MD

92-19

Working Papers

DEPARTMENT OF AGRICULTURAL AND RESOURCE ECONOMICS
SYMONS HALL
UNIVERSITY OF MARYLAND
COLLEGE PARK 20742

[redacted]

Consensus And Disagreement On The Probability Of Global Warming: Implications For International Agreements

by

John Horowitz and John Quiggin

(both authors)
Department of Agricultural and Resource Economics
University of Maryland
College Park, MD 20742

and

(second author)
Research School of Social Sciences
Australian National University
Canberra ACT Australia

Working Paper No. 92-19

November 1992

Consensus and disagreement on the probability of global warming: Implications for international agreements

I. Introduction

The belief that human activities are contributing to a significant increase in global mean temperatures, and perhaps also to increased climatic variability, was dramatized by the series of severe droughts that affected the U.S. in the 1980's. However, opinion appears to remain divided over whether substantial global warming is likely to take place, what the effects of any particular level of warming will be, and how large the economic costs of slowing it are. Scientific uncertainty surrounds nearly every aspect of global warming.

This paper studies the problems that arise when countries disagree about how fast global warming is occurring. The objective is to understand how this divergence of beliefs affects the kinds of international agreements that are likely to be adopted.

The major part of the paper is a decision theory model of international environmental policies when probability beliefs differ. We study this in the context of a particular set of international environmental policies that are likely to be considered. These include joint international commitments to some specified schedule of emissions reductions (such as reducing emissions by a specified proportion from a base year level) and a property rights system involving tradeable emissions quotas.

Until recently, most international pollution problems were handled on an open access basis or, in cases of trans-border pollution, by bilateral agreement. In the last twenty years, however, larger groups of countries have been involved in negotiations and agreements concerning Mediterranean pollution, acid rain in Europe, and worldwide CFC emissions.

Such international agreements have typically taken the form of a set of commitments specifying the time-path of reduction in emissions each country undertakes to provide, as in the Montreal protocols. In most cases, the time-path has been defined as a set of percentage reductions from some historical base. Although the base levels of emissions differ between countries, the percentage reductions are normally the same for all parties to the agreement, or at least are the same for all parties with broadly similar circumstances. We call this the "common reduction path" system. An example of this process was the "30% club" of European countries agreeing to a 30% reduction in SO_2 emissions to control acid rain. The Montreal protocol provides an illustration of a case where large differences in initial circumstances necessitated some modifications of this rule. All of the developed countries took their 1986 emissions as the historical base and agreed first to reduce their emissions to that level by a target year (1992) and then to achieve a fifty per cent reduction by the year 2000. Less developed countries, which had much lower initial levels, agreed to a less stringent timetable and were compensated with some side payments.

This is generally a sub-optimal way of achieving a given reduction in emissions because the marginal costs of reduction will, in general, differ among countries. An analogous problem arises with regulatory controls on pollution applied within a country. If all pollution sources are required to achieve fixed levels of abatement (relative to initial emissions), marginal costs of abatement will not be equalized.

Thus, if continued reductions in emissions are seen as necessary, a more efficient mechanism which allows international trading of emissions permissions, should also be agreed to. We label this a property rights solution. An example, at the national level, is the tradeable permits in sulfur dioxide emissions by power plants under the U.S. 1990 Clean Air Act. There is likely to be considerable support among economists for a such a system of internationally tradeable permits for emissions of greenhouse gases.[1]

The argument for tradeable permits is based on the assumption, often implicit, that the optimal level of emissions is known. The situation under uncertainty is less clear. If there are difficulties in changing the aggregate level of emissions after a fixed number of permits has been issued, then the permits system may not be sufficiently flexible in responding to new information about warming. As has been well recognized in the decision theory literature (*e.g.* deGroot, 1970; in the environmental literature see Arrow and Fisher, 1974), there is a benefit to waiting until more information is revealed before making an inflexible or irreversible decision. Thus, a tradeable permits system may not be optimal under the uncertainty that prevails with global warming.

The common reduction path for all countries may be more flexible. As the history of the Montreal protocols illustrates, it is possible to obtain a revision of the agreement in the light of new information indicating that the optimal reduction in emissions should be greater and more rapid (or smaller and slower) than was estimated at the time of the initial agreement.

In the analysis below, the common reduction path is treated as a completely flexible policy choice and the issuing of a tradeable emissions permit is treated as irreversible. In the real world, it is likely that a tradeable permits system can be changed over time, albeit at some cost.[2] Costs of changing the system include a sensitivity of trades to the time at which a change in the system might take place, and the potential for rent-seeking when a revised level of permits is to be issued. The exact ways in which these features might affect the desired flexibility or efficiency of tradeable permits are not modeled here and are a topic for future research. At the moment, we recognize that the assumption of irreversibility of the tradeable permits system is somewhat *ad hoc*, and note that our analysis applies in general to decision-making whenever there is a choice between an inefficient but flexible policy and a more efficient but inflexible one.

