MIT Joint Program on the Science and Policy of Global Change

Tradable emissions rights and Joint Implementation for greenhouse gas abatement: A look under the hood*

R. Schmalensee
with Commentary by R.G. Prinn

Reprint Series Number JP 99-009

** Reprinted from The Impact of Climate Change Policy on Consumers: Can Tradable Permits Reduce the Cost? (April 1998, Washington, D.C.), pp. 39–55 and 65–71, with permission from the American Council for Capital Formation Center for Policy Research.*
Copyright © 1998 by ACCF Center for Policy Research.

The MIT Joint Program on the Science and Policy of Global Change is an organization for research, independent policy analysis, and public education in global environmental change. It seeks to provide leadership in understanding scientific, economic, and ecological aspects of this difficult issue, and combining them into policy assessments that serve the needs of ongoing national and international discussions. To this end, the Program brings together an interdisciplinary group from two established research centers at MIT: the Center for Global Change Science (CGCS) and the Center for Energy and Environmental Policy Research (CEEPR). These two centers bridge many key areas of the needed intellectual work, and additional essential areas are covered by other MIT departments, by collaboration with the Ecosystems Center of the Marine Biological Laboratory (MBL) at Woods Hole, and by short- and long-term visitors to the Program. The Program involves sponsorship and active participation by industry, government, and non-profit organizations.

To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives.

Henry D. Jacoby and Ronald G. Prinn,
Program Co-Directors

For more information, contact the Program office:

MIT Joint Program on the Science and Policy of Global Change
Postal Address:
77 Massachusetts Avenue
MIT E40-271
Cambridge, MA 02139-4307 (USA)
Location:
One Amherst Street, Cambridge
Building E40, Room 271
Massachusetts Institute of Technology
Access:
Tel: (617) 253-7492
Fax: (617) 253-9845
E-mail: ***globalchange@mit.edu***
Web site: ***http://web.mit.edu/globalchange/www/***

TRADABLE EMISSIONS RIGHTS AND JOINT IMPLEMENTATION FOR GREENHOUSE GAS ABATEMENT: A LOOK UNDER THE HOOD

Richard Schmalensee

In December 1997, the Parties to the Framework Convention on Climate Change will meet in Kyoto, Japan. Since the first such meeting was held in Berlin in 1995, diplomats from many nations have been attempting to produce an agreement that will impose national limits on greenhouse gas emissions for the early years of the next century. Even though the Parties remain divided along several important dimensions, the pressure to reach some sort of agreement somehow is extremely intense and rapidly increasing. When an issue is well understood, this sort of pressure can sometimes force productive resolution of minor differences. When, as here, there are important uncertainties, pressure to reach agreement may cause major issues to be ignored and mishandled in a hastily drafted agreement, to the long-term detriment of all concerned.

As involved Europeans seem to delight in pointing out, the Clinton Administration has not yet put forward a complete proposal for the world's venture into abatement of emissions of carbon dioxide (CO_2) and, potentially, other greenhouse gases. However, the Administration has made clear, particularly in a "Draft Protocol Framework" circulated early this year,[1] the sort of vehicle in which it would like to make this journey. That vehicle is the focus of this paper. I will pay particular attention to its use of tradable emissions rights, both internationally (where I will use the term "quota") and domestically (where I will use the term "allowance"), and of joint implementation.

A commonly posed, threshold question is whether the Administration's proposal is workable: can its vehicle go anywhere? I believe the answer is yes—and the question is not very interesting, because workability is a weak test. After all, past Administrations devised more or less workable systems for wellhead regulation of natural gas prices and regulation of interstate trucking rates and airline fares. Because those who created these programs ignored important economic issues, of course, these regulatory regimes were long-lived, costly mistakes. Similarly, while the economic impact of the Administration's proposal would depend on design parameters not yet announced—particularly the level of emissions allowed—and on details of implementation, that proposal, too, shows neglect of important issues. Even if one takes the risk of climate change seriously, as I do, I believe one must conclude that the Administration's vehicle, despite a number of very attractive features, has the potential to take us for a bumpy ride in the wrong direction. (If, on the other hand, you are absolutely convinced that there is no risk, i.e., no chance that we will ever learn that climate change is a real problem, you should care only about the bumps, not about going in the wrong direction.)

I. THE ADMINISTRATION'S VEHICLE

The so-called "Berlin Mandate," adopted by the Parties in July 1995, decreed that the current round of climate negotiations was to be about limiting the emissions only of the so-called Annex I nations: the OECD circa 1990 (Western Europe, the United States, Canada, Australia, New Zealand, and Japan) and the "economies in transition" (Eastern Europe and most of the former Soviet Union). So far, the Administration has not departed from these instructions, though its proposal would allow other nations to opt in to the Annex I regime. The Berlin Mandate and the Administration proposal focus on national limits on greenhouse gas emissions for the early years of the next century, though the Administration's proposal seems to envision (but does not describe) a deliberative process that would lead to changes in national limits over time.

To my knowledge, the Administration has not yet said anything official about what sorts of emissions limits it has in mind, but it has presented an interagency analysis of the costs of reducing U.S. CO_2 emissions from fossil fuel combustion to 1990 levels by 2010 and maintaining that level through 2020.[2] The European Union (EU), in contrast, has proposed reducing Annex I emissions to 15 percent below 1990 levels by 2010. Whatever approach to emissions limitation is chosen, costs will clearly vary directly with stringency, and they will be particularly burdensome in any case if the EU's proposal is implemented.

The Administration proposes that Annex I nations be given quotas for periods of several years at a time rather than for a single year. (Characteristically, the number of years is left blank, but I believe it would be useful to think of five-year periods.) Nations would be permitted to bank unused portions of their quotas for future use and, to a limited extent and at a cost, to borrow from future quotas. These provisions are clearly intended to provide some flexibility; the year-to-year fluctuations in emissions they would permit would have no discernible climate effect but could permit substantial cost reductions. Perhaps more importantly, the Administration would allow quotas to be transferred between nations. The ability to trade emissions rights internationally can in principle reduce total world costs, though most studies find that trading involving only Annex I nations has relatively little cost-reducing potential.[3]

Though I have not seen this stated officially, all indications are that the Administration plans to ensure that the constraint on U.S. emissions is met by using tradable emission allowances domestically. That is, the U.S. quota would be divided (somehow, see below) among (most likely) a set of domestic firms, and these firms would be free to trade emission rights (allowances) among themselves. At the most abstract level, such a system could operate more or less like a carbon tax and could accordingly ensure that whatever abatement the United States achieves is accomplished at minimum cost.[4] Moreover, such a system could in principle allow private parties, rather than or in addition to governments, to trade emission rights internationally.

The Administration has generally argued that non-Annex I nations should be encouraged to participate in greenhouse gas abatement via "joint implementation." Using this mechanism, the U.S. government (or a U.S. firm) could, for instance, gain credit for some number of tons of reduced CO_2 emissions by investing in reducing emissions from Chinese electricity generation. Of course, in order for this to be counted toward meeting U.S. international obligations, some international organization would have to verify that the investment actually reduced emissions by the amount claimed, compared to a world in which the investment had not been made.

Finally, the Administration's "Draft Protocol Framework" clearly envisions coverage of multiple greenhouse gases from many sources, not just CO_2 from fossil fuel combustion. Since other human-caused emissions are, in aggregate, of roughly equal importance to CO_2 from fossil fuels, this makes sense in principle.[5] Given the real difficulties (discussed briefly below) associated with measuring the emissions of other gases, however, it seems highly unlikely that any agreement signed in Kyoto will extend beyond CO_2 emissions from fossil fuels.

