Carbon Trading with Imperfectly Observable Emissions

O. Odal
Department of Economics, University of Bergen, Norway

Y. Ermoliev, G. Klaassen, and M. Obersteiner
International Institute for Applied Systems Analysis, Laxenburg, Austria

RR-03-008
September 2003

Reprinted from *Environmental and Resource Economics*, **25**(2):151–169, 2003.

International Institute for Applied Systems Analysis • Schlossplatz 1 • A-2361 Laxenburg • Austria
Tel: (+43 2236) 807 • Fax: (+43 2236) 71313 • E-mail: publications@iiasa.ac.at • Web: www.iiasa.ac.at

Reprinted with permission from *Environmental and Resource Economics*, **25**(2):151–169, 2003.

Environmental and Resource Economics **25:** 151–169, 2003.

Carbon Trading with Imperfectly Observable Emissions

ODD GODAL[1], YURI ERMOLIEV[2], GER KLAASSEN[2,*] and MICHAEL OBERSTEINER[2]
[1]*Department of Economics, University of Bergen, Norway;* [2]*IIASA, Schlossplatz 1, A-2361, Laxenburg, Austria (*corresponding author: E-mail: klaassen@iiasa.ac.at.)*

Accepted 15 July 2002

Abstract. The Kyoto Protocol foresees emission trading but does not yet specify verification of (uncertain) emissions. This paper analyses a setting in which parties can meet their emission targets by reducing emissions, by investing in monitoring (reducing uncertainty of emissions) or by (bilaterally) trading permits. We derive the optimality conditions and carry out various numerical simulations. Our applications suggest that including uncertainty could increase compliance costs for the USA, Japan and the European Union. Central Europe and the Former Soviet Union might be able to gain from trading due to higher permit prices. Emissions trading could also lower aggregate uncertainty on emissions.

Key words: carbon, emissions trading, monitoring, simulation, uncertainty

JEL classification: Q35, Q3

1. Introduction

The Kyoto Protocol was established in 1997 under the United Nations Framework Convention on Climate Change (UNFCCC 19920. The main objective of the Convention is to reduce the emissions of greenhouse gases (GHGs) to prevent dangerous anthropogenic interference with the climate system. For each country taking part (referred to as Party), the Protocol specifies an emission level not to be exceeded in the period 2008–2012 (UNFCCC 1997). However, Article 17 allows for emission trading between the industrialized Parties to the Protocol. This means that each Party, or signatory of the Protocol, has the possibility to exceed their prescribed emission level given that another Party carries out an equivalent emission reduction such that the aggregate emission level remains constant. The Protocol also specifies that the Conference of the Parties shall define the relevant principles, modalities, rules and guidelines, in particular for verification, reporting and accountability for emissions trading. So far, however, little progress has been made on defining an appropriate verification mechanism.

Montgomery (1972) demonstrated that the least cost solution of reaching the aggregate target of pollution reduction agreements could be realized through trading in emission permits. The cost-effective solution can be computed and implemented if the abatement cost functions for all countries are known. However, if a permit buyer reveals its abatement cost function, the seller can use this information when bargaining on a permit price such that the buyer is worse off than she otherwise would be. Hence, Parties have incentives to keep this information private and the specific costs of emission reductions remain unknown. Acknowledging this asymmetric information problem, Ermoliev et al. (2000) proposed a decentralized optimization procedure which can be viewed as a specific Walrasian tâtonnement process simulating a scheme of sequential bilateral trade. The element we want to add to the existing analysis of emission trade is that emissions of GHGs are in general not directly measurable and assessments of GHG emissions are thus uncertain. On the basis of specific emission factors, emissions can be estimated with information on GHG-emitting activities. These activities are assessed by a national agency in each Party and the inferred emission levels are reported to the Convention Secretariat according to specific guidelines developed by the Intergovernmental Panel on Climate Change (IPCC 1997). The accuracy of the estimated emissions depends on inter alia the quality of the monitoring system in each specific country and on the accuracy of the emission factors used (c.f. Rypdal and Zhang 2000).

Several papers have examined the relation between uncertainty on (actual) emissions and emissions trading. Victor (1991: 213) identifies the problem of uncertainty by writing "... it is instructive to separate the ends and means of pollution control. The ends may be agreed upon even in the face of great uncertainty, but in designing the mechanism for achieving those ends uncertainty and complexity can prove to be extreme obstacles. This is especially true when highly quantified strategies such as markets are employed." Swart (1993) analyzes the possibility of including sinks and sources of greenhouse gases other than fossil fuel carbon emissions in a comprehensive greenhouse gas trading program. He concludes that, also in the light of uncertainty on the actual emission some gases (methane and nitrous oxide) should not yet be included in a global greenhouse gas trading regime. Farrel et al. (1999) mention different sources of uncertainty surrounding the NO_x trading program in the northeastern part of the USA. They note that uncertainty on monitored emissions requires accurate measurements so as to minimize uncertainties. Carlson and Sholtz (1999) examine the impact of uncertainty on actual emission levels on the optimal design of emission trading schemes so as to limit price volatility and conclude that staggered (overlapping) issuing of permits may enhance the effectiveness of a reconciliation period in reducing volatility. Godby et al. (1998) report on experiments that investigate the impact of uncertainty on production levels and hence emissions on price instabilities. They find that banking reduces price volatility. Montero (2000) looks at the optimal design of an emission trading program given that firms can opt-in to an existing trading program and their baseline emissions are uncertain. He concludes that the first-best equilibrium can be attained if the regulator can freely allocate permits to affected and opt-in firms.

As emissions of greenhouse gases cannot be observed perfectly, we assume that Parties' reported emissions differ from actual emissions because of uncertainty. We call this difference the uncertain volume of emissions or briefly uncertain emissions. In this paper we consider only the simplest case of non-stochastic uncertainty, i.e., when uncertain emissions are characterized only by possible ranges without specifying their likelihoods. It allows us to picture a simple verification rule that implies that when there is uncertainty on actual emissions the Protocol will require that the reported emissions plus the estimated uncertainty in the emission must be below the Kyoto target of that Party. This verification rule follows earlier work by Obersteiner et al. (2000a, b) and Jonas et al. (1999, 2000) on uncertainty and verification. Such a rule allows each Party to reduce the uncertainty surrounding the amount of reported emissions by investing in uncertainty reduction. Other alternatives would be to disallow sources (or even countries) with high levels of uncertainties to trade or to prescribe countries to meet certain minimum standards of uncertainty. From an economic perspective these alternatives seems to be less attractive than our rule since our approach creates the right incentives and minimizes overall costs on an idiosyncratic basis. The general case of stochastic uncertainty requires a more sophisticated approach, for example the use of risk functions associated with the "portfolio" of emissions similar to the Markowitz's (1987) model.