In summary, it is likely that international agreements will involve an initial move from open access to a system of national emissions limits.[3] Then, as uncertainty is reduced, the advantages of the property rights approach increase and eventually a switch will be made to a system of internationally tradeable emissions permits when a relatively accurate estimate of the optimal aggregate emissions level can be made. Broadly speaking, this is the sequence that has been observed in the control of pollution within individual countries. The problem for policy makers is to choose levels of the policy instruments and a date to switch policy from the common reduction path to the property rights system. The date of the switch will depend on current information and on expectations of future information.

Previous research

The problem facing an individual decision-maker who must make an irreversible decision under uncertainty is a canonical question in decision theory (*e.g.*, deGroot, ch. 12 and 13). The problem for a group of Bayesians who must make a group decision under uncertainty is a classic problem associated with de Finetti (see the discussion in Barlow, Wechsler, and Spizzichino, 1988). The initial question raised by de Finetti was whether the decision should be based on an average of opinions or on an average of decisions. Subsequent work has looked at the particular properties of a given decision rule (Winkler, 1968; Bacharach, 1975; French, 1985) and at the problem of waiting for new information (Barlow, Wechsler, and Spizzichino, 1988). Our paper extends this analysis to the problem of global warming. The major problem that arises is that the cost of waiting for new information is random and is itself the subject of disagreement.

II. A model of international pollution control agreements

1. Global warming and emissions

The key variables in the model are e_t, the level of global CO_2 emissions in period t, and w_t, the amount of global warming, *e.g.* the increase (or decrease) in global mean temperature between some historic base period and period t. Define $e^t = \Sigma^t e_s$ as cumulative emissions to t, akin to total CO_2 concentration in the atmosphere (in parts per million), the variable that is typically reported.

Global warming and past emissions are assumed to be related by a function of the form:

$$w_t = \theta_t e^t \tag{1}$$

where θ_t is an i.i.d. random variable drawn from a distribution with unknown mean. Uncertainty about the mean reflects factors such as the ability of global sinks to absorb emissions and the existence of positive or negative feedback mechanisms. The assumption of linearity in the warming function appears to be broadly consistent with prevailing scientific views, at least over relevant ranges.

2. *Costs and benefits of CO_2 emissions*

Emissions for country i at time t are denoted e_{it} with $\Sigma_i e_{it} = e_t$.[4] The current economic benefits (*e.g.*, GNP) for country i from emitting e_{it}, exclusive of any problems engendered by warming, is written $B_i(e_{it})$, with $B_i''(e_{it}) < 0$.

The ways in which global warming reduces country i's well-being are reflected in the per-period damage function $D_i(w_t)$, familiar from the economics of pollution control (*e.g.*, Baumol and Oates). $D_i(w_t)$ reflects the disutility of environmental changes and losses in productivity due to warming. The model assumes that the disutility that arises from any particularly level of warming is known, but the model is applicable to the case where the function $D_i(w_t)$ is unknown. The damage function has derivatives $D_i'(w_t) > 0$ and $D_i''(w_t) \geq 0$.

Per-period utility in country i at time t is equal to economic benefits from emissions minus damages from warming, as given by $B_i(e_{it}) - D_i(w_t)$. Future utility is based on expected per-period damages where the expectation is conditioned on the beliefs of country i at time t. Utility is assumed additively separable over time, with discount factor β.

An international agreement may be modeled in terms of a set of base emission levels e_{i0}, with a corresponding aggregate emission level e_0, and a time path of proportional reductions λ_t, where country i agrees to the constraint $e_{it} \leq \lambda_t e_{i0}$ $\forall$ t. Period t cumulative emissions are thus based on the recursive relationship $e^t = \lambda_t e_0 + e^{t-1}$.

We constrain λ_t to be the same for all countries and call this the *common reduction path agreement*.[5] We envision $\lambda_t < 1$ and decreasing over at least some time interval but this is not necessary. In the analysis, all expressions implicitly depend on initial emissions, e_{i0}, which are taken as given and are not analyzed.

The common reduction path agreement does not minimize the total cost of achieving any given aggregate emissions level. It can be contrasted with a property rights solution, *i.e.*, a *tradeable permits agreement.* This consists of selecting a reduction parameter λ_t^* as in the case of the common reduction path agreement, with $e_{it} \leq \lambda_t^* e_{i0}$. However, this level of emissions is now treated as a tradeable permit, and a market for such permits should arise. The costs of reducing emissions can then be shifted across countries.

An important feature of the analysis is that the tradeable permit agreement be less flexible over time than the reduction path agreement. Such inflexibility may arise because the functioning of the permit market requires that permits be treated like property rights, and we suggest that it may be quite costly for such property rights to be altered over time. To capture this rigidity, it is assumed that the tradeable permits' reduction parameter is constant for all t; thus $\lambda_t^* = \lambda$, with no time subscript. However, all that is needed for our results to hold is that the permit system be less flexible over time than the reduction path regime in responding to new information; it need not have the absolute permanence we've described.

