The abatement of carbon emissions in industrial and developing countries

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1 Introduction

1. The global environment is a matter of great importance to all nations. The Rio Convention acknowledged the potential gains from co-operation in response to the threat to climate changes due to increasing concentration of CO_2 in the atmosphere. Yet differences of opinions prevail about the main problems, and about the institutions to manage cooperation. Industrial countries typically focus on the potential problems posed by the rapid growth of population in developing countries, and the environmental pressure, in particular from carbon emissions, that this could create in 25-50 years time. The developing countries view the carbon emission problem as one which originates, historically and currently, from the industrial countries, and one which requires their immediate action, [7] [8].

2. The problem of finding carbon abatement policies is complicated by the scientific uncertainty about the impact of carbon emissions on the climate. We have limited experience in evaluating and implementing the type of policies which would be needed for the abatement of these emissions [9]. In order to implement global environmental policies successfully it seems crucial to develop a clear evaluation of the facts, of the different positions, and of the economic issues at stake. It also seems crucial to develop, as a starting point, a common language to facilitate communication and negotiation, and to increase the likelihood of finding and implementing cooperative solutions for all countries involved. The conceptual formulation of markets and the economic data provided by the OECD economic model GREEN could prove very valuable, and will be used in this paper.

3. A good starting point is provided by the paper "Implementing Global Environmental Policy" by J. Coppel of the OECD Resource Allocation Division [10]. Coppel's paper is an excellent contribution, providing an interesting discussion of the main issues. Some of its value is its focus, which develops an industrial country' perspective.

4. This paper was commissioned to discuss Coppel's, and to address the same issues while formulating a cooperative approach to carbon emission abatement policy, which takes into consideration the position of developing and well as industrial countries.

5. I will discuss Coppel's paper, and evaluate his proposal for a carbon abatement tax using basic economics and the data offered by GREEN and other sources such as the IAE. I will also propose a complementary set of economic policies, including a modified carbon tax, and other associated policies for containing environmental damage in the context of international trade, and of financial policies by the World Bank and the IMF.

2 Carbon Emissions, Population and Industrialization

1. Historically and presently, the large majority of the carbon emissions, about 73%, originate in industrialized countries. These countries have the lowest population growth in the word, see Table 7 of [10], attached at the end of this paper. The US alone, with 5% of the world's population, contributes 24.6% of the world's total carbon emissions. This is not surprising, since the US consumes about 27% of all the petroleum produced in the world [15]. About 55% of all carbon emissions originate in the OECD countries, and about 17% in the ex-Soviet Union.

2. Almost 4/5 of the world's population is in the non-OECD countries. In per-capita terms the OECD countries contribute at least 450% more carbon emission than do the non-OECD countries.

3. Obviously this could change in the future: the developing countries could indeed deviate from past experience and become a serious source of emissions. It seems wise to take precautions to avoid such outcomes. Yet if immediate action is needed in curtailing carbon emissions to prevent a major climate change, in order to have a substantive effect, significant abatement must take place in the major emitters, namely in the OECD countries and the ex-Soviet Union.

3 Evaluating a Global Carbon Tax

1. J. Coppel's paper [10] proposes a global carbon tax of US$25 per ton of carbon emitted (or equivalent). Certain aspects of his proposal were simulated using the OECD model GREEN. These simulations, which were reported in [10], will be discussed here. They compare GDP loss, tax revenues and emission reductions up to year 2020 (see Table 3, page 23 of [10]).

2. Using basic economic principles, economic data from the OECD's GREEN model and from the International Energy Agency [18]and [17] I will establish that while making a valuable contribution and exhibiting many

positive features, unless certain modifications are introduced, the global carbon tax proposed by J. Coppel:

- (a) would be excessively regressive, imposing a disproportionately large burden on the lower income countries, and decreasing the likelihood of its implementation,

- (b) could be counterproductive in terms of overall economic efficiency.

J. Coppel's proposal:

- (c) concentrates on possible distortions from energy subsidies in developing countries, but makes no reference of similar distortions arising from the large energy subsidies existing in OECD countries, and

- (d) could be associated with higher rates of population growth in developing countries, contradicting its own stated objectives.