In practice the availability of reliable data on the uncertainty surrounding the emissions is poor. With the exception of large industrial sources greenhouse gas (GHG) emissions are usually estimated rather than measured directly. These estimates are usually based on activity data and emission factors (emissions per unit of activity). The easiest way of estimating the uncertainty surrounding the emissions is to combine estimates for the uncertainty (such as the standard deviation) for each input parameter. More elaborate ways consist of simulations (such as 'Monte Carlo' methods) to handle non-normal distributions, correlations between input parameters and extreme uncertainties (Rypdal and Winiwarter 2001). Uncertainties can be assessed under full greenhouse gas accounting (Nilsson et al. 2000), optionally even including checks with top-down atmospheric measurements, or under partial greenhouse gas accounting as proposed by the IPCC (2000). Uncertainties can be also used for verification of the levels of emissions as well differences over time (trend). The goal of level verification is to verify that emission levels in a target year (say 2010) are different from those in 1990, whereas trend verification concerns the verifiability of the emission reduction achieved. For the latter temporal correlations are taken into account, which explains that trend uncertainties are at least by a factor two smaller than level uncertainties.

To our knowledge, we differ from the exiting literature in various ways. First we assume that uncertainty levels surrounding emission estimates need to be included when determining whether the emission targets are met in a verifiable manner. Second, we explicitly allow investment in monitoring to reduce uncertainty on top of domestic emission abatement as well as emission trading. Finally, we offer both an analytical and numerical analysis.

The purpose of this paper is twofold. First, to examine the equilibrium conditions for the carbon permit market given the fact that emission levels are uncertain but uncertainty can be reduced by improved monitoring at a cost. Second, to apply the method using data on the major industrial Parties of the Kyoto Protocol. The paper is organized as follows: Section two derives the optimality conditions for market equilibrium to be achieved. Section three presents the data used in the analysis. In Section four we present and discuss the numerical results of our assessment. Section five concludes.

2. Methodology

We first define the necessary set of variables. Let

i	=	1, . . ., n be Parties (or sources) of the Kyoto Protocol;
x_i:	=	the reported emissions at source i;
u_i:	=	the uncertain volume of emissions at source i;
$c_i(x_i)$:	=	the costs of reducing reported emissions down to, x_i;
$d_i(u_i)$:	=	the cost of reducing uncertain volume of emissions down to u_i, (through investing in monitoring);
y_i:	=	the amount of emission permits acquired by source i (y_i is negative if i is a net supplier of permits) and
K_i:	=	the Kyoto target for source i.

In our model we separate the decision problem each Party faces in two stages. First, for a given amount of permits, each Party has to decide whether to spend resources on abating emissions or on investing in monitoring. This individual decision subproblem involves choosing parameters that do not require the information from any other Party, and we assume that the Party therefore can perform a regular optimization on this problem. Secondly, the Party needs to decide whether or not to exchange emission permits with other Parties. For the individual optimization problem discussed above, we define the least costs for Party i to comply with the Protocol for a given amount of permits, y_i, as the minimization of emission reduction costs and monitoring costs:

$$f_i(y_i) := \min_{x_i, u_i} [c_i(x_i) + d_i(u_i)] \tag{1}$$

$$\text{s.t. } x_i + u_i \leq K_i + y_i, \quad \text{for all } i. \tag{2}$$

Assume that the cost functions $c_i(x_i)$ and $d_i(u_i)$ are positive, decreasing, convex in x_i and u_i respectively. For simplicity of notation, we also assume that these functions are continuously differentiable. With this formulation, marginal costs

$c_i'(x_i)$ and $d_i'(u_i)$ are negative in x_i and u_i respectively, hence being positive in reducing x_i and u_i. We note that constraint (2) will hold with equality in the realistic case where $|c_i'(+0)|$ and $|d_i'(+0)|$ are sufficiently large such that optimal $u_i(y)$ and $x_i(y)$ for given y_i are strictly positive. Furthermore, as $f_i(y_i)$ is the minimum of two convex functions subject to a linear constraint with respect to decision variable x_i, and u_i, then from general convexity analysis we know that the function $f_i(y_i)$ is convex. Hence, the reduced function $f_i(y_i)$ is positive, convex and decreasing. By substituting (2) in (1) through eliminating x_i we obtain:

$$f_i(y_i) = \min_{u_i} \left[c_i(K_i + y_i - u_i) + d_i(u_i)\right]. \tag{3}$$

Then, by making use of the envelope theorem on (3) we obtain

$$f_i'(y_i) = \frac{\partial}{\partial y_i} \min_{u_i} \left[c_i(K_i + y_i - u_i) + d_i(u_i)\right] = c_i'(x_i(y)). \tag{4}$$

If substituting (2) in (1) through eliminating u_i we would equivalently obtain

$$f_i'(y_i) = \frac{\partial}{\partial y_i} \min_{x_i} \left[c_i(x_i) + d_i(K_i + y_i - x_i)\right] = d_i'(u_i(y)). \tag{5}$$

Let $u_i(y)$, $x_i(y)$ be optimal solution of subproblem (1), (2), i.e., reported emissions and the optimal volume of uncertainty for given y_i. As (4) is equivalent to (5), we obtain the optimality condition, namely that $c_i'(x_i(y_i)) = d_i'(u_i(y_i))$. This states that in the cost-minimum for each source i, the marginal cost of reducing emissions down to $x_i(y)$ will be equal to the marginal costs of reducing the uncertain emissions down to $u_i(y)$. If not, the total costs for Party i of reaching K_i for a given amount of permits, y_i, could be lowered.

Minimizing (1) subject to (2) by setting up the Lagrangian, and applying the envelope theorem to this scheme we obtain the condition that

$$f_i'(y_i) = -\lambda_i, \tag{6}$$

where λ_i is the Lagrangian multiplier and is interpreted as the shadow price, or the willingness to pay to Party i, for relaxing constraint (2) with one unit, i.e., the right to emit one more unit of reported or uncertain emissions. We note that λ_i is strictly positive if $c_i(x_i)$ and $d_i(u_i)$ are strictly decreasing. Otherwise, λ_i could be equal to zero. According to (6), the marginal change in the minimum cost of complying with the Protocol by a unit increase in y_i, (which is negative) is also equal to – λ_i. Hence according to (4) to (6), for a given y_i, the value of one additional permit is equal to the marginal cost of holding reported or uncertain emissions down to the optimal level. Outside equilibrium λ_i will differ between two or more Parties; i.e. they have different willingness to pay for a permit, thus making trading in permits in a mutual beneficial way possible.

