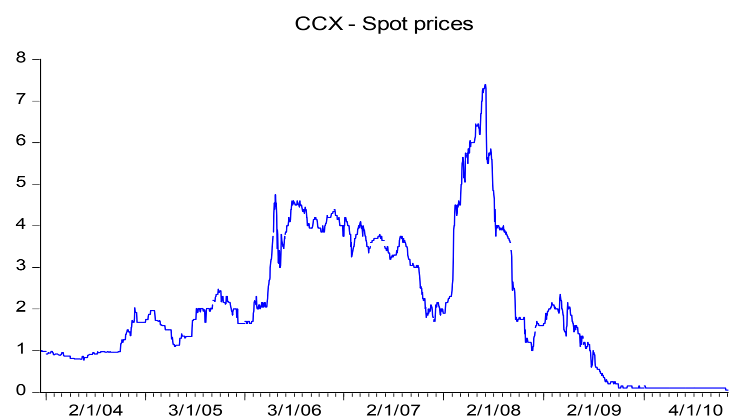

Figure 3.2. Spot prices of CCX (December 2003 to December 2010)

[30] http://www.bluenext.eu/

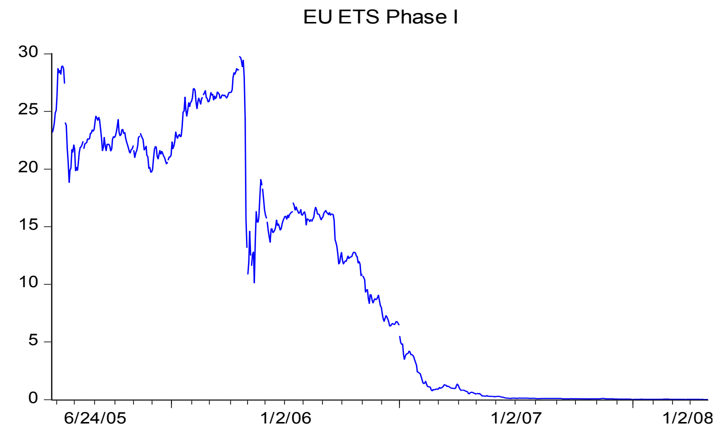

Figure 3.3 Spot prices of EU ETS Phase I (June 2005 – February 2008)

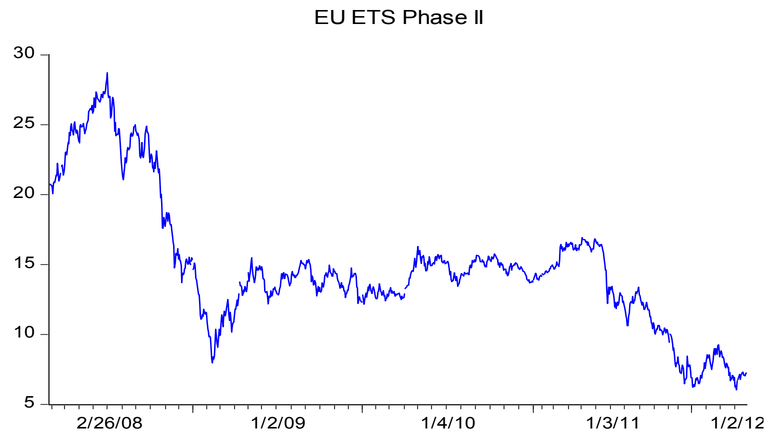

Figure 3.4. Spot prices of EU ETS Phase II (March 2008 to March 2012)

Before estimating the empirical model, daily closing spot prices were converted into log-returns in percentage terms, which can be expressed as $x_t = 100 * (\log(z_t) - \log(z_{t-1}))$. Table 3.1 provides the summary statistics of the data used in the analysis. As mentioned earlier, I estimated the dynamic EVT in two steps. First, the logreturn series using GARCH (1,1) model were estimated and used in obtaining the residuals. In the second stage I employed these residuals to estimate the EVT parameters. In estimating of the extreme value theoretic model, I used MATLAB code of Gilli and Kelezi (2006) and packages, extRemes, fExtremes and fgarch of R. Maximum Likelihood Estimation (MLE) method was used to estimate the parameters of EVT.

From the descriptive statistics (Table 3.1) it can be seen that all three data sets have significantly excess kurtosis when compared to the kurtosis of their normal distributions. This indicates that leptokurtosis and fat-tailed distributions are necessary to correctly describe the log-returns' conditional distribution.

Table 3.1. Summary statistics for log-returns of CCX and EU ETS

Period	CCX Full Sample	EU ETS Phase I	EU ETS Phase II
N	1783	669	1048
Mean	-0.1658	-1.054	-0.1002
Median	0	0	-0.018
Max	27.19	51.08	20.38
Min	-63.25	-51.08	-10.81
Std.dev	4.036	8.713	2.71
Skewness	-3.357	-0.311	0.127
Kurtosis	54.686	11.71	7.48

Negative skewness of CCX and EU ETS Phase I show that both markets are skewed left and suggest that the left tail is longer relative to the right tail i.e., more negative returns than the positive returns. Whereas, the positive skewness of EU ETS Phase II show more positive returns. From their respective means (Table 3.1), it can observed that all three markets experienced negative mean returns. The negative mean retuns might be the result of extreme events that have occurred in the markets.

From figures 3.5, 3.6 and 3.7 we can identify that CCX and EU ETS Phase I had high volatility before they were closed, during this time credits were sold at very low price. CCX reached its maximum trading price ($7/ton of carbon) during the month of June 2008, but the end of the same year the price dropped to $1.65 per ton of carbon. The prices were dropped to 5 cents per ton of carbon credit when it was closed in 2010.