II. GOING IN THE RIGHT DIRECTION?[6]

It is important to acknowledge that there is much in the Administration proposal to applaud—particularly when it is compared to the alternatives advanced by other Parties. The EU tends to stress the use of "common policies and measures," which is best translated as "similar command-and-control regulations for all," and to resist approaches that have the potential to lower total world costs. Developing nations tend to resist playing any role at all in reducing global greenhouse gas emissions and, in particular, tend to be suspicious of joint implementation. The United States appears to be the only Party to think beyond the next few decades and to address the need to employ market mechanisms to provide flexibility and reduce world costs. For all this it deserves much applause. On the other hand, largely because of its adherence to the Berlin Mandate, the Administration's vehicle cannot without substantial modifications move the world toward a strategically sensible response to the risk of potential climate change. It could easily make such a response harder, not easier, to implement.

A. The Terrain

Perhaps the most important features of the climate change issue are the long time-scales and high uncertainty involved. We know that emissions of CO_2 remain in the atmosphere for something like a hundred years and that both emissions and atmospheric concentrations of greenhouse gases have increased substantially over the last century. Even if emissions were stabilized at today's levels, atmospheric concentrations would rise substantially for decades.

Stabilizing atmospheric concentrations at levels that have been discussed in international negotiations would require substantial cuts in CO_2 emissions over the course of the next century.[7] (The Framework Convention on Climate Change makes stabilizing atmospheric concentrations of greenhouse gases its ultimate goal, but it is effectively silent on the level at which they are to be stabilized.) In contrast, most long-run forecasts show substantial global emissions growth in the absence of stringent controls, with the bulk of the growth, and thus a rising fraction of global emissions, occurring in the developing world.[8] It will very likely be impossible to attain stabilization at widely discussed concentration levels without significant abatement by developing nations. In most long-term scenarios, even the extraordinary action of driving Annex I emissions to zero would be by itself insufficient.[9]

It is also generally accepted that higher atmospheric concentrations of greenhouse gases, *all else equal*, will increase the amount of solar energy retained by the

Earth's climate system and tend to raise temperatures at the Earth's surface. But all else is not equal: some poorly understood climate processes amplify this warming effect, while others, no better understood, tend to counteract or delay it. Work in the Massachusetts Institute of Technology Joint Program on the Science and Policy of Global Change indicates that temperature increases in 2100 as small as two degrees Fahrenheit or as large as nine degrees Fahrenheit can easily be defended as plausible. (This range reflects uncertainty about future emissions as well as about climate processes.) Moreover, we know even less about the likely impacts on society of climate change or about the costs of adaptation than about the likely amount of warming. Clearly, though, a temperature increase of nine degrees over the course of the next century would pose significant risks to a variety of important natural processes, including ocean circulation and unmanaged ecosystems, as well as to agriculture and other human activity.

Given all this, it is plainly important to invest in research on the climate system (including determinants of emissions and analysis of effects of climate change), and the United States has long been a leader in this important endeavor. Because of ongoing research we may someday learn that substantial climate change is in prospect, that it poses a serious threat to human civilization, and that substantial reductions in greenhouse gas emissions are required to respond to it. It is also possible, of course, that we will learn that even with no attempt to limit emissions, there will be little or no warming and, on balance, no adverse impacts. But even with continuing heavy investments in research, it appears unlikely that either possibility will be definitively ruled out for years to come.

In this situation, the obvious near-term task, while this profound uncertainty is in the process of being resolved, is to identify and make productive investments aimed at reducing the costs of mitigating climate change and of adapting to its effects—the costs that would be incurred if the news turns out to be bad. Such investments almost certainly include research on new energy technologies with low CO_2 emissions,[10] as well as on agricultural techniques with reduced emissions of such greenhouse gases as methane and nitrous oxide. Similarly, development of new crop varieties and cultivation techniques could substantially lower costs of adapting to climate change in poor nations, and there may be other "adaptation technologies" that could profitably be developed.

Because the developing world's emissions must be controlled if global emissions are to be reduced and because it appears that the cheapest abatement possibilities are to be found in the developing world,[11] investments in making such control possible appear particularly attractive from a strategic perspective. These investments would be largely in designing and developing international institutions.

Since it seems that we have several decades, at least, before global participation in emissions limitation could become vital, and since voters in even the richest nations do not appear interested in spending appreciable sums today to deal with climate change, it is good that institutional development tends to be time-intensive but relatively cheap. On the other hand, the task of developing useful international institutions is complicated by the need to respect national sovereignty, a need that has no counterpart in the domestic policy environment. Imagine the process of making U.S. environmental policy if the federal government had to rely on voluntary compliance by state governments—and then recall how homogeneous the states are as compared to the nations of the world!

A first institutional issue is financial. Today's developing nations are unlikely to spend their own resources to control greenhouse gas emissions, at least until their incomes have risen substantially. Thus, for example, if China is to be induced to control its emissions significantly any time during the next few decades, methods will need to be found to transfer resources to China for this purpose. If tight controls on global emissions are required, substantial resource transfers will also likely be necessary: in plausible scenarios more than two percent of OECD GDP will need to be transferred in some years to achieve widely discussed stabilization goals.[12] It is almost impossible to imagine transfers of this magnitude being made directly by rich nations to individual poor nations. It thus seems that some sort of respected, objective international institution (on the model, perhaps, of the International Monetary Fund and the World Bank) will be required to act as an intermediary.

Large resource transfers will not be forthcoming, of course, unless the donors can be assured that the recipients will meet their obligations. This suggests the importance of developing the ability to monitor emissions with confidence, particularly in the developing world. Doing so will require both advances in knowledge and the transfer of technology and expertise to developing nations. The standard data on CO_2 emissions from fossil fuels are computed by combining unverified national reports of imports, exports, production, and inventory change of various fuel types with assumptions regarding the carbon content of each.[13] This will surely not be adequate when the financial stakes are large and incentives to misrepresent become impossible to ignore.[14] Moreover, we have even less ability to monitor emissions of CO_2 associated with land use changes and cement production or emissions of other greenhouse gases. Because it is hard to imagine that global emissions of greenhouse gases could be reduced substantially with only controls on CO_2 emissions from fossil fuels, there would appear to be a large potential return to investments in developing the capability of monitoring emissions from these other sources. In addition, it is not entirely straightforward to design an efficient

international mitigation regime that covers multiple gases with very different sources, chemical properties, and atmospheric lifetimes.

Finally, while the carrot of resource transfers may be necessary to induce nations to meet their obligations, the international community may also need to employ the stick of sanctions. While explicit sanctions do not play a large role in inducing compliance with most international agreements,[15] no international agreements currently in force (except, arguably, in the defense area) involve economic stakes nearly as high as those potentially at issue in the climate context, and few require governments to impose significant costs on their own citizens. At the very least, the question of sanctions deserves serious study and the serious attention of climate negotiators.[16] The complexity of this question argues that it should be addressed sooner rather than later.

B. The Wrong Direction

Strategically, the Administration proposal concentrates on short-run reductions in rich country emissions of CO_2 from fossil fuels, not on taking steps to reduce the cost of (or, indeed, to render feasible) the substantial long-run global reductions in overall greenhouse gas emissions that may be necessary to deal with the threat of climate change. The Administration proposal does not deal in any serious way with development of new technologies that could lower costs of reducing emissions or of adapting to climate change, even though Administration rhetoric tends to stress the value of new technologies for abatement, at least. The proposal does not even address the problem of moving from a regime focused on CO_2 from fossil fuels to a more comprehensive approach; the "Draft Protocol Framework" is written as if the problem were solved.