This brings us to the main optimization problem, which involves finding the permit vector, or distribution of permits, that realizes the global least cost solution. We define:

$$F(y) := \sum_{i=1}^{n} f_i(y_i) \tag{7}$$

as the total or social costs for reaching the agreement for a given vector of permits, y, where $f_i(y_i)$ are defined in (1). If we had a socials planner that knew $f_i(y_i)$ for all I she could minimize (7) subject to:

$$\sum_{i=1}^{n} y_i = 0 \tag{8}$$

by setting up the Lagrangian, which would yield the first order condition:

$$f_i'(y_i) = -\mu \text{ for all } i. \tag{9}$$

Condition (9) states that the marginal value of a permit (the permit price) shall in equilibrium be equal to a specific level $-\mu$ among all parties. Combining equations (4) to (6) and (9) implies that the necessary condition for a market equilibrium in the permit market is that the permit price equals marginal emission reductions costs and equals the marginal costs of improved monitoring. In addition, condition (2) has to hold: the reported plus the uncertain volume of emissions has to be equal to Kyoto target plus the net emission permits bought.

It can be shown that, in the absence of transaction costs and irreversibilities, a system of bilateral, sequential trading converges to the global least cost solution (see Ermoliev et al. 2000). Although we believe that evidence on sulfur trading in the USA (Klaassen and Nentjes 1997) and carbon trading (Atkinson 2001) indicates that most trading occurs in a bilateral, sequential fashion, we will not elaborate on this here since the focus of this paper is on the impact of including improved monitoring possibilities (to reduce uncertainty on emissions) on the equilibrium outcome of emission trading and not on trade dynamics.

In Figure 1 we give a graphical presentation of how we model the uncertain emissions. The vertical axis depicts the marginal abatement cost function for reducing x and u, (i.e., $c'(x)$ and $d'(u)$ respectively). Without uncertain emissions and trading the source would have to reduce reported emissions to the level K. When uncertain emissions are included in the emission inventory the source has to keep the sum of u and x below the Kyoto target. Then after optimizing between abating reported emissions and investing in monitoring, reported emissions increase to x^*, while the uncertain volume of emissions decreases to u^*, satisfying the constraint $x^* + u^* = K$, $(y = 0)$ while minimizing the costs of reaching the target. In Figure 1 trading in permits would graphically be the same as changing the Kyoto target for this particular source. The choice of a non-stochastic model of uncertainty was motivated by the simplicity of this analysis and availability of data.

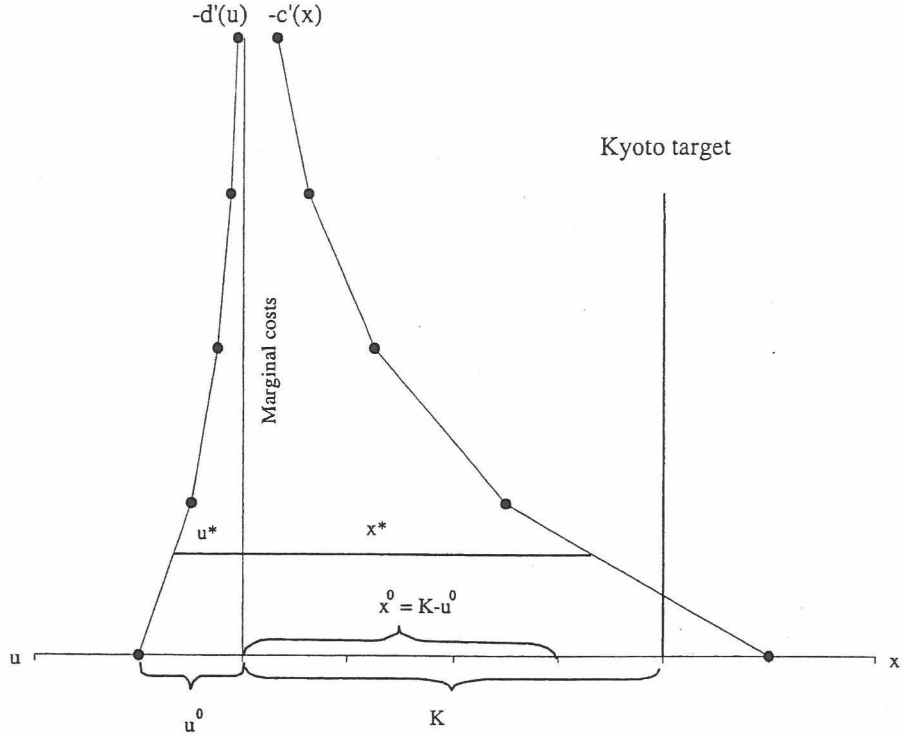

Figure 1. Graphical presentation of the setting.

The general case of stochastic uncertainty requires a more sophisticated analysis, although qualitatively the effects of uncertainty are similar.

3. Data

To apply the model described in Section 2, we employ data on the costs of emissions reductions estimated from the POLES model (see Gusbin et al. 1999) for the countries (or group of countries) of USA, Japan, EU-15 and Central and Eastern Europe (CEE, consisting of the Czech Republic, Hungary, Poland, Slovakia, Bulgaria and Rumania). We also include Russia and Ukraine into the analysis. The cost functions for the latter two countries were derived from the results of the POLES model for the Former Soviet Union, using additional information on emissions from Victor et al. (1998). All emission reduction cost functions employed in the numerical analysis only consider energy related carbon emissions reductions. Other carbon sources or GHG emissions are disregarded. The countries included in the analysis constitute the major participants of the Kyoto Protocol. Piecewise linear marginal cost functions were fitted to the dataset as shown in Figure 2. We use the following notation: One metric ton (t), carbon (C), United States dollars (US$, in 1990 prices), Million (M), and Billion (B).