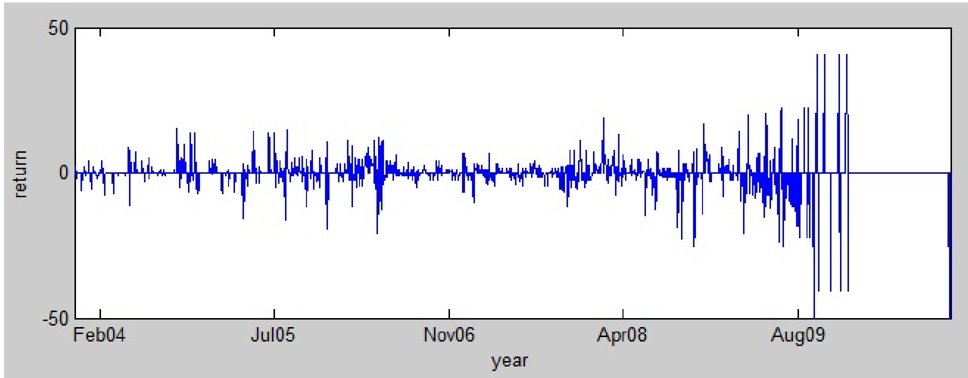

Figure 3.5. Daily log-returns of the CCX (December 2003 to December 2010)

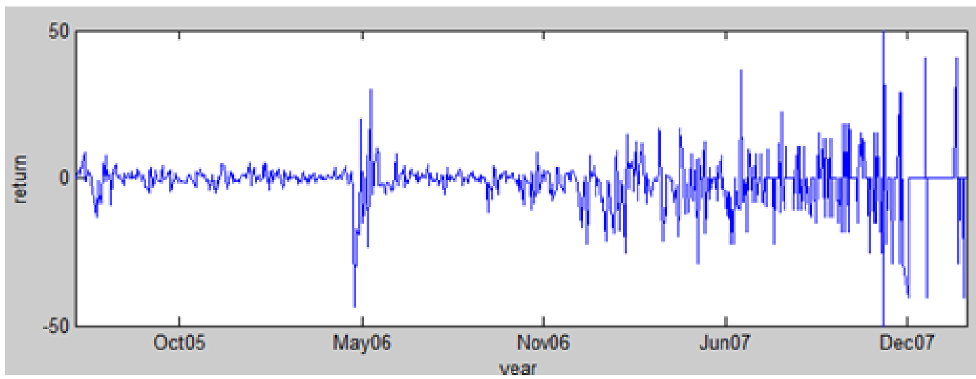

Figure 3.6. Daily log-returns of the EU ETS – I (June 2005 – February 2008)

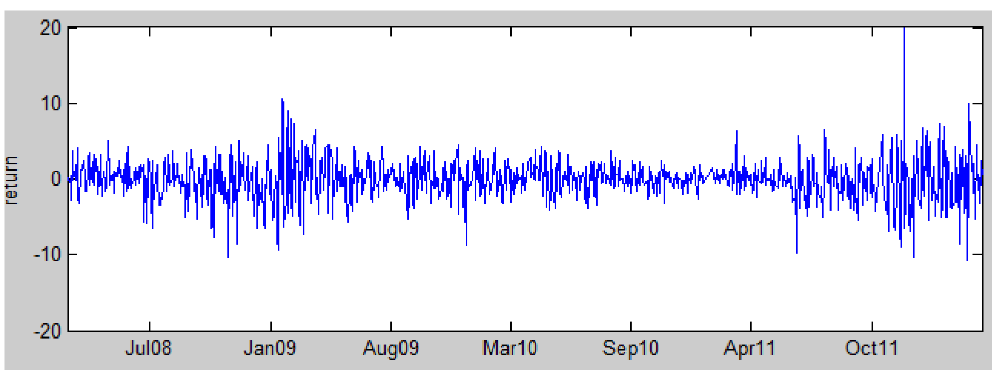

Figure 3.7. Daily log-returns of the EU ETS – II (March 2008 – April 2012)

In the case of EU ETS phase I, the trading was initially started with 23 euros per ton of carbon credit in June 2005. Phase I prices were quite stable until the market reached its maximum in April 2006. During the same month the market experienced a sudden drop in the price from 24 euros to 15 euros, before dropping further all the way to 6 euros at the end of the year.

EU ETS phase II trading started in March 2008. So far it is the stable emission market. The spot prices are oscillating between 10 euros and 30 euros. In the beginning of the Phase II, the market experienced a high growth in prices. The market started with 20 euros per carbon credit and within four months it reached to 30 euros per carbon. After June 2008, the spot prices experienced a steady drop. This may be due to excess supply of allowances, slow industrial productions and credit crunch crisis in the commodity markets (Chevallier 2010). In following subsections 3.3.1, 3.3.2 and 3.3.3, I analyze the level of risk involved in these markets. To estimate the VaR and ES, I estimate the threshold levels using the mean excess plots. Figures 3.8, 3.11 and 3.14 show the threshold levels of the CCX, EU ETS Phase I and II, respectively. The computed threshold levels are 95% quantile of negative log-returns or left tail. The right panels in aforementioned figures are zoomed versions of the left panels.

As explained in the section 3.2, I estimate the Generalized Pareto Distribution (GPD) to calculate the Value at Risk and Expected Shortfall. The log-likelihood function $L(\xi, \sigma|y)$ for the GPD can be written as,

$$L(\xi, \sigma|y = \begin{cases} -n \log \sigma - \left(\frac{1}{\xi} + 1\right) \sum_{i=1}^{n} \log\left(1 + \frac{\xi}{\sigma} y_i\right) & if \;\; \xi \neq 0 \\ -n \; log \; \sigma - \frac{1}{\sigma} \sum_{i=1}^{n} \log y_i & if \;\; \xi \neq 0 \end{cases} \tag{3.11}$$

3.3.1 Risk analysis of CCX

Based on the mean excess plot, the threshold value of left tail (negative log-returns) of CCX is estimated to be u = 5.82. A total of 86 observations (4.82 percent of total observations) are above the threshold level. The threshold level of right tails is estimated to be u = 5.13 and a total of 85 observations (4.82 percent of total observations) exceeded this level. The shape parameter explains the rate of speed at which the tail disappears. The upward linear trend in the right panel suggests a positive shape parameter and refers that the estimated POT is heavy tailed (McNeil and Fray, 2005).