4 A Proposal for a Modified Global Carbon Tax

1. I propose here a complementary global carbon tax , which could also be simulated using the OECD's GREEN model. The simulations could have a starting date of 1995, until 2050. By running this new tax proposal in parallel with Coppel's, one should be able to explore the advantages and disadvantages of the two proposals, and could therefore improve upon both.

2. If properly implemented, my proposal:

- (e) would increase energy prices progressively in all OECD countries over a period of several years so as to reach the levels currently paid in Germany and Japan,

- (f) would phase down gradually over the same period all energy subsidies in OECD countries,

- (g) would initiate the taxation of carbon emissions in low income countries when their contribution to emissions becomes significant, for example, when it reaches a given proportion of the world's emission. At present, developing countries, which make up about 4/5 of the world's population, contribute less than 30% of global carbon emissions,

5 Policies Associated to a Carbon Tax

The following policies could be at least as effective as a carbon tax, and are recommended as means to containing environmental damage:

- (h) Reformulate trade strategies in developing countries away from environmentally intensive sectors such as raw materials and minerals, and into skill intensive and environmentally friendly sectors which use newer technologies and which have higher growth potential.
- (i) Reformulate and implement new international national and international accounting systems which incorporate a measure of international environmental effects,
- (j) Reformulate World Bank and IMF financing criteria so that they become consistent with these environmental objectives.
- (k) Develop better systems of property rights and market-based strategies for protecting those common property environmental resources in developing countries which are most endangered at present such as fresh water, forested and grazable land, and biodiversity reservoirs.

6 Analyzing the Economic Foundations of Carbon Emission Abatement

1. J.Coppel's proposal is for a small global carbon tax of $25 per ton which corresponds to about $3 per barrel of oil ([10], paragraph 22, page 9). About 50% of the expected world revenues, of about US$ 150 billion per annum, would be raised from OECD countries. Coppel's paper [10] uses the OECD GREEN model to analyze the consequences of this tax without any explicit side-payments to non-OECD countries ([10] paragraph 23, page 9). Potential side-payments to developing countries are nevertheless mentioned by Coppel; these are limited to at most 25% of OECD tax revenues ([10], paragraph 52, page 19). In practice, however, no side-payments have been included in the simulations of the GREEN model ([10], page 9, paragraph 23 and footnote 13.
2. A salient feature of Coppel's global carbon tax is that developing countries are taxed at several times the rate of industrial countries, as a proportion of their GNPs. For example, high income countries such as the US and France would pay in taxes approximately 3/4% and 1/3% of their GNP respectively, while lower income countries such as China and Mexico pay instead several times that amount. In fact China pays 4.40% of GNP and Mexico, 1.25% of its GNP's see Table 2, page 22 of [10]. Furthermore, if

computed in terms of GNP per capita, this difference would increases dramatically. This disproportion is maintained across the board: the developing countries in general pay several times the rate paid by the industrial countries, see table 2 of [10].

3. The tax proposed by Coppel imposes a disproportionate large tax burden on lower income countries, see paragraphs 10 and 17 of [10], because although their per-capita emissions are extremely low compared with those of the industrial countries, their output (GNP) is more carbon intensive. Since the tax is levied on output, the lower income countries pay more tax as a proportion of their GNP.

4. Of course, if the carbon tax were levied on the basis of carbon emissions per-capita, then the impact of the tax would be reversed: the industrial countries would pay then several times as much as the developing countries do.

7 The Issue of Abatement Costs

1. The developing countries are said to have lower abatement costs than the OECD countries, see pages 4, 5 and 7 of [10]. Following up on this point, the author then argues that "A well-designed agreement will try to ensure that marginal costs of abatement will be equalized across countries. Countries with lower abatement costs will initiate the largest absolute emission changes", see page 7, paragraph 17 of [10]. Although in principle this observation about costs has little bearing on the actual tax burden of countries as proportion of their GNP, it may appear to be offered as an explanation of the fact that the developing countries' burden is several times higher than that of the industrial countries. For this reason it seems worth examining the question of costs in some detail.