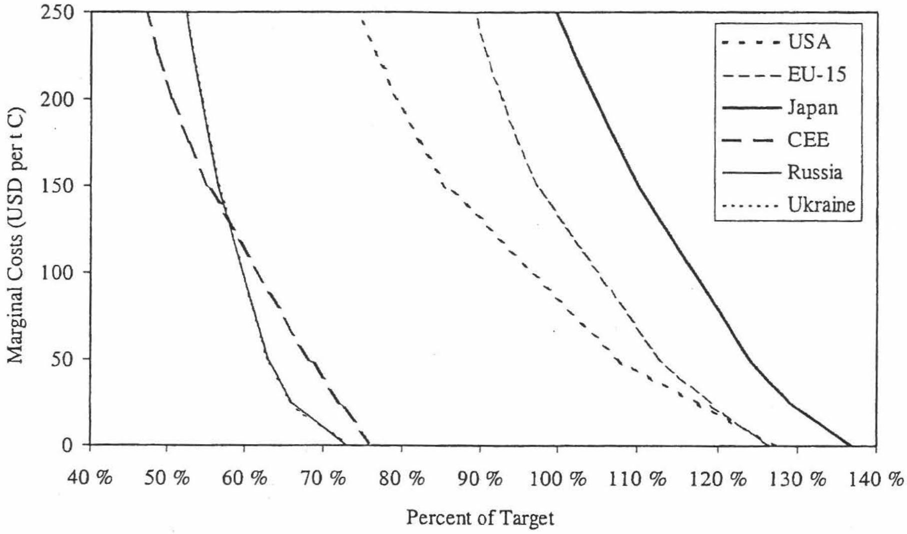

Figure 2. Marginal costs of reducing emissions as a function of the emission level relative to the Kyoto target (US$ per tC). Russia and Ukraine are difficult to separate, as they are almost superimposed on each other.

As mentioned in the introduction the availability of reliable data on the uncertainty surrounding the emissions and the costs of reducing the uncertainty through monitoring is still limited. We have implemented estimates for CO_2 emissions based on estimates of the most recent studies. Rypdal and Zang (2000) have conducted the most in depth analysis of uncertainties of all GHGs on a national scale. According to their estimates, Norway shows a trend uncertainty for all GHGs of $\pm 5\%$. Norway's level uncertainty of all GHGs was estimated to be $\pm 21\%$ in 1990 and $\pm 17\%$ in 2010. Following the IPCC report on Greenhouse Gas Inventories (IPCC 2000), uncertainty assessments have been made available for other countries such as Austria, Europe, Great Britain, the Netherlands, Poland, Russia, and Ukraine (Jonas and Nilsson 2002; Weiss et al. 2000; Winiwarter and Orthhofer 2000; Winiwarter and Rypdal 2001; Charles et al. 1998; Van Amstel et al. 2000; Nilsson et al. 2000; Gawin 2001; Kulik 2001; Cozijnsen 2002). The uncertainty values listed in Table I are in line with the above mentioned references for the EU, CEE countries, Russia and the Ukraine. For the US we used the IPCC (2000) default uncertainty which is at the upper range of recent US estimates (IEA 2001). For Japan we lack information and we conjecture Japan's uncertainty to be between that of the US uncertainty level and that of the EU.

We also made some simplifying assumptions on the costs of reducing the uncertainty surrounding emission which fit reasonably well with the information on the monitoring costs of the sulfur emission-trading program in the USA (Klaassen and Nentjes 1997: 135). The numerical results presented in Section 4 are based on these estimates and should therefore be considered as illustrative. The piece-

Table I. Uncertain emissions as percentage of reported business as usual emission levels in 2010. Percent (%) and levels (MtC)

	USA	EU	Japan	CEE	Russia	Ukraine	Total
Share of BAU, σ(%)	10	20	15	25	30	30	17
Level (MtC)	169	219	61	51	143	39	681

wise linear marginal cost functions of investing in monitoring infrastructure are parameterized in a simplistic manner (see Figure 1). Consider the marginal cost function of reducing reported emissions; $c_i'(x_i) = a_i + b_i * x_i$, and the marginal cost functions of reducing uncertain volume of emissions; $d_i'(u_i) = p_i + q_i * u_i$. We assume that the marginal cost of reducing uncertain volume of emissions at the initial levels defined in Table I are zero. Then we assume that the marginal cost of reducing the uncertain emissions at any percent of the initial level ($u_i^0 = \sigma_i * x_i^0$) is the same as the marginal cost of reducing the reported emissions with the same percentage of the initial level (BAU_i). When employing this scheme, the values of the parameters p_i and q_i are such that $p_i = a_i$ and $q_i = -a_i/(\sigma_i * x_i^0)$. This formulation of $d_i'(u_i)$ represents therefore just a rescaling of the slope of $c_i'(x_i)$, such that $d_i(u_i) = \sigma_i[c_i(x_i]$ for all i.

4. Results

In our numerical experiments we used the procedure of sequential bilateral trades as a specific optimization method for solving problems (7)–(8). In contrast to the standard optimization software it is rather flexible for conducting experiments. Besides, it also provides insights into the possible dynamics of trades. Since the main contribution of our paper is however on the impact of improved monitoring to reduce uncertainty (at a costs) on the performance of emission trading we will not address the trade dynamics at length but instead focus on the analysis of the equilibrium outcomes.

Below we present the results of various simulations. First we simulate the market in a traditional way excluding the uncertain emissions (the base case). This is therefore just a numerical application of the scheme described in Ermoliev et al. (2000). Both the initial and equilibrium states as well as the dynamics of the trading process itself are briefly described. Then we include the uncertain emissions, and show the results for the choice between emission abatement and improved monitoring in a setting with and without emission trading. Finally, we present some sensitivity analysis where only parts of the uncertain emissions are included.

Table II. Emissions, marginal costs and total costs before and after trade

	USA	EU	Japan	CEE	Russia	Ukraine	Total
Emissions (MtC)							
Kyoto target	1,325	867	295	267	650	178	3,582
BAU	1,690	1,097	404	203	475	130	3,999
After trade	1,487	1,003	373	187	418	114	3,582
Traded[a]	162	136	78	−80	−232	−64	376
Marginal costs (US$ per tC)							
Before trade	85	133	248	0	0	0	
After trade	38.6	38.5	38.5	38.5	38.5	38.5	
Emission reduction costs (Million US$ per year)							
Without trading	13,468	13,032	10,873	0	0	0	37,373
With trading	3,907	1,722	556	308	915	248	7,658
Total savings after trade							29,698

[a]Implies current net amount volume bought.

4.1. PERFECT OBSERVATIONS OF EMISSIONS – BASE CASE

The base case is where we assume that the uncertain volume of emissions is not included in the agreement. Parties can then comply with the protocol only by reducing emissions and by trading permits. Some of the key figures before the first and after the last trade are presented in Table II.