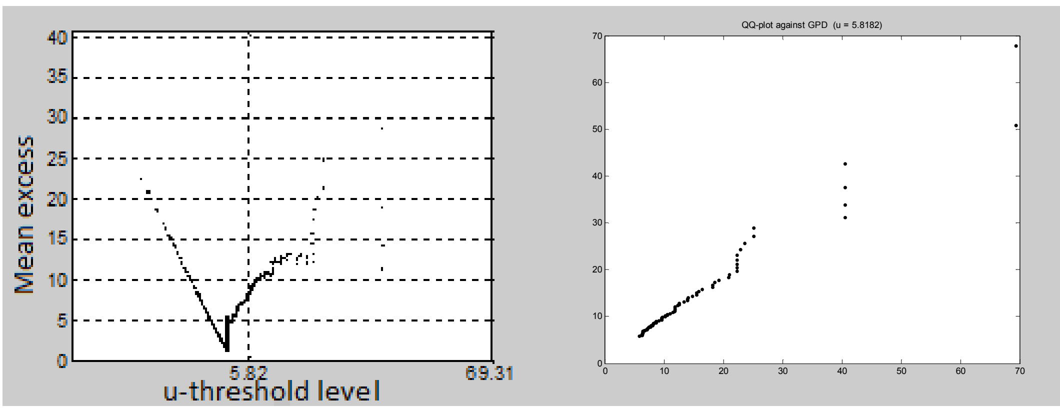

Figure 3.8. Mean excess plot of loss series of the CCX market
Note: the right panel provides the threshold level where the sample excess plot is linear. The upward linear trend suggests a positive shape parameter. The left panel provide closer view around the threshold level, Note: y-axis- mean excess, x-axis-threshold level

Using equation (3.3.1), I compute shape parameter ξ and scale estimators σ, for the sample exceeding the threshold level. Table 3.2 provides 95 percent confidence interval of estimated ξ, σ, VaR and ES for both tails. The left tails gives information of future loss of the corresponding market. The positive point estimation of shape parameter shows that the estimated POT model of the CCX market is heavy tailed. Both VaR and ES are estimated at 1% significance level. The left tail point estimation of VaR provides the loss percentage of tomorrow. CCX market faces a 15% risk if the market exceeds the negative log-returns of 5.82 (threshold level of left tail) and the corresponding expected loss percentage of tomorrow will be 25%. From investor's point of view, holding of this particular asset is highly risky.

Table 3.2. Point and interval estimates of the POT model for both the tails of the CCX market returns

	Lower Bound	Point Estimate	Upper Bound
		Left Tail	
$\hat{\xi}$	-0.1	0.355	0.647
$\hat{\sigma}$	4.320	5.683	7.534
$VaR_{0.01}$	15.117	18.054	22.305
$ES_{0.01}$	24.929	33.588	75.888
		Right Tail	
$\hat{\xi}$	0.061	0.223	0.482
$\hat{\sigma}$	3.936	5.061	6.573
$VaR_{0.01}$	12.613	14.775	17.735
$ES_{0.01}$	19.200	24.065	39.603

I analyzed CCX market in chapter 2 and observed that CCX had high volatility in the second phase, i.e., January 2008 to December 2010. Maximum loss occurred during the period of June 2008- Aug 2009 and more than 50 percent of the permits were transacted between the participated members in this period. During the same period, a large number of offset permits were permitted by the CCX authority. A total of 53 million tons of offsets were released in between the years 2007 – 2008, whereas, for the Phase I, these offset were limited to 6 million (CCX, 2008; 2009; 2010). The excess supply of these offset permits might have caused the price drop and led to higher negative returns to the investors. As, described in the chapter 2, the other reason might be the political parties view on the environmental goals. Investors will not show any interest unless they are sure that the government policies are in strong support of the market for the carbon credits.

In order to support the results in Table 3.2, I computed parameters ξ, σ and the corresponding VaR estimates on 1000 bootstrap samples and plotted in figure 3.9. The right panel provides 95% confidence interval for estimated parameters and the left panel provide 95% confidence interval for risk. Both panels support the above presented values Figure 3.10 gives the sum of loss returns by the month for the period December 2003 and December 2010.

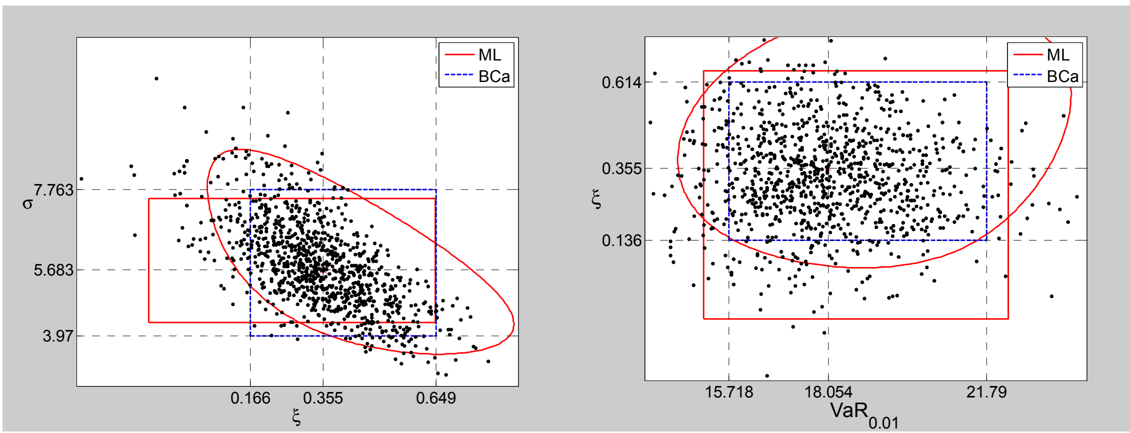

Figure 3.9. Point and Joint 95% confidence intervals for ξ,σ and *VaR* for the POT method of CCX market

Note: ML are Maximum Likelihood estimates; BCa are Bootstrap bias-Corrected and Accelerated estimates; individual dots represent bootstrap estimates (1,000 in number).