2. The argument summarized in the previous paragraph in support of equating marginal costs, and the disproportionate taxation of low income countries, has three flaws. The first pertains data, and the latter two are based on basic economic analysis.

3. The evidence offered in [10] for the fact that developing countries have lower abatement costs than industrial countries, provided in its paragraph 10 and in footnote 7 on page 5 is: "simulations with GREEN and other general equilibrium models suggest that China, India and the ex-USSR could abate at low cost whereas abatement costs could tend to be high in OECD countries". The data reference provided is a 1992 OECD economic study No.19 by A. Dean and P. Hoeller, which does not in fact report on actual data but rather, as its title indicates, on "evidence from six global models". This presents a problem in terms of the interpretation of the

data. Global models are not sources of data, as much as of simulated or projected data which is a resultant of observations plus the assumptions which are built into the models. For example, the simulations carried out in GREEN contain many specifications which may not be a representation of reality but rather a representation of certain assumptions about technology. Therefore the question of whether developing countries have higher or lower abatement costs than the industrial countries is not satisfactorily resolved by referring to simulations in GREEN or in other global models. The information we obtain from these sources depends on the assumptions of these models. In other words, one may be *assuming* that developing countries have lower abatement costs rather than *establishing* it. This issue is of importance, because a way that the "free rider" problem appears in the case of providing public goods– such as for example, abatement which decreases CO_2 concentration in the atmosphere–is by each party proposing that others should provide the good, because it costs them less to do so. For a treatment of free riding problems see e.g. Atkinson and Stiglitz [20].

4. Equally questionable is the assumption that marginal costs of abatement should be equalized across countries for economic efficiency. There are two economic reasons for this. The first reason is that economic activities with large fixed costs may have decreasing marginal costs. Under these conditions, the equating of marginal costs can lead to economic inefficiencies. As a matter of fact, in the presence of fixed costs, the allocations obtained by average cost pricing may be more efficient than those obtained under marginal cost pricing. These are well known facts which were established in the literature several years ago, see e.g. Guesnerie [16], Brown and Heal [11] and [12], and Chichilnisky [5].

5. Abatement technologies have large fixed costs. A typical example is the shift from leaded to unleaded gasoline, a shift which is yet to be made in many developing countries. The development of engines which run on unleaded fuel, the re-equiping refineries to produce unleaded gasoline, and the replacement of existing vehicles, must all be included and lead to very large fixed costs indeed. Republica Dominicana is an example of a country in which leaded gasoline is currently in use, and the only obstacle which is recognized for its substitution by unleaded fuel is the obsolence that this will imply for its stock of vehicles. Large fixed costs for abatement lead to decreasing marginal costs, or economies of scale. In such cases marginal cost pricing may not lead to efficient outcomes, see e.g. Guesnerie [16], Brown and Heal [?], [12], and Chichilnisky [5].

6. There is a second reason for questioning the policy of equalizing marginal costs of abatement. This equalization would lead to efficiency if the goods under consideration were private goods. But in our case we are dealing

with a *public* good, i.e. one which, by definition, is consumed by all in the same quantity: the decreases in atmospheric CO_2 concentration. While the impact of weather changes may vary from country to country, in ways that it is very difficult to predict, the overall CO_2 concentration is shared equally by all nations in the world. The quality of the world's atmosphere is a public good, Heal [14] and Nordhaus [19].

7. This public good is "produced" by the CO_2 emissions (or by the abatement of these emissions) of a finite number of large agents, namely the countries. In this sense, the classical solutions for finding the efficient levels of production of public goods of Lindahl (1919) and Bowen (1943), which were extended subsequently by Samuelson (1954), see Atkinson and Stiglitz, particularly Lecture 16, and page 489, footnote 3, [20], do not apply. In these cases the public good is produced by a single agent. Example of such public goods are a bridge or a road: the relevant efficiency conditions in these cases are to equate the sum of the agent's rate of substitution between the public good and a private good (such as income) and the marginal rate of transformation between the two, at a central production facility.