Table II shows that CEE, Russia and Ukraine can meet their targets without implementing any control measure, as their targets are higher than their BAU emissions. Before trading, Japan has marginal costs of emission reduction of around 250 US$ per tC, the EU of 130 and the USA 85 US$ per tC. Total costs before trading are 37,400 Million US$. After trading, marginal costs settle around 38.5 US$ per tC in all countries. More than 50% of the committed reductions in the USA, EU and Japan are bought from CEE, Russia and Ukraine during trade.

The total savings realized from trade is computable, and estimated to be 29,700 Million US$ per year. Total costs of reaching the aggregate target are thus reduced by approximately 80% as a result of trading. The relatively large reduction in total costs illustrates why carbon trading is attractive in an economic context.

In terms of the dynamics, cost reductions from each trade are larger in the early stages of trade than towards the end. Parties have larger differences in marginal costs in the beginning making the cost saving potentials greater than towards the end. This observation is typical for trading in many commodities. The total benefits from trading are larger the more different Parties are. To give a better view of how the path towards equilibrium varies in different simulations, the model was run 50 times. The results indicate that in the simulation with the slowest convergence trade

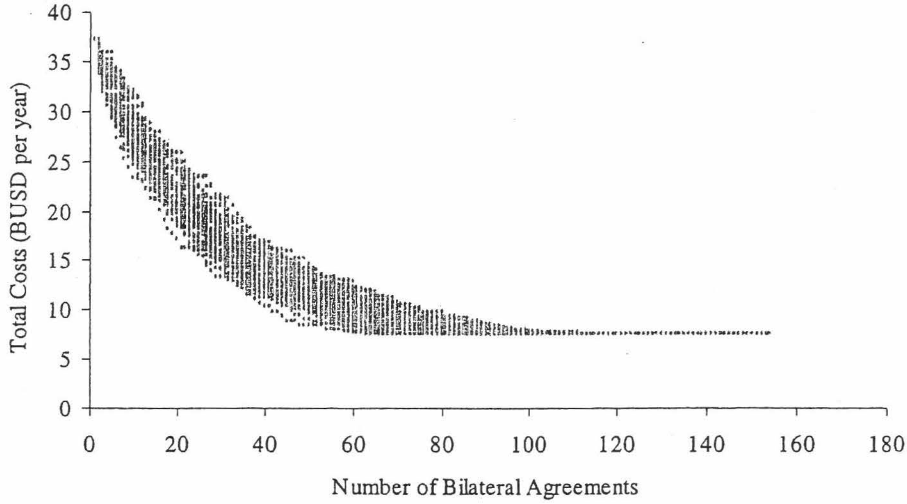

Figure 3. Change in total costs as a function of the number of bilateral agreements in 50 simulations (Billion US$ per year).

stopped after 153 bilateral agreements, the fastest at 80 trades, 90% being between 93 and 143 trades (see Figure 3).

4.2. IMPERFECT OBSERVATIONS OF EMISSIONS

We now introduce imperfect observation of emissions into the calculations. The rules of the agreement are now such that Parties need to find the least cost combination of reducing reported emissions, x, reducing the uncertain volume of emissions, u (by investing in monitoring) and by trading in emission permits, y, such that constraint (2) is satisfied. In Table III we present the initial situation before emission trading starts but after each Party has optimized between reducing reported and uncertain emissions.

Table III shows that marginal cost of each country of reducing reported emissions and of investing in monitoring are equal, in accordance with the analysis in Section 2. The marginal costs are in the range of 0–400 US$ per tC, considerably higher than when only reported emissions are included in the targets. This is because the need for reductions in reported emissions is now considerably larger. We also note that the "hot air" we had in the previous simulation now is reduced since the uncertain emissions are now added to the baseline emissions. Table III also shows that without trading the monitoring costs would be 15.9 Billion US$ and abatement costs would be around 99 Billion US$. This implies that the monitoring costs would be around 16% of the abatement costs. This estimate fits very well with the costs of (continuous emission) monitoring of the sulfur trading program in the USA that were estimated to equal 8 to 13% of the abatement costs (Klaassen and Nentjes 1997).

Table III. Emissions, marginal costs and total costs before trading with imperfect observation of emissions

	USA	EU	Japan	CEE	Russia	Ukraine	Total
Emissions, (MtC)							
Reported	1,197	717	253	214	500	137	3,017
Uncertain	128	150	42	53	150	41	564
Total emissions	1,325	867	295	267	650	178	3,582
Marginal costs (US$ per tC)							
Of emission reduction	127.9	242.8	395.6	0.0	0.0	0.0	
Of monitoring	127.9	242.8	395.6	0.0	0.0	0.0	
Costs (Million US$ per year)							
Emission reduction costs	27,103	47,102	24,093	0	0	0	99,108
Monitoring costs	2,710	9,420	3,736	0	0	0	15,866
Total costs (excl. permits)	29,813	56,522	28,639	0	0	0	114,974

After trading, marginal costs reach 130 US$ per tC and are about 3 times higher than in the base case (without uncertain emissions and without trading) (see Table IV). This is because all Parties now have to do considerably more abatement, as the uncertainty on emissions has to be accounted for. This is an obvious result once one recognizes that including the upper range of uncertainty in the Kyoto cap is equivalent to lowering the cap. The increase in the price is so dramatic since the net emission reduction under the Kyoto Protocol without uncertainty would only be 417 MtC (Million ton carbon). This is due to the fact that Russia, Ukraine and CEE can offer 287 MtC at zero marginal costs since their business-as-usual emissions are much lower (the so called "hot air") than their Kyoto targets (compare Table II). Adding an average uncertainty of 17% is equivalent to an additional volume of emissions of 681 MtC to be reduced. To reduce this extra amount no "hot air" is available anymore and significant additional emissions reductions need to be made at those parts of the cost curves that are relatively steep (see Figure 2).