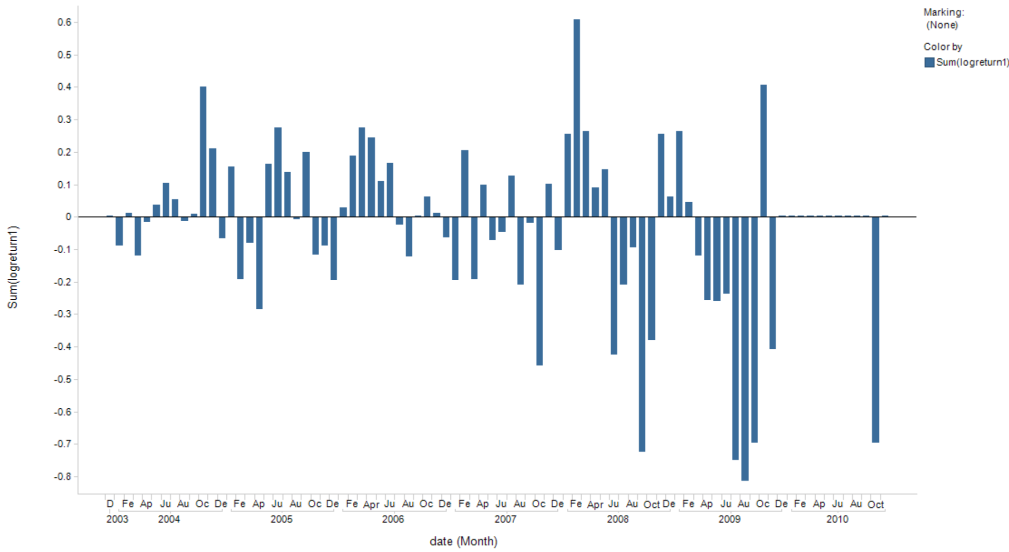

Figure 3.10. Total loss/gain by month for the period the Dec 2003 – Dec 2010 of CCX

3.3.2 Risk analysis of EU ETS Phase I

Figure 3.11 shows the threshold level of EU ETS Phase I; the threshold level of left tail is u = 15.42. A total of 33 observations (4.73 percent) exceed the threshold. For right tail the threshold level is u = 10.54 and a total 32 observation (4.73 percent) exceed the threshold. Table 3.3 provides the corresponding shape and scale parameter. The shape parameter is negative indicating that the tail falls at a rate of 12%. VaR is computed at 1% significance level and predicts that tomorrow's loss will be 30% more compared to previous day if negative log-returns exceed the threshold level. The corresponding ES will be 38% more than the previous day.

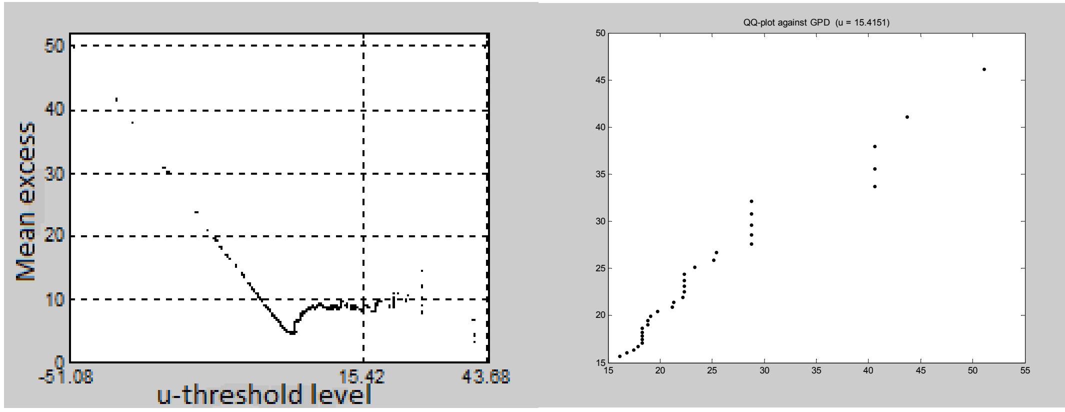

Figure 3.11. Mean excess plot of loss series of the EU ETS phase I
Note: the right panel provides the threshold level where the sample excess plot is linear, the left panel provide closer view around the threshold level, Note: y-axis- mean excess, x-axis-threshold level

Similar to the CCX market, Phase I of EU ETS market also had high volatility in returns. When we look at the kurtosis of the Phase I, we see that the market is leptokurtosis and fat-tailed. The market is negatively skewed, which means that more periods of left tail than right tail. Unlike CCX, EU ETS is a mandatory program and is controlled by a strict regulatory authority governed by the European Union. However, due to organizational problems, these carbon markets may have been rendered unstable. In Phase I (2005-2007), a total of 2.2 billion allowances per year were released under the EU emission allowances scheme and these allowances should consume in the same period. Seitfert *et al.* (2008) and Chavilier *et al.* (2010) argue that these allowances are more than required. Further, Seifert *et al.* (2008) argued that restriction on permits transfers forced the investors to sell at lower price when the market was close to termination period. Chavallier *et al.*, (2010) observed that timing of the announcement of allowances also had a strong influence on the trading market. The investors in the market must have conjectured some drastic changes when these announcements were made. As the above authors noted, the rumors of "*over allocation*" might have created a big confusion among the investors, leading to the market price drop in the month of April, 2006. These market phenomenon can be seen in figure 3.13.

Table 3.3. Point and interval estimates of the POT model for both the tails of the EU ETS phase I returns

	Lower Bound	Point Estimate	Upper Bound
		Left Tail	
$\hat{\xi}$	-0.123	-0.123	0.264
$\hat{\sigma}$	0.001	10.732	8.167
$VaR_{0.01}$	26.568	30.958	36.914
$ES_{0.01}$	33.164	38.821	56.827
		Right Tail	
$\hat{\xi}$	0.004	0.004	0.410
$\hat{\sigma}$	7.055	9.805	14.181
$VaR_{0.01}$	28.012	31.023	39.234
$ES_{0.01}$	35.212	37.091	42.123

In order to test the results in Table 3.3, I computed parameters, ξ, σ and the corresponding VaR estimates on 1000 bootstrap samples and plotted in figure 3.12.