8. When each consumer is also a *producer* of the public good, as it is the case of emissions or abatement of carbon, then efficnet allocations take a different form, closer to the efficient allocations of a market economy with externalities [1]. An efficient allocation now requires that the marginal cost of abatement in each country be inversely proportional to that country's marginal utility of consumption of all other private goods. This point is developed in detail in the last Section of this paper.

9. Economic efficiency in the allocation of private and public goods dictates in this case that countries with higher marginal utilities of private consumption–which are typically the lower income countries–should have lower marginal cost of abatement than countries with lower marginal utility of consumption–which are typically the higher income countries. In particular, one should not expect the efficient allocation to equalize marginal costs of abatement across countries, because doing so could conflict with the Pareto efficiency of the allocation between private consumption and the production of a clean atmosphere. It should be emphasized that this result applies to the case where the good in question is a public good, such as the CO_2 concentration in the atmosphere, and not when it is a private good. In addition, this result applies to the case where abatement is "produced" in each country, and produced at the expense of other private consumption goods, rather than when it is "produced at a central facility" such as a bridge or a road. This is discussed in detail in Section11, Proposition 1.

10. Efficient allocations also require that those countries with a higher income level contribute a higher proportion of the abatement, with the constant of proportionality increasing with the overall productivity of the country's abatment technology. This point is also discussed in Section 11, Proposition 2.

11. Once the optimal allocation of the public good is found, then it is possible that other agreements could emerge about changing the technology of production, so that a central world facility produces abatement, and it does so by allocating abatement efforts in countries with lower marginal costs. But the achievement of this central technology agency seems highly unlikely. This is because carbon emissions are "produced" automatically whenever private goods which use fossil fuel energy are produced. It seems impossible at present to entertain the idea of a central production for emissions without a simultaneous central facility for the production of private goods, an event that seems well beyond the scope of what is possible or desirable at present.

12. Once the optimal consumption/abatement levels in each country are found, then other arrangements could be achieved for the payment and production of the public good. For example, *quotas* on emissions could be assigned to each country on the basis of optimal abatement/consumption levels, and then *permits* could be issued and freely traded as financial instruments across countries, on the basis of these quotas. However, it is not clear that such a permits market would improve welfare, or under what conditions. In economies with public goods, the appropriate pricing system may be one which is personalized to the traders, rather than a competitive pricing system. The matter requires further research. A system of permits for carbon emissions has of course been contemplated for some time, but the country-by-country quotas for these permits, have not been connected so far to the optimality conditions for the allocation of public goods. How the quotas are related to income is the subject of Proposition 2 in the last Section. Typically, Pareto efficiency dictates that quotas for emission be inversely proportional to income levels, see Proposition 2, and also inversely related to the productivity of the country's abatement technology.

8 Coal Subsidies in Industrial and Developing Countries

1. Another interesting aspect of Coppel's paper is the emphasis on phasing out what it calls "energy subsidies" in developing countries. This is one of the policies proposed, see Part b) Page 13 of [10].

2. GREEN measures energy subsidies by the divergence between the world's and the country's price of energy. Therefore it is not entirely appropriate to call these subsidies. They should rather be called differences in factor prices.

3. It is well known, however, that factor prices and indeed most prices in developing countries, are lower than their counterparts in industrial countries. A well known example is the price of labor. Indeed, price differences are so substantial, with the developing countries exhibiting typically lower prices than the industrial countries, that recently the World Bank has taken to measure GNP using "purchasing power parity" rather than international prices. This has made a large difference in the computation of income differentials between industrial and developing countries.

4. It is notable that the differences in labor prices across countries have not led, and are not likely to lead, to international intervention in the form of labor taxes. Coppel in fact proposes such a tax for a similar input, energy.

5. Moreover, in the case of coal there exist very large real production subsidies in the industrial countries. A preliminary observation indicates that they could be at least as large in value as the value of those price differences which GREEN calls "subsidies" in developing countries, although the actual comparison must be made in more detail, see [10], Table 6, [18] and [17].