An important difference compared to the case of perfect emission observation is that the USA now become a net permit supplier even though the quantity is small. This is because the rate of change in marginal costs in USA is lower than in the EU and Japan and because the assumed uncertainty of the emissions in the USA is lower. Comparing the situation before and after trade we see that the volume of uncertain emissions decreases by approximately 1%. Trading in permits leads to increased emission abatement and monitoring investments in permit exporting countries. This effect on the total level of uncertain emissions is larger than the effect of higher volumes of uncertain emission levels in permit importing countries. Total abatement costs after trade are approximately eight times higher compared

Table IV. Emissions, marginal costs and aggregate costs after all trades with imperfect observation of emissions

	USA	EU	Japan	CEE	Russia	Ukraine	Total
Emissions, (MtC)							
Reported	1,188	869	333	154	376	103	3,023
Uncertain	127	182	52	39	124	34	559
Total emissions	1,315	1,052	385	193	500	137	3,582
Amount traded[a]	−10	185	90	−74	−150	−41	275
Marginal costs (US$ per tC)							
Of emission reduction	130.9	130.8	130.2	130.4	130.1	130.9	
Of monitoring	130.9	130.8	130.2	130.4	130.1	130.9	
Costs (Million US$ per year)							
Emission reduction costs	28,270	12,708	3,842	3,046	4,330	1,182	53,378
Monitoring costs	2,827	2,542	576	761	1,299	355	8,360
Total costs (excl. permits)	31,097	15,250	4,418	3,807	5,629	1,537	61,738
Total savings due to trade							53,235

[a]Implies net amount bought.

to the situation where (the estimated) uncertain volume of emissions would have been excluded. The marginal cost functions on emission reduction are, as shown in Figure 2, quite linear in the range 38.5 to 130 US$ per tC. Therefore when the marginal costs in the equilibrium state increase by approximately three times, the level of the annual abatement costs, i.e. the area under the marginal cost curve can be expected to increase about nine times, as this relationship is quadratic. However the additional option to meet targets through investing in monitoring and thus reducing the uncertainty on emissions reduces this factor from nine to eight. The cost savings due to trading in this case are 53.2 Billion US$, or 46% compared to the situation without trading.

Uncertainty on emissions will be present whether the uncertainty is included in the commitments or not. However, when included in the Protocol, the total emission levels without abatement would be higher and the required emission reduction larger, changing the constraint of the minimization problem (equation (2) in Section 2). The results in Table II, III and IV should therefore be compared cautiously as they describe solutions of two very different minimization problems.

4.3. SENSITIVITY ANALYSIS

Bearing in mind the reluctance of some Parties to ratify the Kyoto Protocol as it currently is formulated, it seems unrealistic that these Parties will agree to a scheme where the estimated uncertainty on emissions is fully included in each

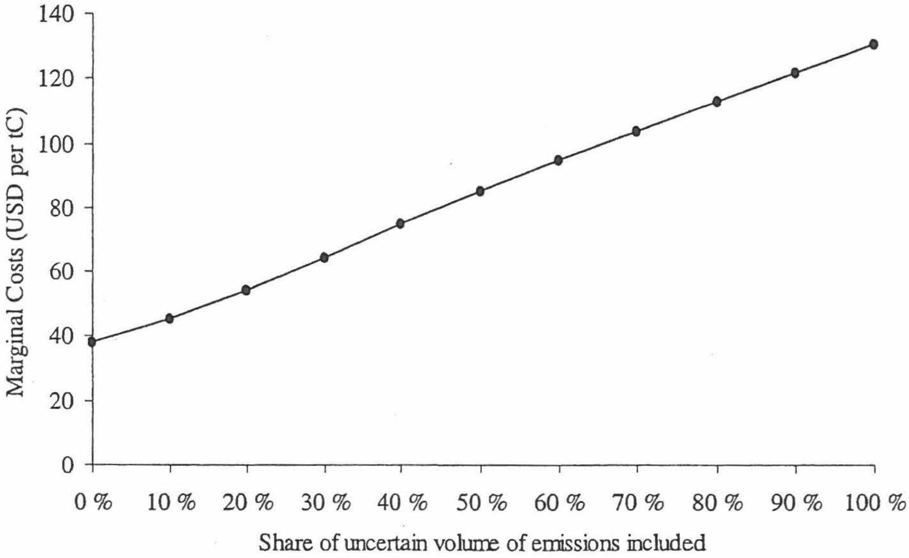

Figure 4. Marginal costs (US$/ton C) after trade as function of the share of the uncertain volume of emissions included in the agreement.

Party's target as described above since this would significantly lower the implicit Kyoto cap. The costs of complying with the agreement would increase dramatically for some Parties. For this reason we explore some more moderate versions of the above scheme. We simulate the model assuming that only a specific part of the uncertainty on emissions is included (10%, 20%...). This is equivalent to saying that given that there are different estimates surrounding the uncertainty, instead of using the highest estimate the Parties to the Protocol may agree on using the median or even lower estimates. The final marginal cost in each case is shown in Figure 4.

The points in Figure 4 between 50 and 150 US$ per tC lay on a straight line because the piecewise linear cost functions in this range as presented include only one line. With a finer grid for these functions in this interval, the curve in Figure 4 would increase more rapidly.

Furthermore, to give some indications on how the various Parties may gain or lose from including various amounts of the uncertain emissions into the scheme, we estimate the total costs for each Party including the expenses/revenues from the permit trade. As pointed out above, we have no unique permit price in our scheme. In the following calculations we therefore apply the marginal cost after trade as a proxy for this parameter. Figure 5 shows that as the amount of uncertain emissions increases, the costs rise quite rapidly for USA, EU and Japan. In these cases, the costs increase both because more reductions will be carried out at home and because the expenses on emission permits purchases increases as all Parties have higher marginal costs. In terms of total costs, EU is the most severely affected