More importantly, the Administration proposal has little to say about the development of international climate policy institutions, largely because it follows the Berlin Mandate and does not aim to induce early participation by non-Annex I nations. The Administration proposal simply obliges each Party to put in place a system for monitoring emissions, and it merely notes that the Parties might wish, sometime in the future, to consider what to do about noncompliance. It does not deal with problems posed by the potential need for large international transfers of financial and technical resources. On a positive note, its proposed requirement that an international secretariat review national policies and emissions projections is a good idea; it would both develop useful expertise and serve to provide some advance warning of noncompliance.

The Administration proposal's main device to involve non-Annex I nations is Joint Implementation (JI). Unfortunately, it seems painfully obvious that JI will do very little to advance this objective. Indeed, by ratifying the principle that developing nations have no emissions control obligations and by providing no mechanism for their transition to Annex I status, the Administration proposal may actually retard the achievement of effective global participation. Developing nations are generally hostile toward JI, fearing (among other things), that it will threaten their sovereignty, reduce flows of useful foreign aid dollar-for-dollar with investments in JI projects, and saddle them with de facto emissions control obligations. But even if they were enthusiastic, the need to reach international agreement on project-specific emissions reductions would guarantee high transactions costs. This is not a problem of monitoring, and it does not even in principle have a technical solution. The problem is not to measure actual emissions (though this must be done) but to estimate what emissions would have been in the unobservable, "but for" world without the project in question. Such estimates are inevitably project-specific, and the process of constructing them is inevitably controversial and detail-intensive. The disappointing U.S. experience with this sort of credit system should make clear the serious difficulties involved.[17]

One final point on JI deserves mention. Inevitably in the evaluation of any JI project, errors will be made in estimating "but for" emissions. Positive errors make the project less attractive to the parties involved by reducing the credits it generates; negative errors make the project more attractive. Because more attractive projects are more likely to be implemented, on average the projected benefits of JI projects will tend to be overstated, and JI will contribute less to reducing emissions than will be claimed.[18]

Taken as a whole, the Administration proposal, or indeed, any proposal strictly consistent with the Berlin Mandate, would work against eventual inclusion of developing nations in a serious greenhouse emission abatement regime. By explicitly or implicitly raising the prices of fossil fuels in Annex I countries and, most likely, lowering the world market prices paid by other nations, the Administration proposal would encourage investment in energy-intensive capital outside Annex I. All else equal, energy-intensive industries would have greater incentives to invest outside Annex I, and households outside Annex I would have reduced incentives to invest in energy-efficient appliances, dwellings, and vehicles. Carbon emissions can be thought of as "leaking" from Annex I to other nations in this fashion; this leakage implies that any given reduction in Annex I emissions would produce a smaller reduction in global emissions.[19]

More important, a country that has just invested heavily in energy-intensive industry, large autos, and poorly insulated housing will clearly be less eager than

otherwise to reduce the value of that investment by explicitly or implicitly increasing energy prices. The process of "leakage" that adherence to the Berlin Mandate implies will make it harder to persuade additional nations to assume abatement obligations. This process thus raises the cost of substantial global emissions reductions, all else equal.

The Berlin Mandate aims at a "deep, then broad" approach to global control of greenhouse gas emissions: first have rich countries control their emissions, then if necessary induce others to play along.[20] Unfortunately, as I have just argued, the first of these steps makes the second more difficult. The obvious alternative is a "broad, then deep" approach: involve most nations in a relatively low-cost abatement regime, then if necessary tighten controls globally. This approach would eliminate leakage; implementing it would obviously require heavy, early investment in institutional development—just the sort of investment that is missing from the Administration proposal.

III. A BUMPY RIDE?

Though it is misdirected from a strategic perspective, it must be acknowledged that the Administration's vehicle can reduce U.S. CO_2 emissions somewhat without wrecking the nation's economy, though, as many studies have found, substantial reductions will inevitably entail substantial costs.[21] The use of tradable allowances within the United States can limit emissions at lower cost than most command-and-control regimes. As I now discuss, however, the Administration design has a number of features and defects that seem likely to produce implementation problems and to inflate compliance costs relative to feasible alternatives.

A. Can We Trade?

A system of domestically tradable emissions rights poses the same basic administrative challenges as a carbon tax. Just as most carbon tax discussions conclude that the tax should be levied on primary energy production and imports, with rebates granted for exports and non-energy uses of fossil fuels (e.g., in chemical manufacturing), so it makes the most sense to issue "allowances" that permit emission of specified quantities of carbon "upstream," to firms that produce and import fossil fuels. Allocation "downstream" to intermediaries and end users would simply raise administrative costs and complicate enforcement, with absolutely no economic benefit.[22] Measurement of the carbon content of fuel sold would be the same in the two systems, and enforcement problems would be similar. While there are some tricky problems

in the details, I do not believe they are insoluble.[23] Moreover, the experience since 1990 with the U.S. acid rain program gives one every reason to expect that efficient markets for carbon allowances would develop in a timely fashion.[24]

The equity issues raised by a domestic system of carbon allowances are also similar to those raised by a carbon tax. Like a carbon tax, a carbon allowance system would hit domestic coal noticeably harder than domestic and imported oil. These impacts would be concentrated in regions that produce coal and in regions that burn coal to generate electricity. There would be pressures to depart from efficient policies to offset these impacts, just as the costs of reducing U.S. emissions of sulfur dioxide have long been increased by policies designed to aid high-sulfur coal interests.[25] Pressures to depart from efficiency in the interest of fairness are ubiquitous and seem to guarantee that any mitigation policies actually implemented in the United States will be noticeably less efficient (i.e., more expensive) than the ideal cases that have been analyzed to date.

Some important implementation issues are unique to a tradable allowance regime. While it is possible to imagine a regime in which carbon allowances will be auctioned instead of given away, there are good political reasons why such regimes exist only in economics textbooks. There is no environmental difference between the two regimes, benefits of auction revenue would be dispersed, and costs of buying allowances would be concentrated on the regulated entities.[26] If, as thus seems highly likely, carbon allowances are to be given away under the Administration proposal, who is to get these valuable assets? This is the domestic analog of the diplomatic problem of determining national emissions quotas. The U.S. acid rain program would seem to demonstrate that this problem can be solved—and that solving it will involve messy political dealing, not comparisons among competing abstract principles.[27] (Indeed, one can argue that this "problem" is really an advantage of the tradable allowance approach; the ability to distribute valuable allowances without compromising efficiency provides a useful tool for building political coalitions.)

A second problem relates to changes in national quotas. As we learn more about the climate issue and as national fortunes ebb and flow, unexpected changes will occur in appropriate global emissions and in national quotas. Implementing such changes would create capital gains or losses for those who held allowances. It is never easy to change tax rates, though in practice they change often in the United States, or command-and-control regulations, but I fear that the prospect of capital gains or losses may well act to make it even harder to change national CO_2 emission quotas when such changes are called for.

A final set of problems relates to the implementation of international emissions trading, which is critical to holding down world and domestic costs, with a domestic

tradable allowance regime. In order to make allowances issued to private U.S. parties effectively tradable internationally, foreign governments would need either to implement compatible tradable allowance programs or to stand ready to buy and sell allowances to and from private U.S. parties on a businesslike basis. The first of these raises issues of sovereignty, while the second raises issues of plausibility. If allowances issued to U.S. private parties were not tradable internationally, however, the only way to expand U.S. use of fossil fuels would be for the U.S. Congress to appropriate funds to buy emission rights from other sovereign governments. But it is more than a little difficult to imagine this Congress, at least, paying billions to the Chinese for the right to compete with Chinese energy-intensive exports.