Because in the absence of transactions costs, entitlements should be traded among countries until the marginal costs of mitigation are equal, this agreement is associated with lower costs of emissions reduction than the common reduction path agreement. We model this by defining a separate benefit function for each of the regimes. Let $B_i^1(e_{it})$ be country i's benefits under the common reduction path. Benefits under the tradeable permits path are denoted $B_i^2(e_{it})$ where e_{it} should now be interpreted as i's permit endowment rather than its actual emissions. The benefit functions are related by:

$$B_i^2(e_{it}) = \max_{q_i} B_i^1(q_i) + r(e_{it} - q_i) + k_i \qquad (2)$$

where q_i is the actual emissions by country i, $\Sigma q_i = \Sigma e_{it} = \lambda e_0$, and r is the equilibrium permit rental price.[6] If the country is a net seller of permits then $q_i < e_{it}$, while if it is a net purchaser then $q_i > e_{it}$. Since each player has the option of making no trades, it must be that $B_i^2(e_{it}) \geq B_i^1(e_{it})$. The variable k_i is a possible lump sum transfer that may be used to ensure that all countries benefit from a switch to the tradeable permits regime.

3. Beliefs about global warming

This section considers the accumulation of information concerning the effects and mechanisms of global climatic change. The random variable θ_t, associated with observed warming in each period, is a random draw from a normal distribution with unknown mean and known variance σ. The prior distribution on θ has mean μ_{i0} and precision τ; for simplicity, let $\sigma = \tau$. Each agent is assumed to start with a different prior on the mean, hence the i subscript. Our treatment assumes that the priors do not have scientific content, which is reasonable when all agents observe both CO_2 emissions and global temperatures. At the same time, the differences in priors cannot be ignored (with a focus instead on, say, differences in policy preferences) since the priors play a crucial role in the decision to wait for new information.

The assumption of normality is not necessary for the results, but there are two crucial assumptions. First, all agents observe the current draw from the distribution. Second, the variance on the prior is shared by all parties.

Let θ_t be the observation in period t. Given our assumptions, agent i's belief at time t about mean warming, written μ_{it}, is:

$$\mu_{it} = \frac{\mu_{i0} + \sum_{s=1}^{t-1} \theta_s}{t} = \frac{(t-1)\mu_{t-1} + \theta_{t-1}}{t} \tag{3}$$

The timing is such that $\mu_{it} = E_{it}\theta_t$, where E_{it} is the expectations operator conditioned on μ_{it}.

4. Regulation and net benefits under the two regimes

Define current period utility for agent i under the common reduction path regime, given θ_t, as $v^1_{it} = B^1_i(e_{it}) - D_i(\theta_t e^t)$. Given the assumption $e_{it} = \lambda_t e_{i0}$ and $e_t = \lambda_t e_0$ this can be rewritten as:

$$v^1_{it}(\lambda_t) = B_i^1(\lambda_t e_{i0}) - D_i(\theta_t(\lambda_t e_0 + e^{t-1})) \tag{4}$$

For the tradeable permits regime define current period utility, v^2_{it}, and future expected discounted utility as:

$$v^2_{it}(\lambda) = B_i^2(\lambda e_{i0}) - D_i(\theta_t(\lambda e_0 + e^{t-1})) \tag{5}$$

$$V_{it}^{2}(\lambda) = \sum_{s=t}^{s=T} \beta^{s-t} v_{is}^{2}(\lambda) \qquad (6)$$

Recall that period t cumulative emissions are based on the recursive relationship $e^t = \lambda_\tau e_0 + e^{t-1}$, so all functions implicitly depend on initial emissions e_{i0} and e_0 as well as e^{t-1} and θ_t. The assumption of a finite time horizon is made to avoid problems with convergence of infinite sums.

III. The switch to tradeable permits and the value of information

The set-up so far describes a choice between adopting a beneficial but inflexible (in fact, irreversible) policy or waiting for new information and using a costly but flexible policy in the interim. This is a classic problem in sequential analysis complicated here by the fact that the cost of waiting is random.

We first explore policy decisions when they are made by a single agent, and abstract from the public choice problem of joint agreement on the policy variables and the switch between regimes. The specific question we address is: For which values of estimated warming will an agent want to wait for new information before making an irreversible decision?

For agent i, utility under each of the two regimes, as expressed in (4) and (6), can be combined to determine i's value function. Let $V_{it}(\mu_{it})$ be i's present value, expected lifetime utility when i's optimal program is continued from time t with beliefs μ_{it} and current stock of emissions e^{t-1}. $V_{it}(\mu_{it})$ is defined recursively according to the following equation:

$$V_{it}(\mu_{it}) = \max(\max_{\lambda} E_{it}V_{it}^{2}(\lambda), \max_{\lambda_t} E_{it}[v_{it}^{1}(\lambda_t) + \beta V_{it+1}(\mu_{it+1})]) \tag{7}$$

The function $V_{it}(\mu_{it})$ captures utility under the two possible regimes. If the tradeable permits regime is selected, the agent must choose the level of aggregate emissions, summarized by λ, that maximizes her future expected discounted utility. If the common reduction path is selected for period t, the agent chooses a λ_t to apply in the current period. She then faces the possibility of a switch in regimes in the next period. The chosen reduction λ_t maximizes expected utility from the continued (optimal) program. Note that $V_{it+1}(\mu_{it+1})$ is implicitly a function of λ_t because of the recursive relationship for e^t.