6. For example, in Germany alone coal production is subsidized at the rate of about US$6 billion per annum. A larger figure of US$8 billion holds for the UK. In total the OECD countries subsidize coal production by about US$16 billion yearly, see [17], page 201, copy enclosed at the end of this paper.

7. Indeed, the European Coal and Steel Community, which was created before the signature of the Treaty of Rome and which was a precursor of the EEC, had as a main purpose the support and rationalization of these industries and included provisions for subsidies to support employment and production. The existence of such sizable subsidies should induce serious inefficiencies in the industrial countries, but the issue is not raised by Coppel, and the figures are not even reported in [10] or [3]. Clearly any policy for eliminating production subsidies should include the subsidies of OECD countries.

9 Incentives for Implementing Abatement Policies

1. As already mentioned, abatement technologies have large fixed costs. A typical example is the shift from leaded to unleaded gasoline, a shift which is yet to be made in many developing countries. Marginal costs may then decrease with volume, leading to increasing returns to scale. In such cases, marginal cost pricing may not lead to efficient outcomes, and it may, in fact, be inferior in terms of efficiency, to average cost pricing. These results have been known in the literature for some time, see e.g. Guesnerie [16], Brown and Heal [?], [12], and Chichilnisky [5].

2. In addition, abatement technologies are knowledge intensive. This leads also to increasing returns to scale, Chichilnisky [6], some of which are internal and others external to the firm. Knowledge often has often spill-over effects for society as a whole. This is another reason why marginal cost pricing may not lead to efficient outcomes.

3. It is seldom noticed that the economies of scale of abatement should be welcome, because this could lead naturally to more cooperation than is to be expected between the countries who are parties to an abatement effort. This is because, for the same costs two countries can achieve proportionately more than each one can. This induces more incentives for cooperation than is normally expected in the problems connected with paying for the provision of public goods, Heal [13], and Carraro and Siniscalco [4]. For example, it checks the tendency towards the standard "free rider" problem to reach agreements to pay for the provision of public goods.

4. The extent of external economies of scale in the adoption of carbon abatement technologies depends on the initial level of knowledge. For example, countries of similar levels of development can benefit more readily from the economies of scale implicit in adopting each other's new clean technologies than do countries at different levels of development.

5. The transfer of technology between countries could therefore have a salutary effect in their ability and willingness to cooperate in international abatement efforts, Heal [13] Carraro and Siniscalco [4].

10 Income, Abatement and Population Growth

1. Coppel mentions that, according to the World Bank, an additional investment of 2-3% of GNP is needed in developing countries to reduce local environmental damages and to provide access to sanitation and clean water, to improve air quality and protect natural habitats, see paragraph 14, page 6 of [10].

2. Coppel also points out to population growth in developing countries as one of the major causes of environmental degradation, to the extent that he recommends using tax revenues to finance the provision of contraceptives in developing countries, see page 3, para 5 and pages 14-17 paragraphs 38 to 43.

3. Since the transfers suggested Coppel's paper have not been simulated with GREEN, see page 9, paragraph 23 and footnote 13, their overall effects and the use of such transfers for the provision of contraceptives is a highly speculative matter. Therefore the recommendation seems somewhat unrealistic.

4. But more fundamentally, the strategy of raising proportionately higher taxes from developing countries could be counterproductive with the stated aims of population control in the paper. The level of income is the only generally accepted and predictable explanation for population growth, and is inversely related to it. Therefore, if a highly regressive carbon tax is levied, as is the one proposed by Coppel, it will decrease the level of income in developing countries, and this could lead to increases in population growth and to further environmental degradation. The tax could defeat its own purposes.

5. A regressive carbon tax as proposed by Coppel could furthermore damage the fragile growth prospects of many lower income countries. To the extent that cleaner technologies require a certain amount of industrialization, regressive taxation could decrease the prospect of industrialization and could therefore damage rather than improve the chances of controlling carbon emissions.

11 Pareto Efficient Abatement Strategies

This section develops the basic economic framework to compute an efficient allocation of abatement strategy across countries. It considers the atmosphere as a public good (see Heal [14] and Nordhaus [19]) which is produced along with the production of private consumption goods, in each country.