B. Should We Trade?

If one is concerned about the total cost of CO_2 abatement, the obvious domestic alternative to a tradable allowance regime is a carbon tax. In the simplest textbook situations, these policies are equivalent. I have argued above that in real life trading remains feasible but, in context, encounters some implementation problems. In addition, a serious greenhouse gas abatement program, one that significantly reduced consumption of fossil fuels from what it would otherwise have been, would have non-negligible economy-wide effects that could not be overlooked. I now want to argue that a consideration of those economy-wide effects reinforces the relative desirability of the carbon tax approach.

A good deal of recent economic research has compared the net static welfare effects of various sorts of environmental policies in economies in which tax systems distort the allocation of resources, as all real tax systems do.[28] This is not the occasion, and I am not the person, to summarize that literature in any detail. Its basic thrust, though, is that systems that involve auctioning allowances or taxing emissions are better for the economy as a whole than regimes in which allowances are given away for free, all else (including total emissions) equal. The difference seems to arise mainly because the first two systems generate revenue that can be used to reduce tax-induced distortions elsewhere in the economy, while this cannot occur if allowances are simply given away. In some simple models the difference is so large that it could be highly desirable to control pollution with a tax but undesirable on balance to do anything if the only available instrument were free allowances. We do not know that the real difference of the net costs of allowances and of taxes is that large in the greenhouse context, but we know its sign and I would expect it to be important. At the very least, this issue deserves serious study before a comprehensive abatement scheme is put in place.

A second set of issues relates to unexpected changes in national output (GDP) and other factors affecting energy consumption. With tradable domestic allowances, total emissions are fixed, while the emissions corresponding to any given carbon tax are uncertain. In particular, unexpected increases (decreases) in GDP will raise (lower) fossil fuel use and thus increase (decrease) CO_2 emissions with a fixed tax but will have no effect on aggregate emissions under a fixed national quota. How then can one reconcile domestic use of a carbon tax to meet a binding limit on total national emissions? The Administration's "Draft Protocol Framework" contains the obvious answer: have the limit apply to multi-year periods instead of to single years, and make some provision for banking and (at a cost) small-scale borrowing from the future. This sort of flexibility should be sufficient to permit nations to employ either carbon taxes or command-and-control regulation of various sorts to stay within their emission quotas.

A first question is whether the Administration's tradable allowance approach could be modified so that it, too could take advantage of this flexibility. If, however, the Administration proposes to announce in advance how many carbon allowances will be issued each year, it would clearly take no advantage of this flexibility. Indeed, because energy is important in at least some major cyclically sensitive industries, there could be significant impacts on the business cycle. If total emissions were absolutely fixed in the short run, national real output would tend to be stabilized. Unexpected increases in aggregate demand would raise energy prices (via raising allowance prices) more rapidly than at present, making purchase of U.S.-produced energy-intensive products less attractive relative to imports and to saving. This would tend to choke off booms, and the same mechanism operating in reverse would tend to mitigate recessions. On the other hand, inflation would be destabilized. Increases in aggregate demand would cause rapid (and non-transitory) increases in energy prices, while energy prices would fall more rapidly than at present in recessions. I do not believe these effects have been seriously studied or that anyone can say with confidence whether they would be important or whether on balance they would be good for the economy. It would seem prudent to perform a serious study of this issue before going forward with a tradable allowance regime with fixed numbers of allowances.

If, on the other hand, the Administration proposes to vary the number of allowances issued from year to year depending on conditions at the time, it would need to set up something like a Federal Reserve Board for carbon allowances, and it would need to develop procedures for increasing *and decreasing* the allowances available in any given year. One could not evaluate any system of this sort without knowing a fair bit about these institutions and procedures and thinking through how they would affect the domestic economy. In addition, there might be interna-

tional effects: trading allowances internationally would certainly be made more complex because relative prices between nations would be affected, at least for a time, by short-run government policy decisions.

This is not a plea for an international regime based on harmonizing carbon taxes. Many authors have noted problems with this approach.[29] It is at the very least exceedingly difficult to compare the average net burdens on carbon emissions imposed by alternative complex tax/subsidy/regulatory systems.

But one can use carbon taxes domestically without adopting such a scheme. The Administration's "Draft Protocol Framework" envisions an expert secretariat evaluating national emissions projections in light of national policies. It would be a small step (and one not inconsistent with important aspects of U.S. environmental policy) to specify that as a condition of compliance, national projections (and, of course, the methods employed to make them) be approved in advance. This would provide at least some ability to differentiate between nations that failed to comply because they failed to adopt appropriate policies and those that failed because of unforeseen events. It would move toward a regime based on evaluation of what governments can control, which is government policies, rather than on what they cannot control, which is economic activity. It would move away from a regime in which sanctions could only be levied well after the fact, after all emissions data are in and vetted, by which time governments may have changed more than once.

IV. SHOULD WE BUY THE ADMINISTRATION'S VEHICLE?

As I noted at the outset, the Administration's approach to climate change passes the weak test of workability. The Administration has partially designed a vehicle that, despite a range of unanswered questions, will move down the road. But, as I have tried to argue, there are two basic problems that suggest we should not buy that vehicle now.

The first problem is that this vehicle may not move us down the *right* road. By concentrating on near-term reductions in rich-country emissions, it fails to attach adequate importance to investments in technologies for mitigating and adapting to climate change. More importantly, it fails to take any steps at all toward solving what may prove to be the most critical problem of all: inducing developing nations to participate in controlling global emissions. Indeed, by providing incentives for energy-intensive industry to expand in developing nations and reducing conservation incentives there, the Administration approach (because it follows the Berlin Mandate), will make it more difficult than necessary to induce broad participation.

The second problem is that the Administration's vehicle promises us a bumpy ride or, in ordinary language, non-negligible implementation problems and poten-

tially excessive abatement costs. A system of tradable carbon allowances with fixed annual total emissions would be inflexible and would tend to destabilize the price level. It is hard to see an economic reason for preferring tradable carbon allowances to a carbon tax, though it is clear that energy producers would prefer allowances if they did not have to pay for them.

I do not intend to suggest that the Administration should trade its vehicle for some other nation's or that I have a fully worked out superior design of my own. I have tried to articulate, here and elsewhere, what I believe is a superior strategic approach to this issue, but going from this approach to an effective international agreement would require an enormous amount of careful analysis and skillful negotiation. Given what has been done so far, in particular how little systematic attention has been paid to the crucial issue of investing now to reduce long-run mitigation and adaptation costs, there does not appear to be enough time between now and the Kyoto talks in December 1997 to finish a good design. Thus, given the power of precedent in domestic policy and international law, any policy regime hastily adopted at Kyoto and hastily implemented at home may prove to be a long-lived mistake.

It is probably unreasonable to hope for a fundamental change in Administration policy at this late date, but it is quite reasonable to expect the U.S. Congress to review carefully what emerges from Kyoto, as well as the legislation that would be necessary to implement any substantive international agreement. In addition, it is reasonable to hope (if not necessarily to expect) that a "Kyoto Mandate" could emerge from December's meeting that would steer the next round of climate negotiations in directions that will be more valuable to us all in the long run.[30] We have time to design and adopt realistic strategies to respond to the threat of climate change; we should not be distracted by political pressures to take short-term symbolic actions that may well be counterproductive in the long run.

NOTES

I am deeply indebted to my colleagues in MIT's Joint Program on the Science and Policy of Global Change [hereafter simply "MIT Joint Program"] for most of what I know about the climate issue, though none of them necessarily agrees with anything in this paper, and to Rob Stavins for useful comments.