Strict concavity of $B_i^1(e_{it})$ and $B_i^2(e_{it})$ and (non-strict) convexity of $D_i(w_t)$ guarantee that there are unique interior maxima for both maximization problems. The agent's choices yield standards $\lambda(\mu_{it})$ and $\lambda_t(\mu_{it})$ as a function of her beliefs, from (7).

Suppose that if a switch does not take place in the current period, then it does take place in the following period. Rewriting (7) shows that the agent prefers to wait for new information rather than make a current switch if:

$$\beta E_{it}[V_{it+1}^{2}(\lambda(\mu_{it+1})) - V_{it+1}^{2}(\lambda(\mu_{it}))] > E_{it}[v_{it}^{2}(\lambda(\mu_{it})) - v_{it}^{1}(\lambda_t(\mu_{it}))] \tag{8}$$

The left-hand-side is the value of being able to make a better decision next period because of the availability of new information, *i.e.*, the value of observing another draw of θ before λ is chosen. The right-hand-side is the cost of waiting, *i.e.*, the improvement in expected current net benefits that arises from using the more efficient regulatory regime.

Consider the case where $V^2_{it}(\lambda)$ is quadratic in λ,

$$EV^2_{it}(\lambda) = E[\lambda - \lambda^2 - \lambda\theta|\mu] \tag{9}$$

Maximization with respect to λ yields $\lambda = (1-\mu)/2$ and $EV^2_{it} = (1-\mu)^2/4$. For a current switch, this gives $E_{it}V_{it+1}{}^2(\lambda(\mu_{it})) \approx (1-\mu_{it})^2/4$. To calculate $E_{it}V^2_{it+1}(\lambda(\mu_{it+1}))$, note that from the standpoint of period t, μ_{it+1} is a random variable. The expectation is:

$$E[\frac{1-\mu_{it+1}}{2} - \frac{(1-\mu_{it+1})^2}{4} - \frac{(1-\mu_{it+1})\theta}{2}|\mu_{it}] = \frac{(1-\mu_{it})^2}{4} + \frac{2t-1}{4(t+1)^2}\sigma^2 \tag{10}$$

The value of information is:

$$\beta E_{it}[V^2_{it+1}(\lambda(\mu_{it+1})) - V^2_{it+1}(\lambda(\mu_{it}))] \approx \beta\frac{2t-1}{4(t+1)^2}\sigma^2 \tag{11}$$

This value is positive, increasing in σ^2, decreasing over time, and independent of the estimate of the mean. The calculation is approximate since $\lambda(\mu_{it})$ maximizes $E_{it}V^2_{it}(\lambda)$, not $E_{it}V^2_{it+1}(\lambda)$; also, both the function $\lambda(\mu_{it+1})$ and the value $E_{it}V^2_{it+1}(\lambda)$ depend on emissions in period t.

The cost of waiting is $E_{it}[v^2_{it} - v^1_{it}]$. Following the above discussion, $E_{it}v^2_{it} \approx \gamma(1-\mu_{it})^2/4$ where $\gamma < 1$ is a proportionality constant. Similarly, v^1_{it} might be approximated as:

$$v_{it}^1(\lambda_t) = \gamma[(1+\alpha)\lambda_t - \lambda_t^2 - \lambda_t\theta_t - L] \quad (12)$$

where α and L are parameters that distinguish utility between the two regimes. Since the common reduction regime is "less efficient" than the tradeable permits regime, an increase in emissions should be more valuable under the common reduction regime; thus $v_{it}^1(x)$ has the property $v_{it}^{2\prime}(x) < v_{it}^{1\prime}(x)$.[7] The parameter L ensures $v_{it}^2(x) - v_{it}^1(x) > 0$.

From (12), λ_t will be approximately $(1+\alpha-\mu_{it})/2$,[8] yielding $E_{it}v_{it}^1 \approx \gamma[(1+\alpha-\mu_{it})^2/4 - L]$. The cost of waiting is:

$$E_{it}[v_{it}^2(\lambda(\mu_{it})) - v_{it}^1(\lambda_t(\mu_{it}))] = \gamma[L - \alpha - \alpha^2 + 2\alpha\mu_{it}] \quad (13)$$

Together, equations (11) and (13) yield the following result: Suppose that agent j is indifferent between waiting for new information and making an irreversible decision now to move to the tradeable permits regime. Then another agent i with the same benefit and damage functions will prefer to make the irreversible decision now whenever $\mu_{it} > \mu_{jt}$.

Although the demonstration is imprecise, it provides a general picture of the issues. The value of waiting is the value of improved precision in the choice of λ. Loosely speaking, under the above specification of preferences, the value of improved precision is independent of the agent's estimate about global warming. The cost of waiting is the cost of a less efficient regulation in the present period. This is higher for an agent who thinks global warming is a serious problem (μ_{it} is high). The argument is based on choices that are contingent on the decision to switch regimes being made in the following period if they are not made in the current period. This is precisely true for period T-1 and the argument extends by induction to all periods $t < T$.