Consider a world economy with N countries, $N \geq 2$, indexed by $n = 1...N$. Each country has a utility function u_n which depends on its consumption of private goods c_n, and on the quality of the world's atmosphere, a, which is a public good. Formally,

$$u_n(c_n, a) \text{ measures welfare, where}$$
$$u_n : R^2 \rightarrow R \text{ is a continuous, concave function.}$$

The quality of the atmosphere, a, is measured by its concentration of CO_2. The concentration of CO_2 is "produced" by emissions of carbon, which are positively associated to the level of consumption of private goods, c_n,: i.e.

$$a = \sum_{n=1}^{N} a_n$$

$$\text{where } a_n = \Phi_n(c_n), \text{ for each country } n = 1...N, \quad \Phi'_n < 0. \tag{1}$$

The "production functions" Φ_n are continuous and concave. For example, consider the standard case where each country has a level of income Y_n and the constraint Φ_n is given by:

$$c_n + a_n = Y_n, \text{ i.e. } \Phi_n(c_n) = Y_n - a_n. \tag{2}$$

An allocation of consumption and abatement across all countries is a vector $(c_1, a_1, ..., c_N, a_N) \in R^{2N}$. An allocation is called *feasible* if it satisfies the constraint (1). A feasible allocation $(c_1^*, a_1^*, ..., c_N^*, a_N{}^*)$ is *Pareto efficient* if there is no other feasible solution at which everybody's utility is at least as high, and someone's utility is strictly higher, than at $(c_1^*, a_1^*, ..., c_N^*, a_N{}^*)$.

A Pareto efficient allocation must maximize a weighted sum of welfare

$$W(c_1...c_n, a) = \sum_{n=1}^{N} \lambda_n u_n(c_n, a)$$

and for simplicity we shall assume that all weights are equal. Each country n faces a constraint in terms of allocating total endowments into either consumption c_n or atmospheric quality, a_n, represented by the function Φ_n. Then a Pareto efficient solution is described by a solution to the problem:

$$Max\ W(c_1...c_n, a) = \sum_{n=1}^{N} u_n(c_n, a), \tag{3}$$

$$\text{subject to } a_n = \Phi_n(c_n),\ n = 1...N \tag{4}$$

$$\text{and } a = \sum_{n=1}^{N} a_n. \tag{5}$$

Note that, by definition, the marginal cost of abatement is the inverse of the marginal productivity of the function Φ_n:

$$MC_n(a_n) = 1/\Phi'_n(a_n) \tag{6}$$

A Pareto efficient solution solves problem (3).

Proposition 1: At a Pareto efficient allocation $(c_1^*, a_1^*, ..., c_N^*, a_N{}^*)$, the marginal cost of abatement in each country, $MC_n(a_n^*)$, is inversely proportional to the marginal utility of consumption for the private good c_n, $\partial u_n/\partial c_n$.

Proof:

The solution to the maximization problem (3) must satisfy the first order conditions:

$$\partial u_j/\partial c_j = -\Phi_j^{'}(\sum_{n=1}^{N} \partial u_n/\partial a)$$

for each country $j = 1...N$. Since at a Pareto efficient allocation the expression $(\sum_{n=1}^{N} \partial u_n/\partial a_n)$ is the same constant for all countries, denoted K, and since, as noted in (6)

$$MC_n(a_n^*) = 1/\Phi_n^{'}(a_n)$$

we have that a Pareto efficient allocation is characterized by:

$$MC_j(a_j^*) = \frac{K}{\partial u_j/\partial c_j}$$

and the proposition follows. ◇

Consider for example the case where there are two countries, each with a Cobb- Douglas utility function,

$$u_n(c_n, a) = c_n^{\alpha}(a)^{1-\alpha} = c_n^{\alpha}(a_1 + a_2)^{1-\alpha},$$

and the abatement production function Φ_n is

$$a_n = \Phi_n(c_n) = k_n(Y_n - c_n)^{1/2},\ k_n > 0,\ \text{for } n = 1, 2$$

where, for example, $k_1 = k$ and $k_2 = 1$. This allows us to accommodate potentially different efficiency of abatement across countries. For simplicity, the two countries are assumed to have the same utility function. Then:

Proposition 2: At a Pareto efficient allocation, the proportion of income which each country allocates to carbon emission abatement must be proportional to that country's income level, and the constant of proportionality increases with the efficiency of the country's emission abatement.