1. This is an eleven-page typewritten document dated 17 January 1997, entitled "U.S. Draft Protocol Framework" and not otherwise identified. Its central elements are discussed in another U.S. government "publication": a document entitled "Climate Change: U.S. Non-Paper" and dated December 1996. I have also relied on conversations with several involved individuals to characterize the evolving Administration position.

2. [U.S.] Interagency Analytical Team, "Economic Effects of Global Climate Change Policies," draft of 30 May 1997.

3. See, generally, Intergovernmental Panel on Climate Change, *Climate Change 1995—Economic and Social Dimensions of Climate Change* (Cambridge: Cambridge University Press, 1996), Section 9.2.

4. A good general discussion is provided by T.H. Tietenberg, *Emissions Trading* (Washington, D.C.: Resources for the Future, 1985). The relation between these two instruments is sometimes misunderstood, so an attempt at clarification seems in order. Suppose a firm is given tradable allowances that permit emissions of ten tons of CO_2, that the market price of emissions rights is $10 per ton, and that at that price, the firm plans to emit ten tons. It pays nothing for its allowances, but it must recognize that the cost at the margin of increasing emissions is $10 per ton, the cost of the allowance it would need to buy. Similarly, the benefit of reducing emissions is $10 per ton, since the allowances no longer required can be sold. Now consider a regime with a carbon tax of $10 per ton. One would normally expect that our hypothetical firm would still plan to emit ten tons, since its cost of emissions at the margin is $10 per ton, as before. The only difference, and it is not likely to be a trivial one from the firm's perspective, is that it must pay $100 for taxes in the carbon tax regime and nothing in the alternative. If allowances are auctioned instead of being given away, and the market price is $10, the two regimes are identical at this most abstract level.

5. In the 1980s, CO_2 accounted for around 60 percent of the increase in net absorption of solar radiation ("radiative forcing") attributable to human-caused changes in the composition of the atmosphere, and about 75 percent of human-caused CO_2 emissions were produced by combustion of fossil fuels. The remaining CO_2 emissions were caused by cement manufacturing and changes in land use. See Intergovernmental Panel on Climate Change, *Climate Change 1995—The Science of Climate Change* (Cambridge: Cambridge University Press, 1996), sections 2.1 and 2.4; and G. Marland et al., *Estimates of CO_2 Emissions From Fossil Fuel Burning and Cement Manufacturing*, ORNL/CDIAC-25, NDP-030, Oak Ridge National Laboratory, May 1989.

6. This section draws heavily on R. Schmalensee, "Greenhouse Architectures and Institutions," MIT Joint Program Report No. 13, November 1996; and H.D. Jacoby, R.G. Prinn, and R. Schmalensee, "Needed: A Realistic Strategy for Global Warming," MIT Joint Program Report No. 21, August 1997.

7. See, for instance, Intergovernmental Panel on Climate Change, *Climate Change 1995—The Science of Climate Change*, section 2.1.3.

8. See, for instance, R. Schmalensee, T.M. Stoker, and R. Judson, "World Carbon Dioxide Emissions: 1950–2050," *Review of Economics and Statistics* 80 (February 1998): 15–27. The authors note that China and India accounted for about 15 percent of 1990 CO_2 emissions from fossil fuels; they project that these two nations alone will account for at least 27–30 percent of emissions in 2050 and 31–44 percent of emissions growth over the 1990–2050 period.

9. See, for instance, H.D. Jacoby, R. Schmalensee, and D.M. Reiner, "What Does Stabilizing Greenhouse Gas Concentrations Mean?" in B.P. Flannery and C.A.B. Grezo, eds., *Critical Issues in the Economics of Climate Change* (London: IPIECA, 1997); and J. Edmonds, J. Dooley, and M. Wise, "Atmospheric Stabilization and the Role of Energy Technology," in *Climate Change Policy, Risk Prioritization, and U.S. Economic Growth* (Washington, D.C.: American Council for Capital Formation Center for Policy Research, June 1997).

10. On the potential importance of low-carbon energy technologies, see Edmonds, Dooley, and Wise, "Atmospheric Stabilization." Caution is called for here, however, since the U.S. government has not historically been very good at developing commercial technologies at reasonable cost; see, for instance, R. Schmalensee, "Appropriate Government Policy Toward Commercialization of New Energy Supply Technologies," *Energy Journal* 1 (1980): 1–40.

11. Intergovernmental Panel on Climate Change, *Climate Change 1995—Economic and Social Dimensions of Climate Change*, Section. 9.2.

12. This issue is explored by H.D. Jacoby and Z.Y. Yang, "Necessary Conditions for Stabilization Agreements," MIT Joint Program Report No. 26, October 1997.

13. See G. Marland et al., *Estimates of CO_2 Emissions From Fossil Fuel Burning and Cement Manufacturing.*

14. For a discussion of the monitoring problem, see United Nations Conference on Trade and Development, *Combating Global Warming: Possible Rules, Regulations and Administrative Arrangements for a Global Market in CO_2 Emission Entitlements* (New York: United Nations, December 1994).

15. A. Chayes and A.H. Chayes, *The New Sovereignty: Compliance With International Regulatory Agreements* (Cambridge, Mass.: Harvard University Press, 1995).

16. Compare R.N. Cooper, "A Treaty on Global Climate Change: Problems and Prospects," mimeo, October 1996 (arguing that sanctions do not have a substantial potential role in this context) and Environmental Defense Fund, "Emissions Budgets: Building an Effective International Greenhouse Gas Control System" (Washington, D.C., February 1997) (arguing that automatic sanctions for excess emissions are critical to an effective regime).

17. See R.W. Hahn and G.L. Hester, "Where Did All the Markets Go? An Analysis of EPA's Emissions Trading Program," *Yale Journal on Regulation* 6 (1989): 109–153.

18. For a theoretical analysis of this point and an empirical study of the relevant portion of the U.S. acid rain program, see J.-P. Montero, *Topics on Market-Based Environmental Policy* (unpublished doctoral dissertation, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, March 1997).

19. This issue is addressed by several studies, including H.D. Jacoby et al., "CO_2 Emissions Limits: Economic Adjustments and the Distribution of Burdens," *Energy Journal* 18 (1997): 31–58.

20. For more on this distinction, see R. Schmalensee, "Greenhouse Architectures and Institutions."

21. For recent studies, see G. Yohe, "Climate Change Policies, the Distribution of Income, and U.S. Living Standards," in *Climate Change Policy, Risk Prioritization, and U.S. Economic Growth* (Washington, D.C.: American Council for Capital Formation Center for Policy Research, June 1997) and H.D. Jacoby et al., "CO_2 Emissions Limits."

22. It would be simple enough to provide end-users with bonus allowances for CO_2 removed from flue gas, should cost-effective removal and sequestration technologies be developed. Downstream price signals and incentives to reduce emissions do not otherwise depend upon where allowances are issued.

23. See, for instance, J.M. Poterba, "Tax Policy to Combat Global Warming: On Designing a Carbon Tax," in R. Dornbusch and J.M. Poterba, eds., *Global Warming: Economic Policy Response* (Cambridge, Mass.: MIT Press, 1991).

24. An analysis of the relevant portion of that experience is provided by P.L. Joskow, R. Schmalensee, and E.M. Bailey, "The Market for Sulfur Dioxide Emissions," *American Economic Review*, forthcoming. While that program has worked well, it has *not* produced drastic reductions in compliance costs, as some have claimed. For an overview of research on this and related questions, see R. Schmalensee et al., "An Interim Evaluation of Sulfur Dioxide Emissions Trading," *Journal of Economic Perspectives*, forthcoming.