IV. International agreement and common interests

This section returns to the public choice problem in which countries participate in international negotiations and must jointly decide what agreement will be signed (common reduction path or tradeable permits) and what the policy parameters of that agreement will be. This is solved by looking first at the choice of the policy parameters given the policy regime, then at the choice of regime.

The first case considered is where countries have common interests. Common interests means that if the countries were to agree on the extent of warming, they would also agree on what the policy parameters should be. While this assumption does not appear to be entirely realistic for the current global warming debate, it is useful for focusing on differences in beliefs.

Let $\lambda_\tau^i(\mu)$ be the standard that maximizes $E[v_{it}^1(\lambda_\tau,\theta) + \beta V_{it+1}(\mu)|\mu]$ for given beliefs μ, and let $\lambda^i(\mu)$ be the standard that maximizes $E[V_i^2(\lambda)|\mu]$. Countries i and j have common interests when $\lambda_\tau^i(\mu) = \lambda_\tau^j(\mu)$ and $\lambda^i(\mu) = \lambda^j(\mu)$. However, because agents differ in their prior beliefs about warming, they will not agree on the optimal λ_τ or λ in any particular period.

1. The median agent

Although agents differ in their priors about warming, it is their differences about what the policy variables should be that will be important for most public choice problems. Define the median agent m as the agent with the median values for $\lambda_\tau^i(\mu)$, for the reduction path regime, and $\lambda^i(\mu)$, for the permits regime. Under a variety of voting rules, this agent will be decisive about the policy parameters. Her choices of λ_τ or λ, along with e_{i0}, then determine emissions for all agents. Other voting rules that do not select the median regulation are possible, of course, but are not considered here.

The median agent's preferences are now defined as:

$$V_{mt}(\mu_{mt}) = W(\max_{\lambda} E_{mt} V_{mt}^2(\lambda), \max_{\lambda_t} E_{mt}[v_{mt}^1(\lambda_t) + \beta V_{mt+1}(\mu_{mt+1})]) \qquad (14)$$

where W(A,B) is the value of the public choice rule (as yet unspecified) that determines the applicable regime; that is, W(A,B) = A if the tradeable permits agreement is in effect and W(A,B) = B if the common reduction agreement is in effect.

The median agent's choices yield standards $\lambda(\mu_{mt})$ and $\lambda_\tau(\mu_{mt})$ as a function of her beliefs, from (14). Then agent i's expected utility is defined recursively as:

$$V_{it}(\mu_{mt},\mu_{it}) = W(E_{it} V_{it}^2(\lambda(\mu_{mt})), E_{it}[v_{it}^1(\lambda_t(\mu_{mt})) + \beta V_{it+1}(\mu_{mt+1},\mu_{it+1})]) \qquad (15)$$

This value function must take into account i's assessment of both the likelihood of switching regimes and the median agent's choice of λ_τ or λ within the relevant regime. Note that because of the decisive role played by the median agent in choosing the policy parameters, the function V_{it} is not simply equal to $V_{mt}(\mu_{mt})$ in (14) with μ_{mt} replaced by μ_{it}; but $V_{mt}(\mu_{mt})$ can be rewritten in the form of V_{it} as $V_{mt}(\mu_{mt},\mu_{mt})$.

The remaining step is to describe the decision to switch between the two regimes. A number of voting rules (*e.g.*, majority rule) or other public choice procedures might plausibly govern such a switch. However, because switching is a binary decision, it is likely that the median agent will not play the pivotal role in this decision; instead, players with extreme beliefs may significantly affect the outcome.

2. Costs and benefits of waiting

This section looks at country i's preferences for a switch between regimes, relative to the preferences of the median agent. The median agent is indifferent between switching when the two terms in (14) are equal. Country i prefers the switch whenever the first term of (14) is greater than the second term and does not prefer it whever the second term is greater.

We again concentrate on a heuristic description of the decision problem. Suppose that if a switch does not take place in the current period it does takes place the next period. We first show that in this situation, the value of waiting is higher for all agents i than for the median agent. This is because if society waits, μ_{mt} will change, and agent i expects μ_{mt+1} to be closer to μ_{it}; thus she expects $\lambda(\mu_{mt+1})$ to approach $\lambda(\mu_{it})$.[9] This adds to the value of improved precision, which is the value of waiting for the median agent.

When countries i and m share the utility function in (9), the value to country i of waiting is:[10]

$$\beta E_{it}[V_{it+1}^2(\lambda(\mu_{mt+1})) - V_{it+1}^2(\lambda(\mu_{mt}))] = \beta(\mu_{mt} - \mu_{it})^2 \frac{2t+1}{4(t+1)^2} + \beta\frac{(2t-1)}{4(t+1)^2}\sigma^2 \qquad (16)$$

which is increasing in $|\mu_{it} - \mu_{mt}|$, increasing in σ^2, and decreasing in t. This exceeds the value of waiting for the median agent, given in (11), by $(\mu_{it} - \mu_{mt})^2(2t+1)/4(t+1)^2$. This value is decreasing over time since the higher is t, the less will be the movement of μ_{mt} toward μ_{it} for any given θ.