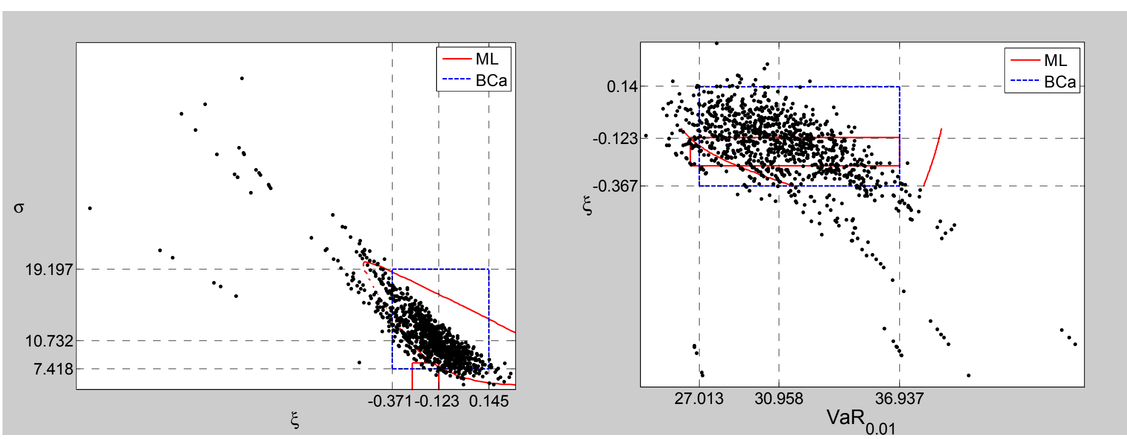

Figure 3.12. Point and Joint 95% confidence intervals for ξ,σ and VaR for the peak over threshold method of EU ETS Phase I market

Note: ML are Maximum Likelihood estimates; BCa are Bootstrap bias-Corrected and Accelerated estimates; individual dots represent bootstrap estimates (1,000 in number).

The right panel in the figure 3.12, provides 95% confidence interval for estimated parameters and the left panel provide 95% confidence interval for risk. Both panels support the above presented values. Figure 3.13 provides the total gain or loss of each month.

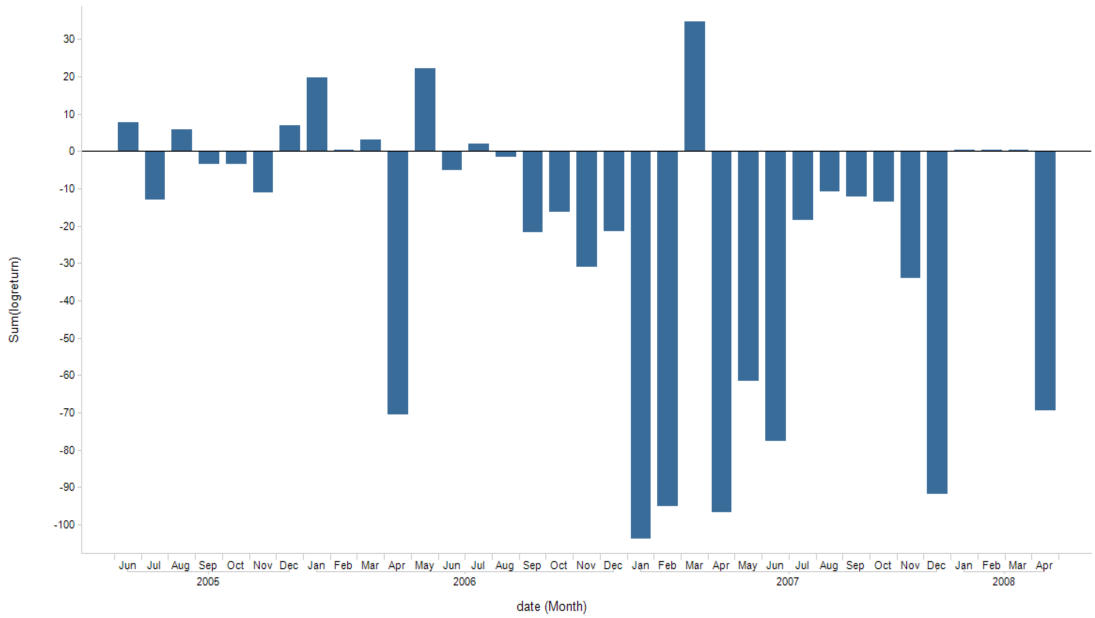

Figure 3.13. Total loss / gain by month for the period the June 2005 – April 2008 of EU ETS phase I.

3.3.3 Risk analysis of EU ETS phase II

EU ETS Phase II started on February 2008 and is still in operation. So far, it is the most stable market among all carbon emissions markets. From the table 3.1, we can observe that EU ETS Phase II has experienced a positive skewness, which indicates more positive returns. Although the mean return is negative, it showed an improvement from the previous Phase. As observerd in other two markets, EU ETS also has high kurtosis in returns and exhibits high taildness. As explained in the above sections, the estimated threshold levels based mean excess plot are given as = 4.811 with 52 observations (4.9

percent of observations) for left tail and $u =$ 3.99 with 52 observations (5 percent of total observations) for right tail. Figure 3.14 provides the estimated mean excess plot. The corresponding scale and shape parameter are provided in the table 3.4. The linear downward trend suggest a negative shape parameter.

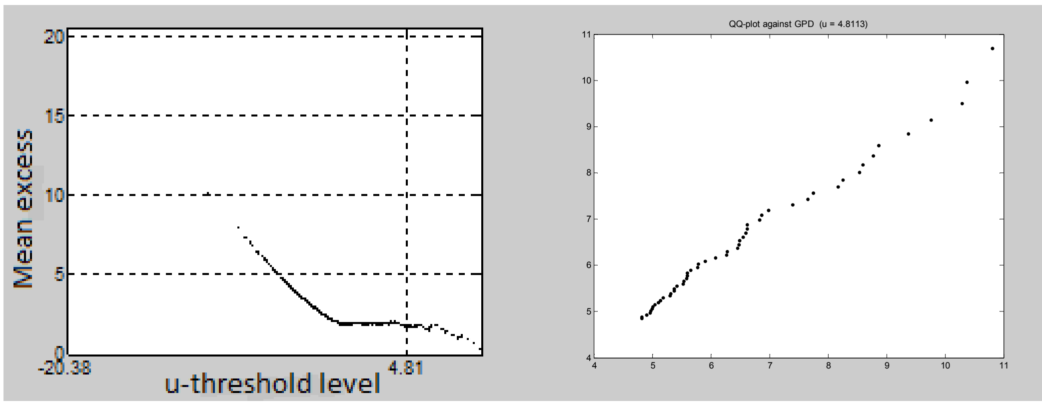

Figure 3.14. Mean excess plot of loss series of the EU ETS phase II
Note: the right panel provides the threshold level where the sample excess plot is linear, the left panel provide closer view around the threshold level, Note: y-axis- mean excess, x-axis-threshold level