25. See, e.g., P.L. Joskow and R. Schmalensee, "The Political Economy of Market-Based Environmental Policy: The U.S. Acid Rain Program," *Journal of Law and Economics*, forthcoming.

26. On the U.S. acid rain experience, see Joskow and Schmalensee, "Political Economy"; for a general discussion, see N.O. Keohane, R.L. Revesz, and R.N. Stavins, "The Positive Political Economy of Instrument Choice in Environmental Policy," in P. Portney and R. Schwab, eds., *Environmental Economics and Public Policy: Essays in Honor of Wallace Oates* (London: Edward Elgar, forthcoming 1998).

27. For details on the acid rain experience, see Joskow and Schmalensee, "Political Economy." T.C.

Schelling, "The Cost of Combatting Global Warming," *Foreign Affairs* 76 (November/December 1997): 8–14, notes that the analogous problem of dividing Marshall Plan aid among European recipient nations was solved by detail-intensive negotiation, not by the application of abstract notions of fairness.

28. The literature on this issue is growing rapidly. Two useful recent contributions are I.W.H. Parry, R.C. Williams III, and L.H. Goulder, "When Can Carbon Abatement Policies Increase Welfare: The Fundamental Role of Distorted Factor Markets," Working Paper 5967 (Cambridge, Mass.: National Bureau of Economic Research, March 1997); and D. Fullerton and G. Metcalf, "Environmental Controls, Scarcity Rents, and Pre-Existing Distortions," Working Paper 6091 (Cambridge, Mass.: National Bureau of Economic Research, July 1997).

29. See Intergovernmental Panel on Climate Change, *Climate Change 1995—Economic and Social Dimensions of Climate Change*, Section 11.6.

30. For more on this, see Jacoby, Prinn, and Schmalensee, "Realistic Strategy."

COMMENTARY

Ronald G. Prinn

A SCIENTIST'S PERSPECTIVE

Richard Schmalensee of the Massachusetts Institute of Technology has provided us with a penetrating analysis of some policies prominent in the Clinton Administration's approach to the Framework Convention on Climate Change. Tradable permits and joint implementation are policy vehicles for achieving emissions reductions apparently favored by the Administration, and Professor Schmalensee uses the useful metaphor of looking under the hood of these policy vehicles. As a scientist I do not think I can either improve on or amend his expert analysis. I want instead to extend his metaphor and touch on who and what should drive these vehicles.

The origin of this issue lies in the climate sciences community, but in my opinion scientists have now become largely spectators as the policy vehicles themselves are being designed. Because the science is both uncertain and evolving, I will argue that scientists should be inside that vehicle; if not as drivers, then at least in the back seat. As a preamble to making that case, I will briefly say something about what science underlies this issue, how reliable the forecasts are, and why detection of the human influence on climate is important to the debate. A good deal of what I have to say here has also been recently presented elsewhere by me and my colleagues, so this presentation is in part a review. I will borrow shamelessly from this previous work with, of course, appropriate attribution.

What do we mean by the word *climate?* Climate is usefully defined as the average of the weather we experience over a ten- or twenty-year time period. Long-term temperature and rainfall changes are typical measures of climate change, and these changes can be expressed at the local, regional, country, or global scale. When the global average temperature changes we call that global warming or cooling.

What produces global warming or cooling? Fundamentally, it can be driven by any imbalance between the energy the Earth receives, largely as visible light, from the sun, and the energy it radiates back to space as invisible infrared light. The greenhouse effect is a warming influence caused by the presence in the air of gases and clouds which are very efficient absorbers and radiators of this infrared light. The greenhouse effect is opposed by substances at the surface (such as snow and desert sand) and in the atmosphere (such as clouds and aerosols[1]) which efficiently reflect sunlight back into space and are thus a cooling influence.

Easily the most important greenhouse gas is water vapor, which typically remains for a week or so in the atmosphere. Water vapor and clouds are handled internally in climate models, although with considerable uncertainty. Concerns about global warming, however, revolve around less important but much longer-lived greenhouse gases, especially carbon dioxide. The concentrations of carbon dioxide and some other long-lived gases (methane, nitrous oxide, chlorofluorocarbons) have increased substantially over the past two centuries due at least in part to human activity. When the concentration of a greenhouse gas increases (with no other changes occurring), it temporarily lowers the flow of infrared energy to space and increases the flow of infrared energy down toward the surface. The Earth is then temporarily receiving more energy, for example 1 percent more, than it radiates to space. This small imbalance, which is often called "radiative forcing," tends to raise temperatures at the surface and in the lower atmosphere. The rate of surface temperature rise is slowed significantly by uptake of heat by the world's oceans. The greenhouse effect as quantified by this radiative forcing is real and the physics relatively well understood. What is much more uncertain, and the cause of much of the scientific debate, is the response of the complex system that determines our climate to this radiative forcing. Feedbacks in this system can either amplify or dampen the response in ways which are only partially understood at present.

HOW GOOD ARE THE CLIMATE ROAD MAPS?

Much of the climate change debate is driven by forecasts of significant warming over the next century. The computer models used to make these forecasts attempt to simulate the behavior of clouds, water vapor, ocean circulation, and many other essential climate processes on the regional and global scale. These models are remarkable in their complexity and are invaluable tools for scientific research. However, many critical small-scale features such as clouds are not resolved individually in these models because the computational demands involved in these simulations already tax the capabilities of the world's largest computers. But even

more fundamental is our incomplete knowledge about the key processes that control these clouds, the ocean circulation, the natural cycles of greenhouse gases, and natural and man-made aerosols. Current climate models cannot simulate realistically the remarkable natural climate changes exemplified by the succession of ice ages and warm periods over the last 250,000 years and the important decade-to-decade oscillations in our current climate. There may even be serious limitations to predicting climate due to chaotic processes such as we already see in weather predictions. As a result, forecasts of future climate changes due to future emissions of greenhouse gases are very uncertain. The uncertainty in these forecasts is increased even further because the predictions of future emissions of greenhouse gases are dependent on equally uncertain global forecasts of populations, economies, and energy technologies.

To shed more light on the uncertainty in forecasts, a group at the Massachusetts Institute of Technology has recently developed a coupled model of global economic development, climate processes, and ecosystems.[2] This model is unique in its combination of coverage of critical areas and level of scientific and economic detail. Within this model the researchers have made some plausible but differing assumptions about future human activity and about fundamental climate processes to produce a family of seven forecasts of various climate indicators. Each forecast in the family can be defended as possible given current knowledge, and each forecast assumes no specific regulations are enacted to restrict future greenhouse gas emissions.

Figure 1 shows the predictions for the change in global average surface temperature from its 1990 value, with the mid-range forecasts being more probable than the extremes.[3] Evidently by 2100, temperature changes as small as one degree or as large as five degrees centigrade (2 to 9 degrees Fahrenheit) cannot be ruled out. About two-thirds of the overall range in the seven forecasts is due to differing assumptions affecting climate and the other one-third to assumptions affecting emissions. What is very important to realize from Figure 1 is that we do not know which of these roads (or indeed other possible roads) we are heading along in the absence of regulation. If we are on the lowest warming road, the impacts are likely to be relatively small. If we are on the highest warming road, the impacts and resultant concern are likely to be very large and there are compelling reasons therefore to take very significant action to avoid this road. I emphasize also that there may be significant changes in climate over the next hundred years driven by purely natural processes not well handled by this or any other current climate model. In this case, the whole family of forecasts in the figure may be invalidated.