More generally, the value of waiting is higher for i than it is for the median agent because:

$$E_{it}[V_{it+1}(\mu_{mt+1},\mu_{it+1})) - V_{it+1}^2(\lambda(\mu_{mt}))] \geq E_{mt}[V_{mt+1}(\mu_{mt+1},\mu_{mt+1})) - V_{mt+1}^2(\lambda(\mu_{mt}))] \qquad (17)$$

The farther is μ_{it} from μ_{mt}, the greater is the expected change in λ_τ and λ. Inequality (17) then follows from the concavity of the utility functions and the assumption that i and m have common interests.

The cost of waiting for the current period is higher for agents with higher estimates of μ_{it}, as suggested in Section III. The difference in the cost of waiting between agents i and m, from (13), is approximately $2\gamma\alpha(\mu_{it} - \mu_{mt})$, which is linear in $\mu_{it} - \mu_{mt}$.

3. Alliance of the extremes

The median agent is indifferent between waiting and switching whenever the first term of (14) is equal to the second term. Whenever this is the case, all agents with $\mu_{it} < \mu_{mt}$ will prefer to wait, as equations (13) and (17) suggest. When $\mu_{it} > \mu_{mt}$, a country must weigh the benefits of waiting, which are quadratic in $\mu_{it} - \mu_{mt}$, with the costs of waiting, which are linear. For μ_{it}

sufficiently high, the quadratic term will outweigh the linear term, so this country will also prefer to wait. We are now ready to state the following result:

(Alliance of the extremes): Assume countries have common interests. Suppose that the median country is just indifferent to switching from the common reduction path regime to the tradeable permit regime. Then there exists a cut-off belief μ_t^c, greater than μ_{mt}, such that all countries i with $\mu_{it} < \mu_{mt}$ or $\mu_{it} > \mu_t^c$, will prefer not to switch.

Countries whose beliefs are higher than the median and countries whose beliefs are lower than the median will be allied in wanting to wait for new information, in the case where the median agent is indifferent. This alliance occurs because each country believes m's beliefs will converge to his,[11] and regardless of the regulatory regime that prevails, the standard that will be adopted will be better for i the closer is μ_{mt} to μ_{it}. The more extreme are an agent's beliefs, the higher this expected benefit. Some agents, however, whose beliefs are close to the median, with $\mu_{it} > \mu_{mt}$, will not want to wait because the benefit from waiting is slight and the cost of waiting (the benefit of switching regimes) is relatively large. The benefit is slight because the movement of μ_{mt} toward μ_{it} over time will not add much to i's utility. This result about the alliance of the extremes can be generalized to include the case where a single agent, not necessarily the agent with median beliefs, is always decisive in the choice of λ_t or λ.

Benefits of waiting exceed the costs (given that the median agent is indifferent) when $\mu_{it} > \mu_t^c$. The cut-off value for beliefs μ_t^c can be approximated by combining (13) and (16) for the case in which i's preferences are identical to m's and a switch will be made in the following period if it isn't made in the current period. Suppose σ^2 is small. Then μ_t^c can approximated by:[12]

$$\mu_t^c \approx \mu_{mt} - \frac{2\gamma\alpha(t+1)^2}{\beta(2t+1)} \qquad (18)$$

V. Differences in interests

It is valuable to consider international agreements when agents do not necessarily share the same benefit or damage function. For example, country i may find it more expensive to cut back on emissions than country j because j has a larger stock of energy efficient technology at time 0. For the damage function, it may be that country i believes a given amount of warming will result in less environmental disruption or it values environmental amenities less.

Country i is said to like warming more than country j if $\lambda^i(\mu) > \lambda^j(\mu)$ and $\lambda_t^i(\mu) > \lambda_t^j(\mu)$ for all μ. In words, country i prefers a less strict standard for given beliefs about warming. This could occur either because $B_i^{1\prime}(e_{it}) > B_j^{1\prime}(e_{it})$ or because $D_i'(w_t) < D_j'(w_t)$. Country i is said to like warming less than country j if $\lambda^i(\mu) < \lambda^j(\mu)$ and $\lambda_t^i(\mu) < \lambda_t^j(\mu)$. Of course, it is possible that country i and j cannot be ranked by either of these criteria.

The following result describes the decision to switch regimes when countries' interests diverge: Suppose that the agent with the median beliefs is always decisive in choosing λ_t and λ and that she is just indifferent between switching and not. Then for beliefs sufficiently far from the median, an agent i will (weakly) prefer not to switch from the common reduction path regime to the tradeable permits regime whenever one of the following two conditions holds:

(i) $\mu_{it} > \mu_{mt}$ and $\lambda^i(\mu) \geq \lambda^m(\mu)$ and $\lambda^i_\tau(\mu) \geq \lambda^m_\tau(\mu)$; or

(ii) $\mu_{it} < \mu_{mt}$ and $\lambda^i(\mu) \leq \lambda^m(\mu)$ and $\lambda^i_\tau(\mu) \leq \lambda^m_\tau(\mu)$.