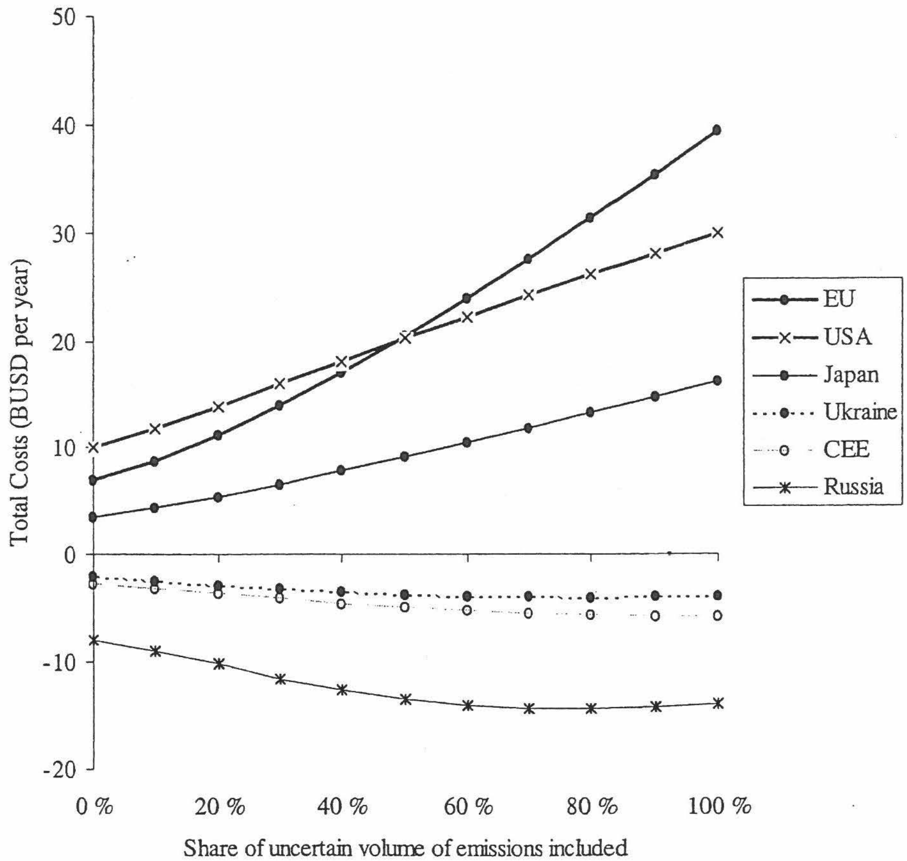

Figure 5. Change in the net total costs as a function of the share of the uncertain volume of emissions included in the Protocol after trading (Billion US$ per year.

due to the assumption of larger levels of uncertain emissions in combination with a relatively steep marginal cost function.

For Russia, Ukraine and CEE, the (net) costs of complying with the Protocol before including uncertainty on emissions are negative, i.e. they make positive profits. This is because the value of the permits sold is higher than the costs of emission reductions and monitoring investments. The more surprising finding here is that these countries may actually benefit from including uncertainty on emissions in the agreement even though these countries are assumed to have the highest share of these uncertain emissions. As uncertain emissions are gradually included, this negative effect on profits is dominated by the increase in permit price, which contributes to higher profits on permits sold. In the case of Russia and Ukraine, profits are increased to its maximum (being 80–100% higher than in the base case without uncertain emissions) when 80% of the uncertain emissions were to be included in the Protocol. From this point, the effect of the increased permit price is less important than the need for reductions, making profits fall slightly. For CEE however, the positive effect from the higher permit price dominates in all cases the effect of the need for larger reductions. This is because CEE is assumed to have a lower share of uncertain emissions than Russia and Ukraine. Of course one should be aware that who gains or loose depends on the way uncertainty is treated in the model and on the actual uncertainties included.

5. Concluding Remarks

The objective of this paper was to examine the outcome of the carbon permit market given uncertain emission levels and the possibility to reduce this uncertainty by investing in monitoring and to apply this method for the Kyoto Protocol. In the analytical part we derive the equilibrium conditions. In the equilibrium, the permit price has to be equal the marginal costs of abatement as well as the marginal costs of improved monitoring. In addition, reported emissions plus the uncertainty surrounding emissions (the uncertain emissions) have to be equal to the emission target plus any net permits bought.

Our main findings regarding the application of the model suggest that when uncertainty on emissions is included in the Kyoto agreement, in the way we envisage by reducing the uncertain volume of emissions from the allowed Kyoto target, and when countries can reduce the uncertainty through investing in monitoring, marginal emission reduction costs would increase. Compliance costs may even increase significantly for the USA, the EU and Japan since the options for buying cheap emission permits are restricted. Quite surprisingly we find that Russia, Ukraine and CEE might experience financial gains when uncertainty on emissions were to be included in the Protocol commitment. This is so because the resulting rise in the permit price and associated revenues outbalances the need for additional monitoring and domestic emission reduction costs due the larger levels of uncertain emissions. Perhaps also surprisingly, we also find that trading in carbon permits, in this particular setting, may also lead to a reduction in the volume of uncertain emissions and hence, reduce the overall uncertainty in emissions. This is so since improved monitoring is to a certain degree cost-effective.

It is important to note the limitations of this analysis. First, not all Parties of the Kyoto Protocol are included in our numerical analysis. The omitted (industrialized) countries are in aggregate likely to be net buyers of permits, which gives rise to higher equilibrium marginal cost than our results indicate. Moreover, the opposite effect would be expected if emission trading would be expanded to developing countries since these are likely to act as net sellers thus reducing the permit price (compare Gusbin et al. 2000). In addition including more carbon sources and sinks, as well as emissions of other greenhouse gases would also improve the numerical analysis. Furthermore, it is important to bear in mind that the data on business as usual emissions are uncertain, as are the marginal cost functions for reducing reported emissions. Especially the figures used for the uncertainty on emissions are themselves uncertain. Moreover, as indicated in section 3 we have implicitly assumed that reported emissions and the uncertainty surrounding the emissions, in optimum, are reduced in the same proportions. If the cost for reducing the uncertainty were higher (for a given level of uncertainty) than we assumed, including the uncertainty in the targets would result in smaller reductions in uncertainty, larger reductions in reported emissions and higher permit prices than we have calculated. This would increase compliance costs for permit importing countries. The effect on compliance costs for permit-exporting countries is ambiguous, since higher permit prices and less flexibility in meeting targets work in different direction. Finally, we recognize that our data on the cost functions for reducing reported emissions including the baseline emission levels in 2010 could depend on how the uncertainty on emissions is modeled. Such changes in baseline emissions and cost functions were not considered here. Although the actual levels of costs when uncertainty on emissions is included should be considered as illustrative, our findings on the direction of change are probably more reliable.

Nevertheless, it is good to recall that the treatment of uncertainty on emission levels and compliance is still an open issue in the Kyoto Protocol. In spite of the above limitations, this study has given some insights on how the distribution and level of compliance costs may change (and perhaps significantly) if uncertainty on actual emissions were to be included in a verification mechanism under the Kyoto Protocol.

Acknowledgements

The authors would like to thank Sjur D. Flåm at the Department of Economics, University of Bergen in Norway for discussions and comments and Tatiana Ermolieva (IIASA) for helping with software. The provision of data from the POLES model was greatly appreciated. Financial support from the Norwegian Research Council is gratefully acknowledged. Comments from two anonymous reviewers were helpful in improving the paper.