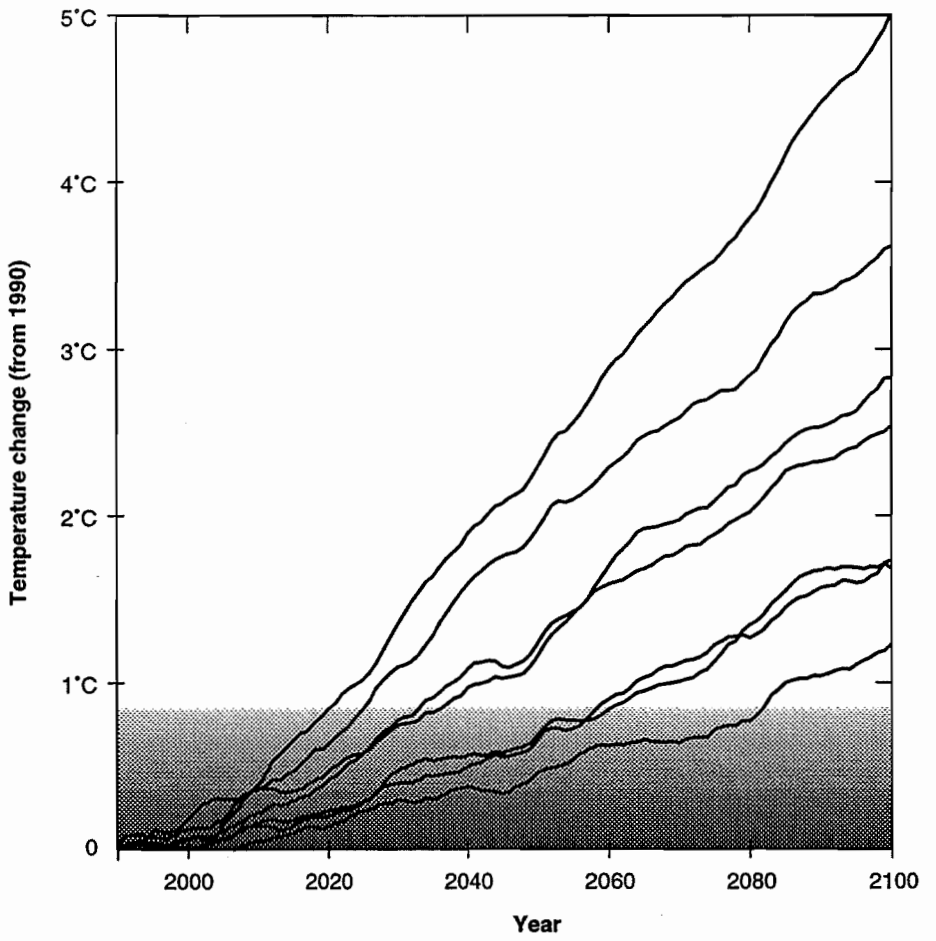
So the climate road maps are uncertain. I stress, however, that this uncertainty is not a good argument for waiting for more knowledge before taking some action. The long-lived greenhouse gases emitted today will last for decades to centuries in

the atmosphere. Therefore, if scientists can not presently rule out the rapid warming roads in the climate road map, then we should at least prepare for the actions we would take if we later find out we are indeed headed along a rapid warming road.[4]

WHAT ROAD ARE WE ON?

How can we determine which road, absent regulations, we are really on? Obviously, further research focusing on testing and improving the climate and emissions forecast models should help to narrow the range in these forecasts. The difficulties here for climate models include the need for more observations and

Figure 1 Sample Forecasts of Future Temperature Change



better understanding of the roles of oceans, aerosols, and clouds, and of chaos and other processes limiting predictability. But another, not unrelated, approach is to determine definitively whether human activity has already begun to substantially change the climate.

To this end, in 1996, the Intergovernmental Panel on Climate Change (IPCC) declared in its Summary for Policymakers that "the balance of evidence suggests a discernible human influence on climate."[5] There were qualifications and hedging in the Summary and much more so in the Working Group Report upon which it was based. Nevertheless this statement, largely in isolation, became widely reported and began to influence policy discussions around the world. But was this isolated, unqualified summary statement a scientifically defensible conclusion?

Human influence is indicated if the observed global patterns of climate change over the past one hundred years are shown to be consistent with those predicted by climate models which include the human influences, but not consistent with the patterns predicted when the human influences are neglected. The latter predictions are a measure of the natural variability of climate and represent the "noise" out of which the human "signal" must arise for a definitive detection. Herein lies a major problem. The imperfections of current climate models make them both inadequate tools for defining natural variability and uncertain predictors of the climate response to human forcing. There are other difficulties associated with the inadequacies in climate observations and poor knowledge of past levels of aerosols and their quantitative effects on sunlight reflection.

For these and other reasons, there were a few scientists who were skeptical about the IPCC's "balance of evidence" statement from the beginning. But now there are a growing number of scientists, including some who were involved significantly in the original IPCC conclusions, who are expressing doubts. In an important editorial on this subject, Richard A. Kerr describes the growing skepticism about the original IPCC Summary conclusion, and the growing realization that it may be a decade or more before the human effects can be discerned above the noise of natural variability.[6]

CAN A BACKSEAT DRIVER HELP?

The road map for policy vehicles is uncertain because the science is uncertain. How can scientists help in the evolving policy process? A definitive detection should be one important goal for scientists in the upcoming years and decades in order to inform policy. To illustrate this in a simplified way, we refer again to the predicted temperature changes in Figure 1. The shaded region at the bottom of the graph is intended to represent the albeit uncertain range of natural variability or

noise.[7] Evidently, the greater the predicted warming, the sooner the signal of the human effects arises from this noise. This conclusion holds irrespective of the uncertainty in defining the noise level itself. Achievement of a detection therefore helps to calibrate both the climate response to changes in human-induced radiative forcing, and the needed level of policy response.

Another calibration for policy response is provided by estimation of the climate changes avoided by enacting specific regulations. To do this well requires significant improvements in the climate forecasts as noted earlier. To illustrate this exercise, the MIT model has been used to examine one sample proposal in which the twenty rich OECD countries return their carbon dioxide emissions to 1990 levels by 2000, then bring their emissions down to 20 percent below 1990 levels by 2010, and finally hold them at this level thereafter.[8] There are no restrictions on any of the countries outside the OECD. The predicted temperature increases are reduced by only about 15 percent relative to the mid-range no-policy forecasts shown in the earlier graph. This analysis makes it clear that if we are heading along one of the rapid warming roads, the necessary emissions reductions to avoid this road will need to be substantially greater than those proposed in the above policy. Another important point that arises from analyses like these is that the predicted warming in 2100 is sensitive to the total emissions up to that time but relatively insensitive to the temporal pattern of the emissions. Hence higher emissions in the near term can potentially be offset by lower emissions later on (and vice versa).[9] This provides potential breathing time, but we need to use it very wisely.

The policy response can be further calibrated by quantifying the expected impacts of climate change on natural and human systems. Here the research is much less mature but it has high priority. For example, we need many more observations and much better fundamental understanding of the processes controlling ecosystems, as well as significant improvement in the accuracy of climate predictions at the country and regional level. The challenges here are great, but accurate quantification of impacts is essential to define the appropriate balance between the costs of policies to lower greenhouse gas emissions and the impacts avoided by these policies.

How can the needed intimate interaction between natural scientists, economists, and policymakers best be achieved? The IPCC process, while it has its merits, is not structured to provide the required continuous integrated assessment mechanism for policy. This task can, however, be undertaken by suitably cohesive and interdisciplinary research groups; this is a major goal of the program we have developed at MIT.

I will conclude by noting that if improved scientific understanding shows that we are on one of the rapid warming roadways shown in Figure 1 then very significant action to lower total long-term greenhouse gas emissions may become necessary.