The argument is similar to the one made in Section IV. Over time, an agent expects the median agent's beliefs to converge to his own. This is advantageous if, as beliefs converge, the value to the agent of the regulation that the median agent would choose rises. It is possible, of course, that as beliefs converge the median agent would choose a regulation that would be less desirable to an agent. In such a situation, those agents would prefer to switch regimes now, despite the divergence of beliefs, rather than wait for what they anticipate as a less desirable regulation.

VI. Disagreement and unilateral action

The analysis so far assumes that all countries produce the amount of emissions that the agreed-upon rules specify, but there is the possibility that some agents will take unilateral action to emit less than their specified amounts, as Hoel (1990), in a game-theoretic setting, has recently discussed. Prior even to a reduction path agreement, some countries will take actions to reduce emissions below the benefit-maximizing level. An agent i for whom $\lambda^i_\tau(\mu_{it}) < \lambda^m_\tau(\mu_{mt})$ will desire a move from an open access regime to a common reduction path, and the larger this difference the larger the gain to this agent of coming to a reduction path agreement. Such agents are labeled pessimists. Once such a reduction path agreement is achieved, unilateral action by pessimists to emit less than allowed is likely.

There may also be unilateral action under a tradeable permits regime. It takes the form of "idling" of permits, such as purchasing of permits from other countries or retaining unsold ones and then emitting less than the number of permits owned. For simplicity we consider the case where there is idling for one period only, in the present period. Let $\delta_i \geq 0$ be the emissions idled by country i and let q_i be actual emissions. In period t, country i chooses (q_i, δ_i) to maximize:[13]

$$B_i^1(q_i) + r(e_{it} - q_i - \delta_i) - E_{it}\sum_{s=t} \beta^{s-t} D(\theta_s e^s - \theta_s \delta_i) \tag{19}$$

The assessment of damages must take into account the effect of current idling on all future warming. In the absence of any idling, aggregate damages are unaffected by an individual country's action. Equilibrium is characterized by the following conditions:

$$B_i^{1\prime}(q_i) = r \tag{20}$$

$$B_i^{1\prime}(q_i) - E_{it}\left[\sum_{s=t} \beta^{s-t} D_i'(\theta_s q^s)\theta_s\right] \geq 0 \tag{21}$$

with strict equality in (21) if $\delta_i > 0$ and a strict inequality if $\delta_i = 0$. Equilibrium also requires market-clearing, $\Sigma(q_i + \delta_i) = \Sigma_i e_{it}$.

Unilateral action by country i is more likely the higher is its estimate of global warming. Because the marginal benefit terms are identical for all agents, by (22), the likelihood of unilateral action depends on the size of the cumulative marginal damage term. Expected marginal damage is increasing in μ_{it} because of the higher expected values of θ_s and the convexity of damages.

Unilateral action is also subject to the free-rider problem. Agents who are concerned about global warming may want to see global emissions reduced through permit idling, but would prefer that some other agent do it. In equilibrium, the public good is provided by the pessimistic agent whose emissions are the largest share of global emissions.

Consider an agent i who believes current allowable aggregate emissions are too high in the present period. Differentiate (6) with respect to a change in period t's λ (keeping λ unchanged for the other periods) to see that (20) and (21) imply:[14]

$$B_i^{2\prime}(e_{it})e_{i0} - E_{it}[\sum_{s=t} \beta^{s-t} D_i^{\prime}(\theta_s e^s)\theta_s e_0] < 0 \tag{22}$$

Define $\pi_i = e_{i0}/e_0$ and consider agents i and j such that:

$$B_i^{2\prime}(e_{it})\pi_i - E_{it}[\sum_{s=t} \beta^{s-t} D_i^{\prime}(\theta_s e^s)\theta_s] = B_j^{2\prime}(e_{jt})\pi_j - E_{jt}[\sum_{s=t} \beta^{s-t} D_j^{\prime}(\theta_s e^s)\theta_s] < 0 \tag{23}$$

Suppose (21) holds with equality for agent i. Then it holds with strict inequality for agent j whenever $\pi_j < \pi_i$. Thus, idling of permits is more likely the higher is the agent's share of aggregate emissions. If the damage functions are identical for all agents, then (21) also implies that only the agent(s) with the highest assessment of warming will idle emissions permits in equilibrium, a typical public goods result.

The possibility of unilateral action changes the agreements that might be reached under the median voter rules discussed in the previous sections. The present section has outlined the nature of the idling problem, but determining fully the characteristics of equilibrium and the implications for regime switching is complex, and is left for a later paper.

VII. Concluding remarks

There appears to be a great deal of disagreement over the extent to which global warming is occurring, and this may affect the kind of international agreement that is adopted to deal with the problem of greenhouse gases. Under a specific set of conditions, disagreement creates an *alliance of the extremes* in which countries that are optimistic and those that are pessimistic are joined. Because they disagree with the median belief about the size of the problem, both types of countries may be unwilling to enter into any long-term, inflexible agreement. The justification for such an alliance will be based on a desire to wait for additional information, because a country holding either type of beliefs will believe that new information will bolster its current position. Country i believes that if it delays an agreement, other countries will "see things its way" in time and a better agreement, from i's standpoint, can then be reached. The logic of this alliance is not restricted to the case of global warming but can be extended to many situations where substantial disagreement exists about a policy's consequences, and the adoption of a specific inflexible policy is proposed.