Table 3.4. Point and interval estimates of the POT model for both the tails of the EU ETS phase II returns

	Lower Bound	Point Estimate	Upper Bound
		Left Tail	
$\hat{\xi}$	-0.196	-0.196	0.314
$\hat{\sigma}$	0.001	2.135	2.752
$VaR_{0.01}$	7.073	7.744	8.526
$ES_{0.01}$	8.274	9.048	11.019
		Right Tail	
$\hat{\xi}$	-0.100	0.298	0.671
$\hat{\sigma}$	0.913	1.279	1.817
$VaR_{0.01}$	5.836	6.589	7.789
$ES_{0.01}$	7.651	9.521	11.927

The market had few jolts in between 2008 and 2009 due to financial crisis throughout Europe, post-Kyoto negotiations and Copenhagen summit (Chavallier, 2010). The market was stable until June 2011, thereafter the permit price went down and large number permits traded. This type of phenomenon was observed by Seifert *et al.* (2008) for EU ETS phase I. They suggested that investors sell all the leftover permits at the ending of the trading period. Chavillier (2010) observed that the allocated allowance of the Phase II period were less than Phase I, but can be still considered as larger than the required permits. After all these problems, investors and traders showed more interest in participating in the market. When we look at the VaR of both phases, the risk from Phase II market is much less than that of Phase I. The computed VaR is 7% and the corresponding shortfall is 9%. The bootstrap samples are plotted in figure 3.15 and the monthly loss/gain for EU ETS II is plotted in the figure 3.16.

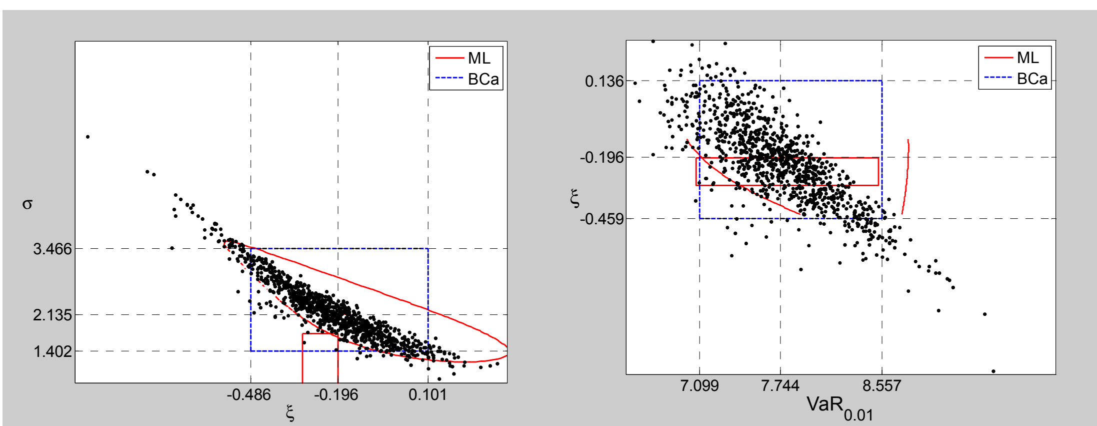

Figure 3.15. Point and Joint 95% confidence intervals for ξ,σ and VaR for the peak over threshold method of EU ETS Phase II market

Note: ML are Maximum Likelihood estimates; BCa are Bootstrap bias-Corrected and Accelerated estimates; individual dots represent bootstrap estimates (1,000 in number).

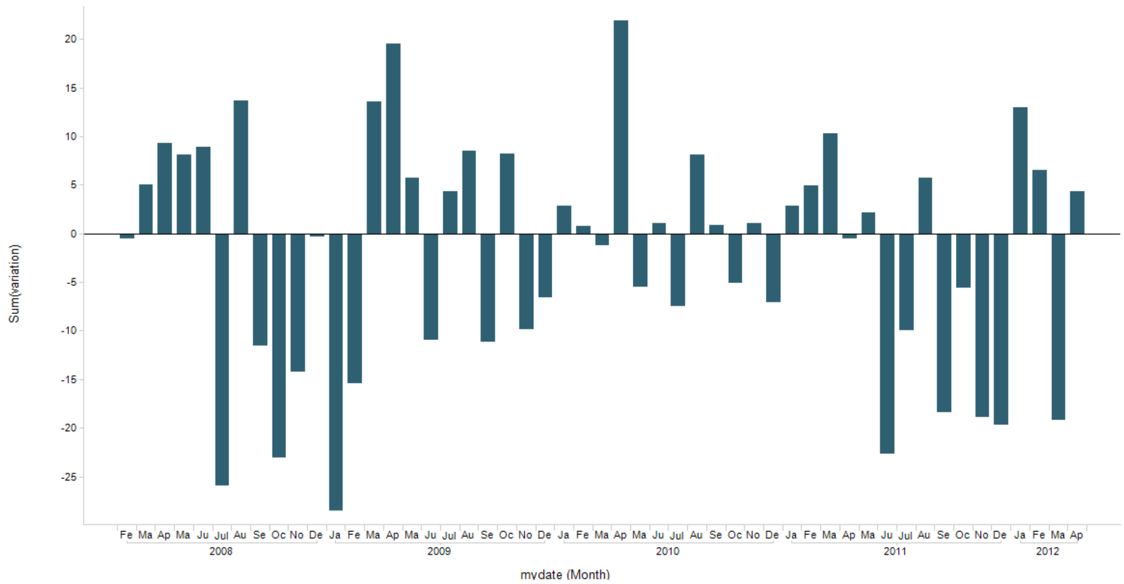

Figure 3.16. Total loss / gain by month for the period the Feb 2008 – Mar 2012 of EU ETS Phase II.