References

Atkinson, T. (2001), 'Trading in Practice – Why Should Industry Get Involved?', Natsource Environmental Brokerage Desk, Presentation 29th November 2001, Vienna.

Carlson, D. and A. Sholtz (1999), 'Designing Pollution Market Instruments: Cases of Uncertainty', *Contemporary Economic Policy* **12**(4), 114–125.

Charles, D., B. M. R. Jones, A. G. Salway, H. S. Eggleston and R. Milne (1998), 'Treatment of Uncertainties for National Estimates of Greenhouse Gas Emissions', Report Nr. AEAT-2688-1. AEA Technology, Culham, United Kingdom.

Cozijnsen, J. (2002), 'CO_2 Is No the Only Gas', *Environmental Finance* (December 2001/January 2002), 38–39.

EIA (2001). 'Emissions of Greenhouse Gases in the United States 2000', DOE/IEA-0573, Energy Information Administration, Department of Energy, November. Washington DC.

Ermoliev, Y., M. Michalevich and A. Nentjes (2000), 'Markets for Tradable Emission and Ambient Permits: A Dynamic Approach', *Environmental and Resource Economics* **15**, 39–56.

Farrell, A., R. Carter and R. Raufer (1999), 'The NO_X Budget: Market-Based Control of Tropospheric Ozone in the Northeastern United States', *Resource and Energy Economics* **21**(2), 103–124.

Gawin, R., (2001), 'Level and Trend Uncertainties of Kyoto Relevant Greenhouse Gases in Poland', Interim Report, IIASA, Laxenburg, Austria (forthcoming).

Godby, R., S. Mestelman, R. A. Muller and D. Welland (1998), 'An experimental Economic Analysis of Emissions Trading with Shares and Coupons in the Presence of Uncertainty', *Environmetrics* **9**, 67–79.

Gusbin, D., G. Klaassen and N. Kouvaritakis (1999), 'The Costs of Ceiling on Kyoto Flexibility', *Energy Policy* **27**(14), 833–844.

IPCC (1997), 'Revised 1996 Guidelines for National Greenhouse Gas Inventories (3 Volumes)', Intergovernmental Panel on Climate Change, WGI Technical Support Unit, Bracknell, UK.

IPCC (2000), 'Good Practice Guidance and Uncertainty Management in national Greenhouse Gas Inventories', Intergovernmental Panel on climate Change (IPCC). Available on the Internet: http://www.ipcc-nggip.iges.or.jp/gp/report.htm.

Jonas, M., S. Nilsson, M. Obersteiner, M. Gluck and Y. Ermoliev (1999), 'Verification Times Underlying the Kyoto Protocol: Global Benchmark Calculations', Interim Report, IR-99-062, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Jonas, M. and S. Nilsson (2002), 'The Austrian Carbon Database Study Overview', Interim Report, IR-01-064, IIASA, Laxenburg, Austria.

Jones, M., M. Obersteiner and S. Nilsson (2000), 'How to Go From Today's Kyoto Protocol to a Post-Kyoto Future that Adheres to the Principles of Full Carbon Accounting and Global-scale Verification? A Discussion Based on Greenhouse Gas Accounting, Uncertainty and Verification', Interim Report, IR-01-064, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Klaassen, G. and A. Nentjes (1997), 'Creating Markets for Air Pollution Control in Europe and the USA', *Environmental and Resource Economics* **10**, 125–146.

Kulik, M. (2001), Personal Communication January 2002. Energy Systems Institute of the Academy of Science, Kiev.

Markowitz, H. M. (1987), *Mean Variance Analysis in Portfolio Choice and Capital Markets*. Oxford: Blackwell.

Montero, J-P. (2000), 'Optimal Design of a Phase-In Emissions Trading Program', *Journal of Public Economics* **75**, 273–291.

Montgomery, D. W. (1972), 'Markets in Licenses and Efficient Pollution Control Programs', *Journal of Economic Theory* **5**, 395–418.

Nilsson, S., A. Svidenko, V. Stolbovoi, M. Gluck, M. Jonas and M. Obersteiner (2000), 'Full Carbon Account for Russia', IR-00-021, IIASA, Laxenburg, Austria.

Obersteiner, M., Y. M. Ermoliev, M. Gluck, M. Jonas, S. Nilsson and A. Shvidenko (2000a), 'Avoiding a Lemons Market by Including Uncertainty in the Kyoto Protocol: Same Mechanism – Improved Rules', Interim Report, IR-00-043, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Obersteiner, M., M. Jones and S. Nilsson (2000b), 'The Political and Economic Costs of a Fully Verifiable Kyoto Protocol', Interim Report, IR-00-062, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Rypdal, K. and L-C. Zhang (2000), 'Uncertainties in the Norwegian Greenhouse Gas Mission Inventory', Reports 2000/13, Statistics Norway, Oslo, Norway.

Swart, R. (1993), 'Climate Targets: An Comprehensive Greenhouse Gas Emissions Trading', *Natural Resource Forum* **17**(1), 43–49.

UNFCCC (1992), *United Nations Framework Convention on Climate Change*. Available at http://www.unfccc.de/.

UNFCCC (1997), *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. Available at http://www.unfccc.de/.

Van Amstel, A., H. Olivier and P. Ruyssenaars, eds. (2000), 'Monitoring of Greenhouse Gases in the Netherlands: Uncertainties and Priorities for Improvement', Report 773201 003, National Institute of Public health and the Environment, Bilthoven, the Netherlands.

Victor, D. (1991), 'Limits of Market-Based Strategies for Slowing Global Warming: The Case of Marketable Permits', *Policy Sciences* **24**, 199–222.

Victor, D., N. Nakicenovic and N. Victor (1998), 'The Kyoto Protocol Carbon Bubble: Implications for Russia, Ukraine and Emission Trading', IR-98-094, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Weiss, P. K., K. Schieler, K. Schadauer, K. Radunsky and M. Englisch (2000), 'The Carbon Balance of Austria's forest and Considerations to the Kyoto Protocol', Monograph, M-106, Federal Environment Agency, Vienna, Austria (in German).

Winiwarter, W. and R. Orthhofer (2000), 'Uncertainty of Austria's Greenhouse Gas Emissions Inventory', Final Report, OEFZSS-0072, Austrian Research Center Seibersdorf, Seibersdorf, Austria.

Winiwarter, W. and K. Rypdal (2001), 'Assessing the Uncertainty Associated with National Greenhouse Gas Emission Inventories: A Case Study for Austria', *Atmospheric Environment* **35**, 5425–5440.