Proof: Our problem (3) can now be written as:

$$Max_{c_1,c_2}\ W(c_1, c_2) =$$
$$Max \left\{ c_1^{\alpha} \left[k(Y_1 - c_1)^{1/2} + (Y_2 - c_2)^{1/2} \right]^{1-\alpha} + c_2^{\alpha} \left[k(Y_1 - c_1)^{1/2} + (Y_2 - c_2)^{1/2} \right]^{1-\alpha} \right\}$$

Let

$$A = \left[k(Y_1 - c_1)^{1/2} + (Y_2 - c_2)^{1/2} \right].$$

The first order conditions for a maximum are then:

$$\alpha c_1^{\alpha-1} A^{1-\alpha} - 1/2(Y_1 - c_1)^{-1/2} k \left\{ c_1^{\alpha} A^{-\alpha}(1-\alpha) + c_2^{\alpha}(1-\alpha)A^{-\alpha} \right\} = 0$$

and

$$\alpha c_2^{\alpha-1}A^{1-\alpha} - 1/2(Y_2 - c_2)^{-1/2}\left\{c_1^{\alpha}A^{-\alpha}(1-\alpha) + c_2^{\alpha}(1-\alpha)A^{-\alpha}\right\} = 0,$$

which simplify to:

$$\left(\frac{c_1}{c_2}\right)^{\alpha-1} = k\left(\frac{Y_1 - c_1}{Y_2 - c_2}\right)^{-1/2}.$$

Since $\alpha < 1$ this implies that for Pareto efficiency, the income allocated to abatement by each country ($a_n = Y_n - c_n, , n = 1, 2$) must be proportional to the income level, or the level of consumption, of the country (c_n). Furthermore the larger is the abatement productivity of a country ($k = k_1$), the larger is its abatement allocation as a proportion of income. $\diamondsuit$

Conclusions.

It follows that the problem of efficient allocation of abatement among countries does not yield the usual condition for the optimal provision of public goods. For a detailed discussion of this problem for economies with uncertainty, see also Chichilnisky and Heal [9]. The first order conditions for the provision of a public good (see Atkinson and Stiglitz [20]) assumes that agents make independent consumption decisions, but that the good is provided by a central production facility. It is then straightforward to derive the classical first-order conditions stating that the sum of agents' marginal rates of substitution between the public good and a private good, must equal the marginal rate of transformation between the two *in the central production facility.* From this one may be tempted to deduce that the marginal cost of abatement must be equalized among all countries, but this would be incorrect. In contrast with the classical case, each country produces emissions or abatement on its own, and it may do so with different technologies. The results are then significantly altered. There is no central production facility which transforms a consumption good into a better atmosphere concentration or a lower climate risk: this process is undertaken independently in each country via its own emission or abatement efforts. Hence while the atmosphere is a classic public good, the way it is produced is not classic, and the first order conditions for efficient provision of this "good" are different from the classical one, and closer to those characteristic of a general externality. In fact our model in this Section is consistent with that of Baumol and Oates [1], Section 4.

The analysis of Pigouvian taxes for markets with external effects which deals with the optimal tax for the provision of *private* goods which produce externalities, but are nevertheless private in the sense that one person's consumption precludes others' consumption, is not applicable here. By contrast, here the good a in question (e.g. the concentration of CO_2 in the atmosphere) is a public good. This is because CO_2 in the atmosphere mixes very uniformly, and the whole world is subject to similar concentrations.

Propositions 1 and 2 imply that the equalization of marginal costs of abatement is therefore not a reliable guide to efficient economic allocations. Another implication is that there is no economic reason for placing the burden of the largest initial emission changes on those countries with lower marginal costs. Placing the burden of the initial adjustments on the higher income countries could in fact be more efficient, as demonstrated in Propositions 1 and 2.

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