3.4 Comparative study of the CCX and EU ETS markets

Both markets have experienced certain regulatory and operational issues, such as over allocation of the permits through higher caps or allowing third-party offsets. For the purpose of comparison, I divided CCX market into two periods, pre-democratic (December 2003 – December 2007) and democratic (January 2008 – December 2010).

Table 3.5 presents the descriptive statistics as well as the computed VaR and ES. Looking at the table, we can say that all these markets have fat tails and also it can be seen that about five percent of the observations exceeded the threshold levels in all the markets. Based on the threshold levels, shape and scale parameters, VaR and ES were estimated. The predicted tomorrow's loss at 1% significance level were 9%, 28%, 31%, and 7% for CCX pre-democratic period (December 2003 – December 2007), democratic period (January 2008 – December 2010) , EU ETS Phase I (June 2005 – April 2008) and Phase II (April 2008 – December 2012), respectively.

Table 3.5. Point estimation of the POT model of the CCX, EU ETS phase I and II returns

	CCX pre democratic	CCX democratic	EU ETS Phase I	EU ETS Phase II
N	1020	763	669	1048
Mean	0.0701	-0.4782	-1.054	-0.1002
Skewness	-0.241	-3.23	-0.311	0.127
Kurtosis	14.512	39.996	11.71	7.48
Threshold level	4.763	9.53	15.42	4.81
N_u	50	34	33	52
% of exceedence	5	4.5	5	5
$\hat{\xi}$	0.349	0.16	-0.123	-0.196
$\hat{\sigma}$	2.16	10.68	10.73	2.14
$\boldsymbol{VaR_{0.01}}$	**9.34**	**28.28**	**30.96**	**7.74**
$\boldsymbol{ES_{0.01}}$	**15.11**	**44.72**	**38.82**	**9.05**

The corresponding ES was 15%, 44%, 38%, and 9% for CCX pre-democratic period, democratic period, EU ETS Phase I and Phase II, respectively. The VaR and ES results of these markets indicate an operational problem. CCX market was developed based on the United States sulfur dioxide emission trading program. The pre-democratic period was quiet stable and experienced a positive mean return. Investors were interested in assets that gave positive returns. As mentioned earlier, during this period 6 million offsets were released to meet the demand. Whereas, in the democratic period, more offsets were released than the demand. First phase of CCX was more stable and less volatile than the later period. It was also seen that holding an asset from democratic period was 19% more risky compared to the pre-democratic period. The risk level increased because of the excess supply of permits in the market. In the second phase of CCX, prices dropped drastically, this situation might have happened as a result of the regulatory board decision, which allowed more offsets in the market than required.

Similar to CCX market, in EU ETS allotted permit allowances were more than those required. EU ETS, Phase I was more volatile than Phase II. The yearly allowances allotted in Phase I were 120 million more than Phase II. The Phase I was in operation for three years and a total of 6.6 billion allowances were released; the total number of allowances were 360 million more than Phase II. Moreover, these allowances were not transferable to` Phase II. The restriction on *inter-phase banking* probably made investors desparate to sell the leftover allowances for any positive price when the market approached the termination period. In Phase II, the number of allowances was reduced and restricted to 2.08 billon per annum, and an auction of 10% of the allowances was allowed (Hepburn *et al.*, 2006). These new developments in the EU ETS market minimized the risk loss to the investors. The computed expected loss ($ES_{0.01}$) from Phase II (9.05) is 29 percent points less of Phase I (38.82). Further, EU ETS has proposed the auctioning of permits in phase III and allow more industries into the permit trade.

3.5 Conclusion

This essay attempted to analyze the tail behavior of three well-known emission trading markets, Chicago Climate Exchange, European Union Emission Trading Scheme Phase I and Phase II by using the extreme value theory. The financial risk literature has long recognized that estimating the Value at Risk and Expected Shortfall by traditional methods such as GARCH or ARCH will give narrow results and that these methods are not adequate when the markets are having high volatility, excess kurtosis and skewness. The method of dynamic EVT is a powerful tool; it examines the tail behaviors of the observations which are above certain threshold level.

The estimated results from dynamic extreme value theory model suggested that both CCX and EU ETS have similar sort of problems in relation to the operational and policy issues. Phase I of CCX was more matured than the later phase. Phase I was designed based on the US's successful sulfur dioxide emission trading program. The CCX authorities allowed fewer offset providers and encouraged trading between the existing members. Whereas in phase II of CCX, the market authorities overestimated the demand for credits and allowed more offset providers. The excess supply of the permits had a huge impact on the price; it ultimately led the price to 5 cents per permit.

Similar problems had occurred in the EU ETS program. The authorities of EU ETS created 2.2 million per year allowances in phase I of EU ETS program which were more than the required. The program also had required the permits to be sold in the same period i.e. inter-phase banking/ trading was not allowed. Because of the restriction, traders have sold the saved permits at a lower price when the phase I reached to the termination period. The EU ETS authorities were allowed 1.9 million allowances; a small reduction in the allowances compared to previous phase and proposed further reduction in the later period. The authorities allowed auctioning of fewer excess permits in phase II and extended the auction feature in the next phase. Based on the estimated results, we observed that these changes made in the phase II reduced the risk of holding the carbon asset. Our study also observes that political ambiguity on the climate and cap and trade programs have great impact on the emission prices.

In conclusion, I believe that climate change negotiations at international and national level have greater impact on permit trading markets. Proper measures of spot price dynamics and related risk measures are essential for investors, risk managers and public agencies to help gauge the carbon market performance. As illustrated in this study, early warnings of excessive market reactions to regulatory, technological and economic changes can be easily developed by way of accurate risk measures. Such measures could motivate appropriate preventive and reaction policies in order to avoid or at least minimize the losses associated with severe market collapses.