This paper has concentrated on disagreement over the actual physical effects of global warming but the results are directly applicable to the case where there is disagreement over the extent to which any particular level of warming will be detrimental to a country's economy. Indeed, it may not be possible to distinguish between disagreement over the level of global warming and its ecological consequences. Our results do not, however, cover disagreement over the economic costs of controlling emissions, and although the debate has seemed to focus on the amount of warming, there may also be important disagreements with respect to the costs of abatement. Disagreements over variability might also be important, although the argument that "global warming is highly uncertain" often appears to be more correctly framed as an argument about the mean, not the variance, of warming. In other words, statesmen who claim that there is a lot of uncertainty surrounding warming estimates often are considering only a higher probability that warming will be slow and are ignoring the implication that there is also a higher probability that it will be fast.

The most useful line of research we see is a discussion of this problem under other rules (*e.g.*, cooperative bargaining) about which policies are adopted or how they are enforced. Also, little appears to be known about what makes one particular agreement or policy amenable to revision and another not. Disagreements about both the costs of abatement and or the variability of warming are interesting, and we hope to take them up in future work. One source of uncertainty, which we have not addressed, is over exactly how much is being emitted and by whom.

Endnotes

1. Tradeable permits at the international level may not be as far-fetched as they sound. We would argue that the Persian Gulf war of 1991 was essentially financed through a tradeable permits scheme.

2. The issuing of short-term permits cannot solve this problem.

3. Carbon taxes are also a possible response, although they are more likely to be useful within a country than to govern relations between countries.

4. It may be difficult in practice to determine the CO_2 emissions of individual nations. This problem is even more severe for methane because the sources of emissions are poorly understood. Our model concentrates on changes in CO_2 stocks as determined, say, by the burning of fossil fuels and by changes in the area of forest; contributions by individual countries can then be determined relatively accurately.

5. It's not crucial to the results that the reduction path be identical for all countries so long as any country-specific reduction path treaty does not precisely mimic the emissions that would occur under a tradeable permits regime.

6. A more precise statement of the problem should include a time subscript on q_i and r. Expenditures on or revenues from permits are then $r_t(q_{it-1} - q_{it})$.

7. Utility under the common reduction path should be such that $\lambda_\tau > \lambda$. The specification in (12) also implies that agent i expects to be a net purchaser of the permits, but our conclusions are valid without this feature.

8. This calculation abstracts from the fact that choice of λ_τ must consider the effect of current emissions on future warming as well.

9. Note that although the tradeable permits level λ is constant over time once the tradeable permits regime is entered, the λ actually adopted will depend on the period in which the switch is made.

10. It is possible for agents to have common interests even if they do not have the same utility function.

11. The belief that current beliefs will be further supported by new data is widespread; for example: "[NASA's] Cosmic Background Explorer has another year of unanalyzed data "in the can" that is *expected to strengthen the revelations* [about ripples in the fabric of space-time], the scientists said." -- *Washington Post*, May 3, 1992 ("Big bang 'ripples' leave major impact"), emphasis added.

12. This expression is approximate since it ignores the possibility that the inefficient regime prevails in future periods. It also ignores the role of σ and the ways in which utility changes over time.

13. This expression is not net benefits in period t, which is what (5) is. It is the portion of discounted benefits from equation (6) that includes δ_i when idling occurs in period t.

14. Note that by (20) and the envelope theorem, $B_i^{1\prime}(q_{it}) = B_i^{2\prime}(e_{it})$.

References

Arrow, Kenneth, and Anthony Fisher. (1974), "Environmental preservation, uncertainty and irreversibility," *Quarterly Journal of Economics* 2, 312-9.

Bacharach, M. (1975), "Group decisions in the face of differences of opinion," *Management Science* 22(2):182-191.

Barlow, R.E., Wechsler, S., and Spizzichino F. (1988), "De Finetti's approach to group decision making," in *Bayesian Statistics 3*, J.M. Bernardo *et al.*, eds. London: Oxford University Press.

DeGroot, Morris H. (1970), *Optimal statistical decisions,* New York: McGraw-Hill Book Company.

French, Simon (1985), "Group consensus probability distributions: A critical survey," in *Bayesian Statistics 2*, J.M. Bernardo *et al.*, eds. Amsterdam: Elsevier Science Publishers.

Hammitt, James K., Robert Lempert, and Michael Schlesinger. (1992), "A sequential-decision strategy for abating climate change," RAND, unpublished manuscript.

Hoel, Michael. (1991), "Global environmental problems: The effects of unilateral actions taken by one country," *Journal of Environmental Economics and Management* 20(1):55-70.

Winkler, Robert L. (1968), "The consensus of subjective probability distributions," *Management Science* 15(2):B61-B75.

Young, Peyton (1991), "Sharing the burden of global warming," paper presented at the Thirteenth Annual Research Conference of the Association for Public Policy Analysis and Management, Bethesda MD, October 24-26 1992.