Hence I fully endorse the plea by Professor Schmalensee and others that we take the steps now to make the political agreements and develop the technological capabilities to substantially lower emissions if and when the science shows that to be necessary.[10,11] This is just one reason why the policymaking process needs to be more receptive and responsive to the evolving scientific understanding. The decisions based on today's scientific understanding may not be the best decisions a decade from now. Hence there are compelling reasons to keep scientists inside the policy vehicles, whatever they turn out to be: a lot of good can come from even a backseat driver who knows the status of the imperfect climate road map.

NOTES

1. Aerosols are submicroscopic particles, ten or more times smaller than cloud particles, that are suspended in air. Volcanoes are important natural sources, and coal combustion important human sources of aerosols.

2. Ronald Prinn, Henry Jacoby, Andrei Sokolov, Chien Wang, Xiangming Xiao, Zili Yang, Richard Eckaus, Peter Stone, A. Denny Ellerman, Jerry Melillo, Jean Fitzmaurice, David Kicklighter, Gary Holian, and Yuexin Lin, "Integrated Global System Model for Climate Policy Assessment: Feedback and Sensitivity Studies," submitted to *Climate Change* (1997).

3. Prinn et al., "Integrated Global System Model."

4. Henry Jacoby, Ronald Prinn, and Richard Schmalensee, "Needed: A Realistic Strategy for Global Warming," MIT Joint Program on the Science and Policy of Global Change Report No. 21, August 1997.

5. Intergovernmental Panel on Climate Change Working Group 1, *Climate Change 1995: The Science of Climate Change*, ed. John Houghton et al. (Cambridge: Cambridge University Press, 1996).

6. Richard A. Kerr, "Greenhouse Forecasting Still Cloudy," *Science* 276 (1997): 1040–1042. See also Klaus Hasselman, "Are we seeing global warming," *Science* 276 (1997): 914–915.

7. Jacoby, Prinn, and Schmalensee, "Needed: A Realistic Strategy."

8. Henry Jacoby, Richard Eckaus, A. Denny Ellerman, Ronald Prinn, David Reiner, and Zili Yang, "CO_2 Emissions Limits: Economic Adjustments and the Distribution of Burdens," *Energy Journal* 18 (1997): 31–58.

9. T.M.L. Wigley, Richard Richels, and Jae Edmonds, "Economic and Environmental Choices in the Stabilization of Atmospheric CO_2 Concentrations," *Nature* 379 (1996): 240–243.

10. Jacoby, Prinn, and Schmalensee, "Needed: A Realistic Strategy."

11. Jae Edmonds, James Dooley, and Marshall Wise, "Atmospheric Stabilization and the Role of Energy Technology," in *Climate Change Policy, Risk Prioritization and U.S. Economic Growth* (American Council for Capital Formation Center for Policy Research, Washington, 1997): 73–94.

MIT JOINT PROGRAM ON THE SCIENCE AND POLICY OF GLOBAL CHANGE
REPRINT SERIES

Joint Program Reprints are available free of charge (limited quantities.) To order: please use contact information on inside of front cover.

JP 98-001. Parameterization of urban sub-grid scale processes in global atmospheric chemistry models, J. Calbo, W. Pan, M. Webster, R. Prinn, and G. McRae, *Journal of Geophysical Research*, 103(D3):3437-3467, 1998. (Also JP Report No. 20)

JP 98-002. Kyoto's unfinished business, H.D. Jacoby, R.G. Prinn, and R. Schmalensee, *Foreign Affairs*, 77(4):54-66, 1998. (Also JP Report No. 32)

JP 98-003. World carbon dioxide emissions: 1950-2050, R. Schmalensee, T.M. Stoker, and R.A. Judson, *Review of Economics and Statistics*, 80:15-27, 1998. (Also JP Report No. 5)

JP 98-004. A flexible climate model for use in integrated assessments, A.P. Sokolov, and P.H. Stone, *Climate Dynamics*, 14:291-303, 1998. (Also JP Report No. 17)

JP 98-005. A global interactive chemistry and climate model: formulation and testing, C. Wang, R.G. Prinn, and A. Sokolov, *Journal of Geophysical Research*, 103(D3):3399-3417, February 1998. (Also JP Report No. 24)

JP 98-006. Transient climate change and net ecosystem production of the terrestrial biosphere, X. Xiao, J.M. Melillo, D.W. Kicklighter, A.D. McGuire, R.G. Prinn, C. Wang, P.H. Stone, and A. Sokolov, *Global Biogeochemical Cycles*, 12(2):345-360, June 1998. (Also JP Report Report No. 28)

JP 98-007. Uncertainty in the oceanic heat and carbon uptake and its impact on climate projections, A. Sokolov, C. Wang, G. Holian, P. Stone, and R. Prinn, *Geophysical Research Letters*, 25(19):3603-3606, October 1998. (Also JP Report No. 23)

JP 99-001. Global thermohaline circulation. Part I: Sensitivity to atmospheric moisture transport, X. Wang, P.H. Stone, and J. Marotzke, *Journal of Climate*, 12:71–82, January 1999.

JP 99-002. Global thermohaline circulation. Part II: Sensitivity with interactive atmospheric transports, X. Wang, P.H. Stone, and J. Marotzke, *Journal of Climate*, 12:83–91, January 1999.

JP 99-003. Interhemispheric thermohaline circulation in a coupled box model, J.R. Scott, J. Marotzke, and P.H. Stone, *Journal of Physical Oceanography*, 29 (3):351–65, March 1999.

JP 99-004. Integrated Global System Model for climate policy assessment: Feedbacks and sensitivity studies, R. Prinn, H. Jacoby, A. Sokolov, C. Wang, X. Xiao, Z. Yang, R. Eckhaus, P. Stone, D. Ellerman, J. Melillo, J. Fitzmaurice, D. Kicklighter, G. Holian, and Y. Liu, *Climatic Change* 41(3/4):469–546, March 1999. (Also JP Report No. 36)

JP 99-005. Adjustment time, capital malleability and policy cost, H.D. Jacoby and I. Sue Wing, *The Energy Journal Special Issue: The Costs of the Kyoto Protocol: A Multi-Model Evaluation*, J.P. Weyant (ed.), Cleveland: IAEE, June 1999.

JP 99-006. Sequential climate decisions under uncertainty: An integrated framework, L.J. Valverde A., Jr., H.D. Jacoby, and G.M. Kaufman, *Environmental Modeling and Assessment* 4 (1999) 87–101. (Also JP Report No. 38)

JP 99-007. The uses and misuses of technology development as a component of climate policy, H.D. Jacoby, *Climate Change Policy: Practical Strategies to Promote Economic Growth and Environmental Quality*, pp. 151–69, May 1999. American Council for Capital Formation Center for Policy Research, Washington, D.C. (Also JP Report No. 43)

JP 99-008. Obstacles to global CO_2 trading: A familiar problem, A.D. Ellerman, *Climate Change Policy: Practical Strategies to Promote Economic Growth and Environmental Quality*, pp. 119–32, May 1999. American Council for Capital Formation Center for Policy Research, Washington, D.C. (Also JP Report No. 42)

JP 99-009. Tradable emissions rights and Joint Implementation for greenhouse gas abatement: A look under the hood, R. Schmalensee, pp. 39–55, with Commentary by R.G. Prinn, pp. 65–71, in *The Impact of Climate Change Policy on Consumers: Can Tradable Permits Reduce the Cost?* April 1998. American Council for Capital Formation Center for Policy Research, Washington, D.C.

Massachusetts Institute of Technology
Joint Program on the Science and Policy of Global Change
One Amherst Street (E40-271)
Cambridge, Massachusetts 02139-4307