APPENDIX 2

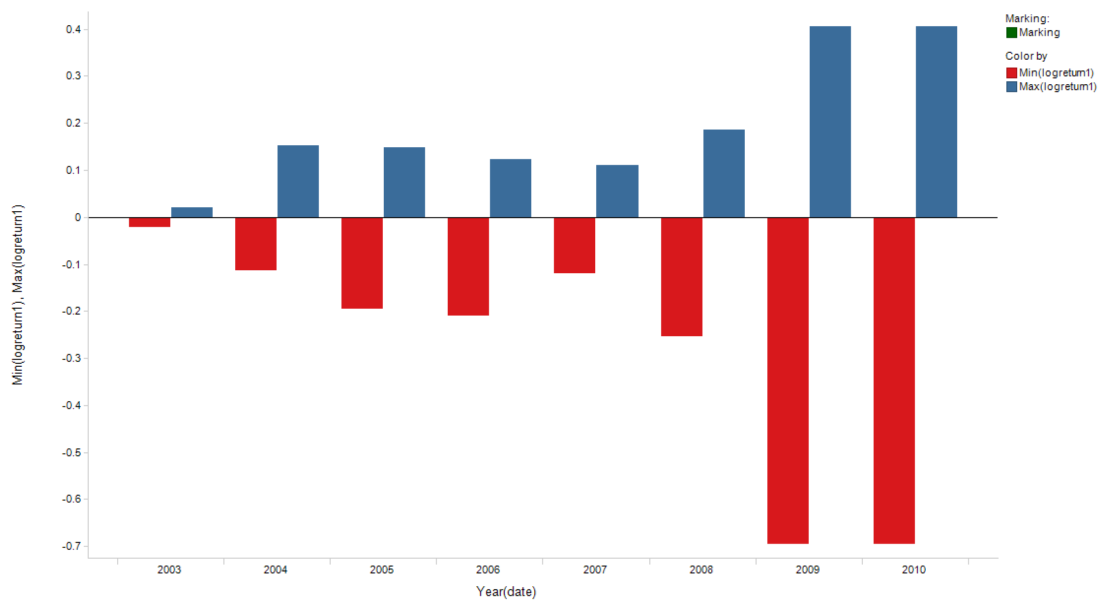

Figure 3.17.Yearly maximum and minimum log-returns of CCX

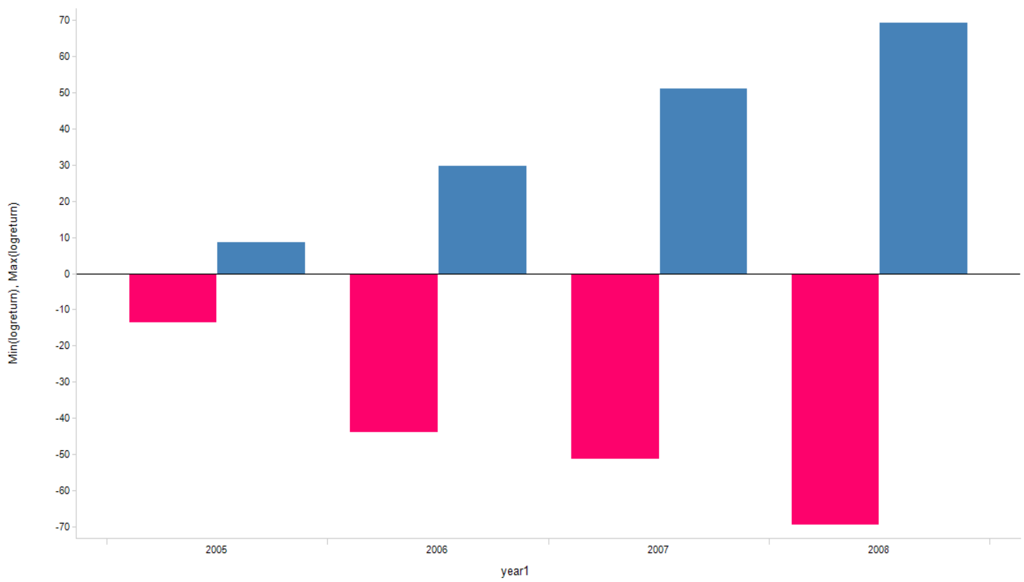

Figure 3.18.Yearly maximum and minimum log-returns of EU ETS -I

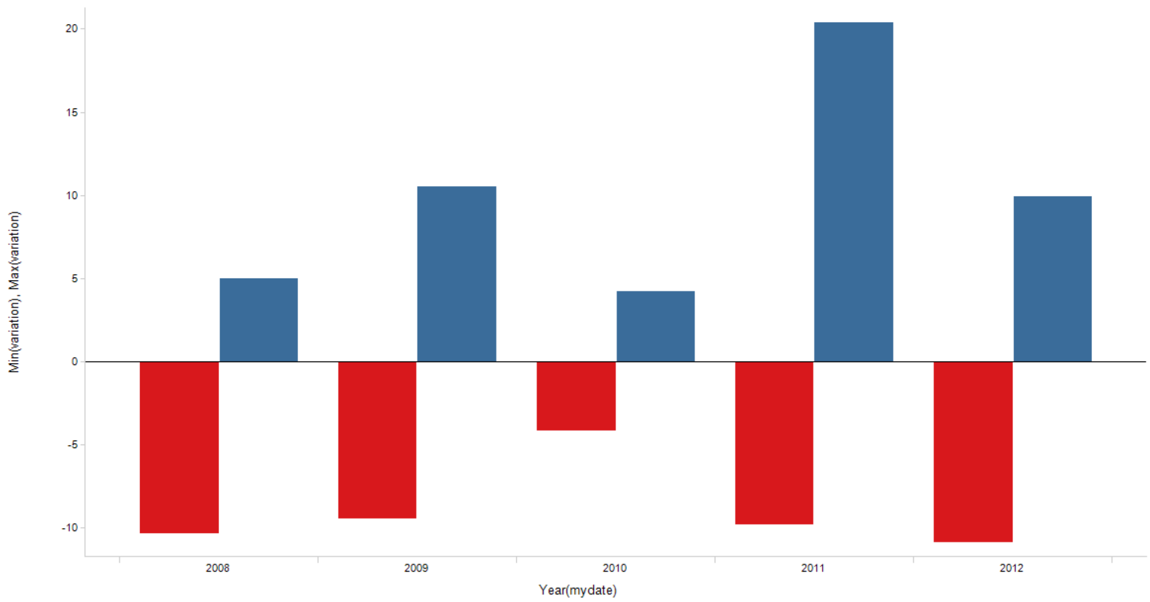

Figure 3.19.Yearly maximum and minimum log-returns of EU ETS -II

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